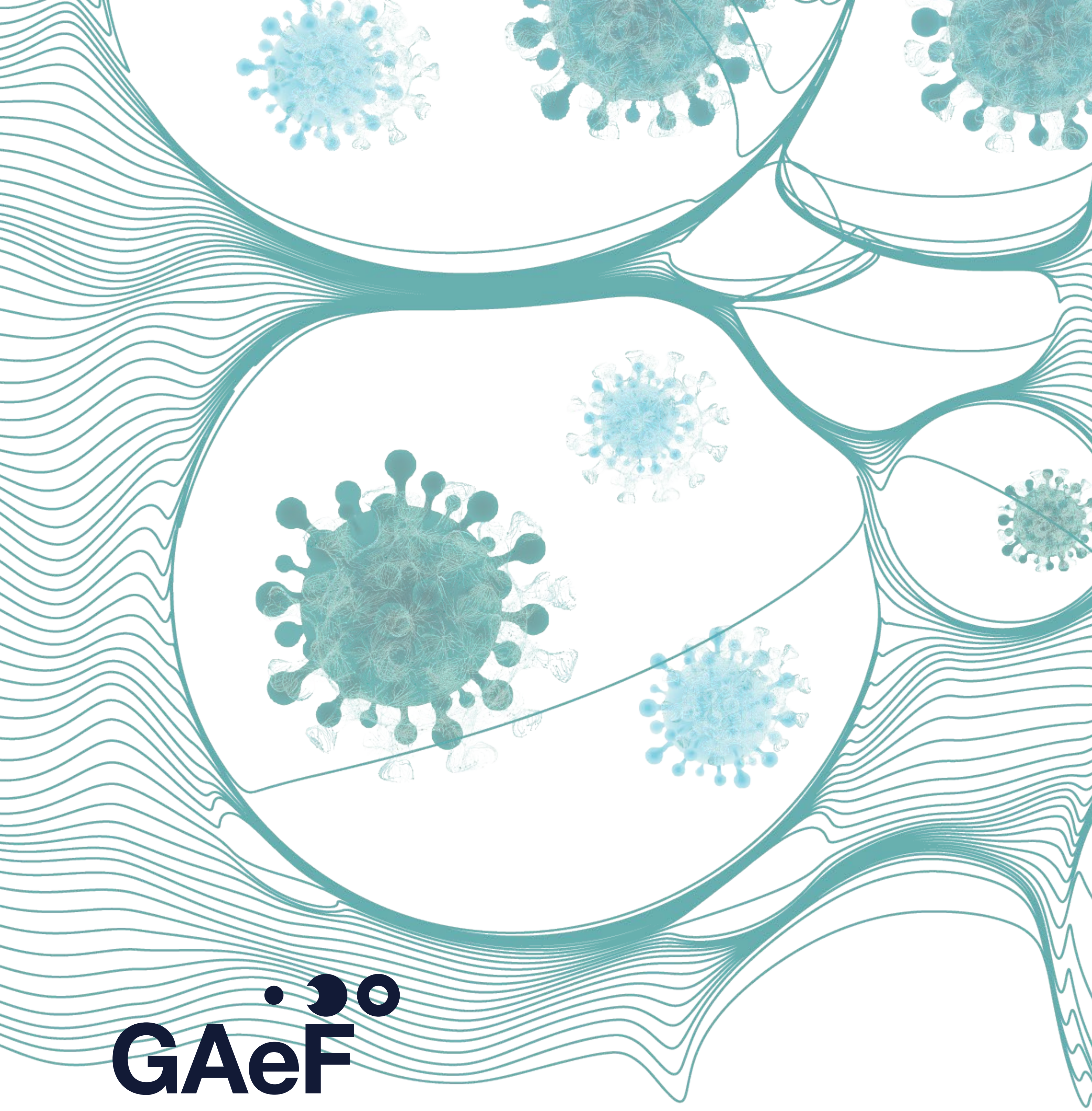

GAeF
Gesellschaft für Aerosolforschung
Association for Aerosol Research

Position paper of the Gesellschaft für Aerosolforschung

on understanding the role of aerosol particles in SARS-CoV-2 infection

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Further information on the GAeF: www.info.gaef.de

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Who is the Gesellschaft für Aerosolforschung?

The Gesellschaft für Aerosolforschung (GAeF) was founded in 1972 as a non-profit association of pioneers of aerosol research in German-speaking countries (Germany, Austria, Switzerland) and beyond. Its mission is to promote scientific aerosol research both nationally and internationally. For example, the GAeF regularly organizes the European Aerosol Conference with up to 1000 participants, the last one - online for the first time - in September 2020. The members of the society include leading national and international researchers as well as many students and PhD students from all aerosol research fields (atmospheric environmental aerosol, aerosol technology, aerosol measurement technology, medical aerosol, basic research). The GAeF has about 350 members from 35 countries and is coordinated with all other European societies for aerosol research in the European Aerosol Assembly (https://www.info.gaef.de/eaa) and is also globally networked in the International Aerosol Research Assembly (IARA, http://www.iara.org).

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Executive Summary

Many studies have already shown that viruses can spread via aerosol particles. An aerosol is a mixture of air with solid or liquid particles dispersed in it. To understand the role of aerosol particles as a transmission path of SARS-CoV-2, knowledge of the different processes in an aerosol is therefore of particular importance. With this paper, GAeF would like to contribute to a better understanding of the term “aerosol” and the relevant aerosol processes. In the context of this paper only the essential basics will be discussed. For a deeper understanding of the partly complex processes, please refer to the literature mentioned at the end of the paper. The paper summarises a large number of studies on the formation of virus-laden aerosol particles and their spread. Based on this, it can be concluded that exhaled aerosol particles may play a prominent role in the spread of viruses in the corona pandemic. Finally, this paper discusses possible measures to reduce the spread of aerosol particles. The measures discussed are based on the current public debate including ventilation, air purifiers, HVAC systems and masks. Advice is given on the correct and sensible use of these measures.

An aerosol is always dynamic, as particles are newly formed, transported in or with the air, removed from the air or change in the airborne state. Aerosol particles have sizes between approx. 0.001 and several 100 micrometres (and not < 5 µm as currently defined in many publications) and spread relatively quickly with air currents, even over longer distances. Larger aerosol particles sink to the ground, depending on their size and density, while small aerosol particles can remain in the air for a very long time (see Section 3). Every person emits liquid aerosol particles of various sizes through breathing and when speaking, coughing and sneezing (see Section 4). If a person is infected with a virus, such as SARS-CoV-2, these aerosol particles can contain viruses that can be released into the air and inhaled by other people. SARS-CoV-2 has a size of 0.06 to 0.14 micrometres, but the exhaled liquid aerosol particles are larger. The liquid aerosol particles can shrink by evaporation, depending on the ambient conditions (see Section 3.3). Particle size is relevant for particle transport and particle separation. The highest risk of infection exists in closed indoor spaces, as aerosol particles can accumulate there. Here in particular, appropriate measures must be taken to reduce the concentration of aerosol particles (see Section 5).

Against the background of aerosol science, the GAeF classifies the current measures to contain the pandemic as follows:

- In principle, no measure can work on its own! According to the current state of knowledge, the interaction of the most varied measures is the best way to minimise the risk of infection.
- Keeping distance is important, because with increasing distance, directly exhaled viruses are diluted and the probability of infection decreases. The often prescribed minimum distance can be used as a guide, but it should be increased and supplemented by other measures (see below), especially for longer meetings and also indoors with reduced air movement.
- Masks help to filter some of the exhaled particles (and viruses). This reduces the concentration of exhaled particles (and viruses) in a room and thus the risk of infection. It should be noted here that the exhaled aerosol particles are relatively large due to adhering moisture and can therefore also be efficiently retained by simple masks (see Figure 6). However, since these particles shrink with longer dwell time in the room air, simple mouth-nose masks are less efficient for self-protection. Respiratory masks are required for this purpose, which show a high degree of separation even for fine particles, e.g. of classes FFP2, N95 or KN95. These are efficient for both self-protection and protection of others unless they have an exhalation valve. Masks with an exhalation valve, on the other hand, are only for self-protection and therefore contradict the solidarity concept that fellow human beings are protected by collective mask wearing (see Section 6).

- Face shields which are used without additional masks are largely useless with regard to aerosol particles, as the air with particles (and viruses) flows unfiltered around the shields. In everyday clinical practice, facial shields are worn in addition to masks to prevent droplet infection via the mucous membranes of the eyes. Mobile or permanently installed Plexiglas barriers are also largely ineffective against the spread of aerosols indoors. These can only prevent the small-scale spread of an aerosol in the short term, e.g. in the checkout area of a supermarket, but offer no protection in the longer term. Face shields and Plexiglas panels essentially serve as spit and splash protection against large droplets.

- Outdoors, there are practically no infections caused by aerosol transmission. However, droplet infections can still occur, especially in crowds, if minimum distances are not observed and/or masks are not worn. In closed rooms, ventilation is essential to replace the exhaled air in a room with fresh air from outside. Frequent airing and cross-ventilation is just as effective as leaving the window open all the time. From an energy point of view, however, it is more efficient to ventilate the room, especially in winter. CO_2 monitors can help to monitor indoor air quality. They indicate when it is necessary to ventilate and when the air in a room has been sufficiently changed during ventilation. However, they can only be used as an indicator and even if the proposed CO_2 limit concentrations are met, they do not prevent direct infection by people in the immediate vicinity.

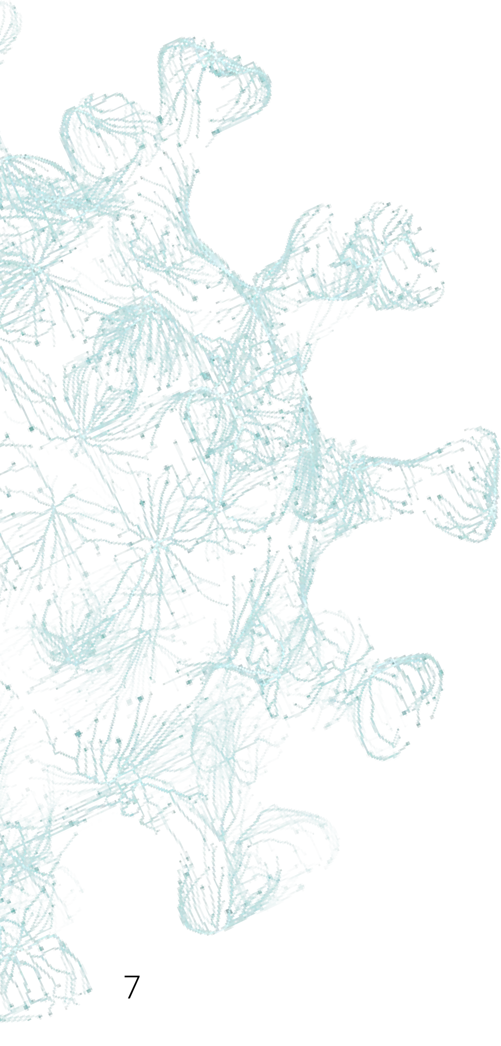
- Air purifiers can make a useful contribution to reducing the concentration of particles and viruses in a room. When procuring air purifiers, care must be taken to ensure that they are adequately dimensioned for the room and application in question in order to significantly reduce the particle and virus load. The air throughput of the unit is more important than the pure efficiency of the filter. For energy and cost reasons, the use of highly efficient filters can even be counterproductive (see Section 5.2). Permanently installed ventilation systems can also be useful, provided they filter the air to reduce the particle and virus load in a room. To avoid infections, it is advisable to operate them with 100 % fresh air if possible (see Section 5.3).

From the point of view of the Gesellschaft für Aerosolforschung, there is a considerable need for research, especially at the interdisciplinary borders to research fields of epidemiology, infectiology, virology, ventilation technology and fluid mechanics. The implementation of targeted studies should be made possible at short notice with special funding and research programmes (see Section 7).

This paper was written originally in German by members of the Gesellschaft für Aerosolforschung and is supported by a large number of international aerosol experts (see Section 8). Both the English and German version as well as all images in the paper are available for free download at the following link: https://www.info.gaef.de/positionspapier. The “Gesellschaft für Aerosolforschung e. V.” must be named as the source, whenever an image is used.

1. Goal of this paper

The present position paper is addressed to representatives of the media, authorities, administration and politics, as well as to the interested public. With this paper, the Gesellschaft für Aerosolforschung (GAeF, https://www.info.gaef.de) would like to contribute to the management of the pandemic caused by the SARS-CoV-2 virus by aiding the understanding of possible transmission routes. In the context of research into transmission paths, aerosol transmission has been discussed for some time as an important route of infection in addition to smear and droplet infection [1, 2]. The virus can survive for several hours in an airborne state [3]. From the GAeF's point of view, however, some things are mixed up in the public discussion. As the possible transmission routes are close to measures to prevent transmission, GAeF would like to contribute the necessary expert knowledge in a generally understandable way. The topic is viewed purely from the perspective of aerosol research and no medical, epidemiological, virological or conclusions on infectiology are drawn. In our view, increased cooperation between the various disciplines is necessary to clarify the transmission routes, even beyond the current pandemic.



2. What is an aerosol?

The word aerosol is an artificial word, composed of the ancient Greek word ἀήρ (aēr) for "air" and the Latin word solutio for "solution. Physically speaking, an aerosol is a heterogeneous mixture of particles together with the gas or gas mixture surrounding them (here: air, see Figure 1). The airborne particles can be solids such as soot or mineral dust as well as liquid droplets. In a stable aerosol, the liquid or solid components are homogeneously distributed as suspended particles. Correspondingly, for example, our ambient air together with the fine dust[1] suspended in it is an aerosol. In this paper, the term "aerosol particles" or "particles" for short is therefore used for all airborne particles. Often, however, especially in the current public discussion, the term aerosol is used incorrectly when only referring to aerosol particles (e.g. [4]). Since the majority of air consists of gaseous molecules such as nitrogen and oxygen, the solid or liquid particles are the special feature of aerosols. Aerosol particles are so small and light that they can float in the air for a certain time depending on their size. Aerosol particles can remain in the outside air for many hours or days and thus be transported over long distances.

One litre of air normally contains many millions of aerosol particles, which influence, among other things, the climate and the formation of clouds [5] as well as chemical reactions in the atmosphere [6]. In higher concentrations, they can also affect human health [7] as fine dust. In the course of a day, an adult person inhales an average of about one hundred billion particles. The effect of aerosol particles depends on their number, size, mass and chemical composition. These properties, in turn, are influenced in different ways by a wide variety of natural and man-made sources [8]. The size range of aerosol particles is not precisely defined, but is typically specified for particle diameters from about 1 to 2 nanometres (nm, millionths of a millimetre, i.e. 0.001-0.002 μm) to >100 micrometres (μm, thousandths of a millimetre) [9, 10]. The majority of atmospheric aerosol particles (such as soot or ammonium sulphate particles) are smaller than 1 μm. Mineral dust or sea salt particles, but also bacteria are usually larger than 1 μm. The size of pollen is between 10 μm and 60 μm. SARS-CoV-2 viruses have sizes between about 0.06 μm and 0.14 μm [11], and may also be slightly smaller [12]. For comparison: human hairs have diameters between 20 μm and 80 μm.

Viruses are formed in or on tissue. They cannot detach themselves individually from a surface. Consequently, viruses typically do not exist as individual particles, also called virions, in an aerosol, but are transported in the air in larger solid or liquid particles. Particularly in the medical literature and also in the public discussion on SARS-CoV-2, the misleading and arbitrary distinction between aerosol particles with diameters < 5 μm and droplets with diameters > 5 μm is frequently found, which assumes a different behaviour of aerosol particles and droplets. This differentiation of aerosol particles and droplets is not useful either with regard to the transport behaviour [13, 14] (see Section 3.1) or the infectiousness of the particles (see Section 4), especially since the liquid components of the aerosol particles

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[1] *Particles with a so-called "aerodynamic diameter" smaller than 10 μm (PM10) or 2.5 μm (PM2.5) are also known as fine dust*

evaporate quickly. In any case, the size distribution of the particles is decisive. In the literature, there are various classifications of size classes, which are, however, often determined by the measurement technology used and not exclusively by the particle behaviour relevant to the infection.

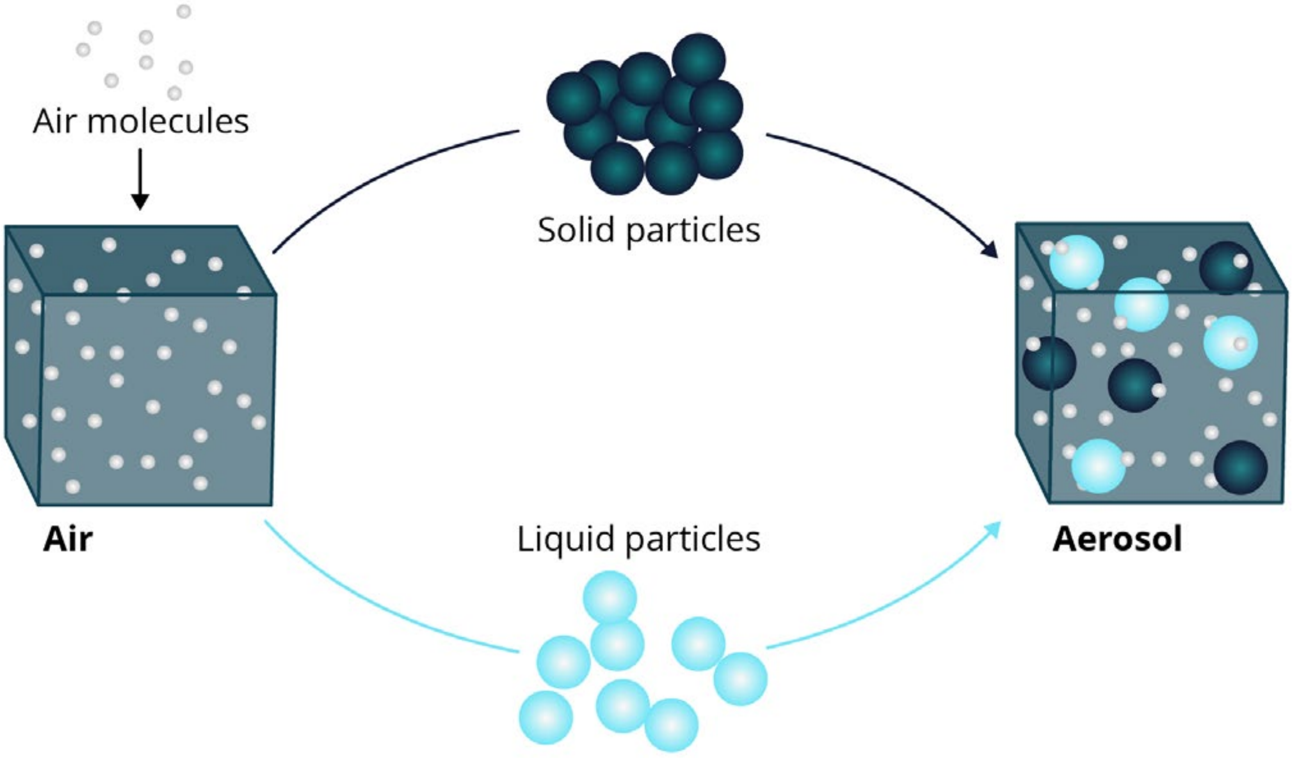

Figure 1: Definition of an aerosol: air with liquid and/or solid particles dispersed therein

3. COVID-19-relevant fundamentals of aerosol physics

3.1 Fundamentals of particle motion

The relevance of aerosol physics for the understanding of the infection process was recently highlighted by Drossinos and Stilianakis [13] in an editorial for the journal Aerosol Science and Technology. An essential component of aerosol physics is the movement of aerosol particles, which is highly dependent on the size of the particles [4, 9]. Since aerosol particles do not always have a defined geometrical shape, the geometrical diameter of a sphere is only used to describe the particle size in the simplest and idealised case. In order to take into account the influence of the particle geometry (aerodynamic resistance) and the chemical composition (density of the particle), the size of particles is usually specified as the socalled aerodynamic diameter. The aerodynamic diameter is defined as the diameter of a spherical particle with a density of 1 gram per cubic centimetre (e.g. a drop of water), whose behaviour corresponds to that of a real particle moving in the air flow.

Aerosol particles are transported with the often turbulent air flow and are thus quickly distributed both indoors and outdoors. In order to understand particle transport, it is also necessary to describe the particle movement relative to the air flow, which is determined by the forces acting on the particles in an aerosol. Depending on the temperature, air molecules are in constant thermal movement with random direction and speed and thus collide with the aerosol particles distributed in the air. This causes them to transfer energy and momentum and thus leads to frequent changes in the speed and direction of movement of the particles. This so-called Brownian molecular movement results in diffusive transport [15, 16], which increases as the particle diameter decreases and is particularly relevant for particles with diameters of less than 0.1 µm. In this particle size range, diffusion is the most important transport mechanism over short distances, which is important for particle filtration [17] or particle deposition, i.e. the depositing/removal of particles, for example in the lungs [18]. For particles larger than approx. 0.1 µm, diffusion plays an increasingly subordinate role as the particle size increases, and gravity becomes more important. Whenever particles move relative to the surrounding air, a braking frictional force acts in the opposite direction to the movement, due to the aerodynamic resistance. Thus, when aerosol particles sink due to gravity in still air, a stable sedimentation speed is quickly established, which depends on the particle geometry and density, i.e. the aerodynamic diameter of the particles. In still air, a 1 µm spherical aerosol particle with the density of water would take about 7.5 hours to sink to the ground from a height of 1 meter. A 10 µm particle would need only about six minutes. Some examples of the time it takes for particles to sink one metre under gravity alone are shown in

Figure 2. This deposition rate assumes that the particle size does not change during transport. Exhaled liquid aerosol particles, on the other hand, typically release water and shrink as a result. For a better understanding of this process, please refer to Section 3.3.

The numbers in Figure 2 refer to still air. However, particles are also transported by air movement outdoors and indoors (advection and turbulent transport) and may therefore remain in the air much longer than shown in the figure if upwardly directed forces counteract the gravitational force. Through the so-called advection (horizontal transport) with the air flow, aerosol particles can be transported over very long distances outdoors. With the turbulent air movement, aerosol particles are also transported vertically. Indoors, typical flow velocities of around 0.1 m/s can keep particles up to an aerodynamic diameter of 20 µm in suspension for a long time [19] and distribute them quickly throughout the room. In the process, exhaled air, which may contain particles laden with viruses, is mixed with the room air and rapidly diluted. If, however, the room air is not exchanged (ventilation) or filtered (ventilation system or air cleaner), it accumulates over time. In contrast, the exhaled particle concentration in the outside air is quickly diluted and removed, so that no accumulation occurs. Only for particles with diameters well over 100 µm can a ballistic trajectory be assumed to describe the transport, so that these particles sediment quickly and are no longer airborne. This describes the spread of particles that are ejected at high speed when coughing or sneezing, as with a thrown ball (see Section 4.2 and Figure 3).

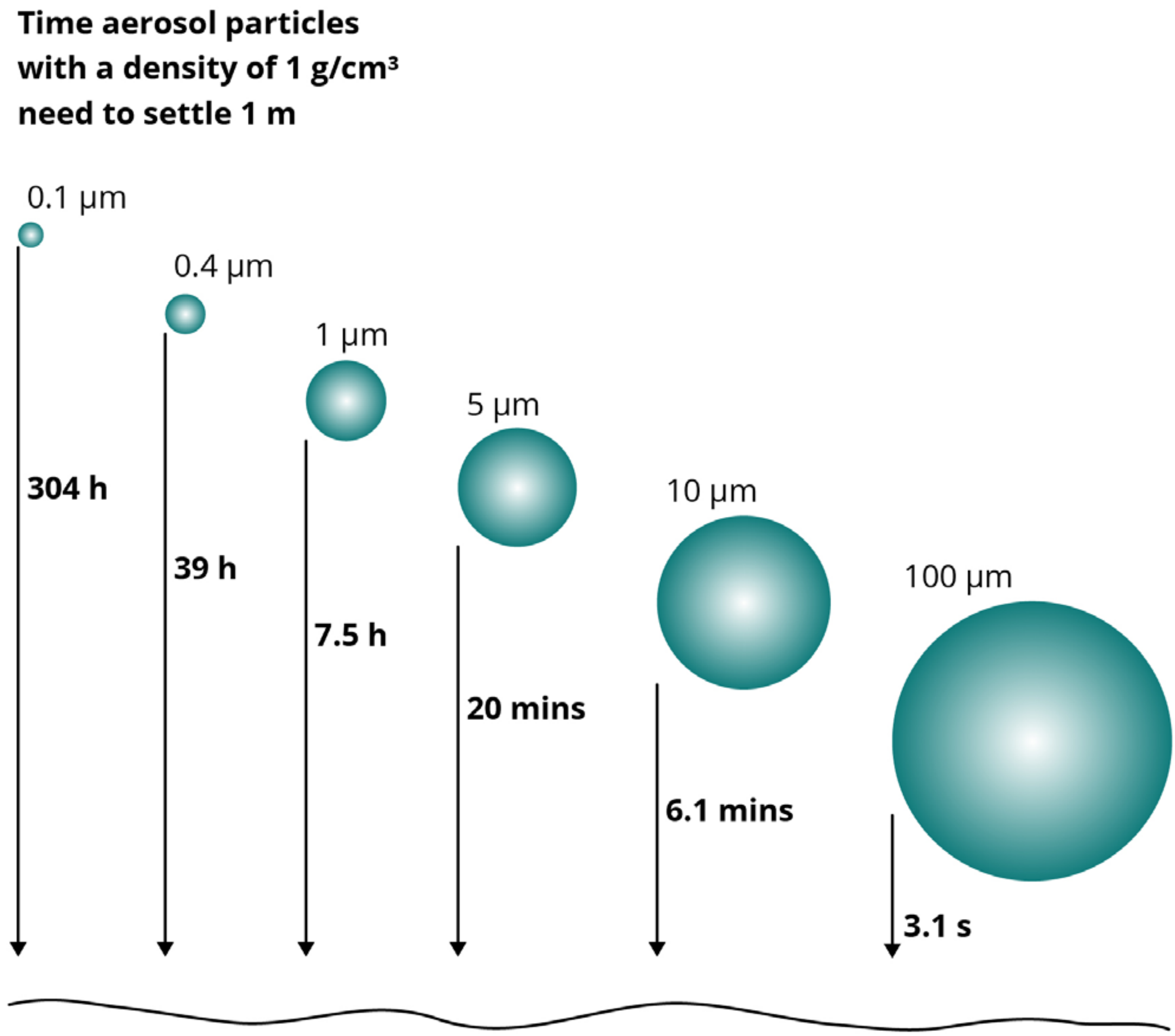

Figure 2: Exemplary illustration of the gravity-induced sedimentation of spherical particles with a density of 1 g/cm³ in still air
**representation not to scale*

3.2 Particle deposition

Various processes result in aerosol particles being removed from the air. Particle deposition, i.e. the deposition of aerosol particles on the ground or on surfaces, plays a very important role. For larger particles (typically > 1 µm) gravity is relevant for the deposition, i.e. the sinking of the particles to the ground. At high relative humidities, even originally small particles can, due to their chemical composition, absorb and accumulate moisture and thus sediment faster [20, 21]. Conversely, liquid particles shrink at low humidity. Smaller particles (approx. < 0.1 µm), on the other hand, can be deposited on surfaces due to Brownian molecular movement. If air flows are directed at obstacles, larger particles cannot follow the change in direction due to their inertia, these large particles are deposited on the obstacle by the impact [9]. If aerosol particles can follow the air flow around an obstacle but are deposited because of their size and proximity to the obstacle, this is called interception [9]. These separation mechanisms are specifically exploited in particle filters to remove particles from the air [17]. Particle filters are explained in Section 5.1.

Depending on the local conditions, particle deposition is typically lowest in a particle size range of about 0.1 - 0.3 µm (the proportions are shown graphically in the particle filtration section of Figure 5). This means that these particles remain in an airborne state for a very long time and can float in the air for more than 24 hours in closed rooms without air exchange.

3.3 Evaporation of liquid particles

Aerosol particles are in constant exchange with the surrounding water vapour. This is particularly true for liquid aerosol particles, which often consist largely of water. The particles strive for an equilibrium with the water vapour in the air. How much water an aerosol particle contains depends on its composition and relative humidity. This applies in particular to exhaled liquid particles that are particularly relevant in the context of COVID-19. In the respiratory tract there are warm and humid conditions (relative humidity of about 100 %), so that aerosol particles have a high water content there. After exhalation, water evaporates from the particles. This process was described by Wells in 1934 [22]. The particles dry and shrink at a rate that depends on the particle surface, air temperature and relative humidity [23]. For particles of the same composition, the larger surface to volume ratio means that smaller particles evaporate faster [24]. Drewnick et al. [25] have calculated that an initially 100 µm diameter pure water droplet needs 15 s at a relative humidity of 50 % to shrink by evaporation to the size of a SARS-CoV-2 virus (0.14 µm), a 10 µm water droplet 0.1 s and a 1 µm droplet only 0.003 s. At 90 % relative humidity, the water droplets need about four to five times as long. This change in size influences both transport and filtration properties. Therefore, the size change of the particles after exhalation must be taken into account. While the exhaled particle size - that is the size of the particle immediately after exhalation - is relevant for deposition in a mask during exhalation, the size reduced by drying must be taken into account for the duration of the aerosol particles‘ stay in the ambient air and for their deposition in masks for self-protection, in air purifiers and in ventilation systems.

4. When and how are viruses or virus-containing aerosol exhaled?

Aerosol particles are released in the human respiratory tract. Obviously, this happens when sneezing and coughing. However, particles are also generated during normal breathing, speaking, singing, whispering and shouting. The particle sizes mentioned below refer to freshly exhaled particles, but they can shrink due to evaporation after exhalation (see previous Section 3.3).

A much discussed mechanism of viral infection with respiratory involvement is pure breathing. Since we breathe 24 hours a day and an adult inhales and exhales between 10 and 25 m^3 of air each day [9], even low aerosol concentrations during release are sufficient to release considerable quantities of potentially viral aerosol particles into the environment. Compared to the typical particle concentrations prevailing in indoor and outdoor areas, however, these quantities are small, so that the exhaled particles make only a negligible contribution to the fine dust concentration. A healthy person breathes out between one hundred and several hundred aerosol particles per litre[2] of air during normal resting breathing, which are produced in the peripheral lung during inhalation by "reopening collapsed airways". The phenomenon was first described in 1988 by Gebhart et al. [26], and Johnson and Morawska [27] confirmed the mechanism in 2009. Olin et al [28, 29, 30, 31] then investigated in detail what these exhaled particles are made of and found that they are mainly lung fluid (*surfactant*), with viruses also found in the particles. Hohlfeld et al. [32, 33, 34] were able to determine the particle size, which is between 0.2 and 0.4 µm. However, since many studies on exhaled aerosol particles only measure from a size of 0.3 µm or 0.5 µm due to metrological restrictions, many publications report number concentrations for exhaled particles that are clearly too low. Current studies have shown that the number of exhaled particles can rise dramatically to values of several tens to hundreds of thousands of particles per litre of air in the case of a respiratory tract infection. However, this does not necessarily happen in every infected person. After the infection has subsided, they only exhale a few particles per litre of air [35, 36].

Another mechanism for spreading viruses via the airborne pathway is speaking and singing [37, 38]. In these activities, several thousand to a hundred thousand aerosol particles per litre are produced by the vibration of the vocal cords and the movement of the tongue, teeth and lips [39]. However, these particles are usually larger than those generated by breathing. Asadi et al. [40] found that the particles have a size of about 1 µm and that more particles are produced with increasing volume. Previously unpublished studies by Jensen et al. showed particle sizes around 2 µm[3].

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[2] *1 l = 1000 cm^3*

[3] *Personal communication with Prof. Dr. Keld A. Jensen, NRCWA, Copenhagen, Denmark*

4.1 The spread of viruses by breathing air

In 2008, the group led by Patricia Fabian and Donald Milton from the University of Massachusetts was able to detect influenza viruses in exhaled aerosol particles [41]. The authors showed that 87 % of the exhaled aerosol particles had sizes of less than 1 µm. Later, Milton et al [42] again detected influenza viruses in the air exhaled by infected patients. In 35 out of 37 influenza-infected patients, they found significant amounts of influenza viruses in the small particle size range caused by normal breathing, while they could only detect viral RNA when coughing in 16 out of 37 patients. The amounts of virus material collected were also many times smaller than those found in the small aerosol particles during normal breathing.

Lindsley et al [43] were also able to detect significant amounts of influenza A viruses in the exhalate. Although the authors found slightly more viruses in coughing than in normal breathing, they noted that coughing occurs much less frequently than breathing, and therefore the spread of viruses probably occurs much more frequently and effectively through normal breathing.

Fabian et al. [44] also found rhinoviruses in the exhalation of infected patients. These were mainly found in the smallest particles that could be measured. The fact that the spread of different viruses occurs through the normal breathing of infected persons has now also been proven by various other research groups. For SARS-CoV-1 viruses, the results can be found in the studies by Wang et al [45] and Gralton et al [46]. Mitchell et al [47] found rhinovirus, RSV, influenza A, influenza B, parainfluenza viruses 1, 2 & 3 and human metapneumovirus, Yip et al [48] influenza A viruses. Shiu et al [49] found influenza A RNA in aerosol in ambient air in a children's ward in a patient's room. It can be assumed that the findings of these investigations can also be transferred to SARS-CoV-2 viruses.

Morawska and Cao [50] point to the many observations which make it extremely plausible that the SARS-CoV-2 epidemic is also influenced at least to a large extent by the transmission of exhaled viruses and that this must be taken into account in the measures to contain the pandemic.

Van Doremalen et al [3] investigated how long SARS-CoV-2 viruses remain active in an aerosol. They found half-lives of between 1 and 1.1 hours. Smither et al. [51] found half-lives of between about half an hour and three hours in daylight, depending on the humidity. In darkness, however, the viruses were stable for a long time. Brlek et al. [52] were able to show that athletes in a squash hall in Slovenia became infected with SARS-CoV-2 after an infected person played squash there. Fears et al. [53] showed that airborne SARS-CoV-2 viruses can remain infectious for over 16 hours under certain circumstances.

Ma et al. [36] found in a study that there are individuals who exhale up to 400,000 viruses per minute. Numerous studies have also found viruses and virus RNA in the air in hospital rooms and even in hospital corridors, although they found no virus in exhalation in 75 % of patients. Lednicky et al [54] were able to detect infectious SARS CoV-2 viruses in airborne aerosol particles at a distance of 4.8 m from a Covid-19 patient in hospital. Zhou et al. [55] found SARS-CoV-2 viruses in the exhaustive respiratory condensate of two of the nine patients examined who were to be discharged from hospital after suffering from covid-19 disease. The concentration was about 100 viruses per litre of respiratory air.

In a study of infection chains, Qian et al. [56] found that COVID-19 infection is essentially an indoor phenomenon and that almost no infections occur outdoors, i.e. outside enclosed spaces. Out of more than 7000 observed and documented infections, only one single infection occurred outdoors. This is probably due to the fact that a rapid dilution of virus-laden aerosol particles is to be expected in outdoor areas, which reduces the risk of infection (see Section 3.1). However, especially in large crowds with small distances between people, an infection cannot be ruled out even outdoors.

Based on the large number of available studies and findings, it can be assumed that exhaled aerosol particles also play a prominent role in the spread of the viruses in the corona pandemic. Sections 5 and 6 therefore deal with how the spread of viruses can be contained.

4.2 Droplet infection

When coughing, sneezing, talking or singing, drops larger than 100 μm in diameter are emitted, which, as explained above, no longer behave like aerosol particles. However, these can play an important role in direct droplet transfer. Due to their much larger volume compared to aerosol particles, they can contain more viruses, which means that droplet infection often plays a dominant role. The trajectory of such particles is strongly dependent on the emission speed and direction. Figure 3 shows examples of trajectories of 200 μm droplets for ejection velocities such as those that can occur in particular when coughing. When sneezing, the ejection velocities are often even higher, so that the particles can be transported even further. For the calculation it was assumed that the drops are ejected at a mouth height of 1.70 m and that the drop size does not change during transport. It can be seen that the distance rule of 1.5 m is very sensible with regard to such particles, or perhaps even rather tight. Face visors or poorly fitting masks, which are only slightly effective for small aerosol particles, can be effective for these large droplets. It should be noted that for droplets larger than 100 μm the dilution is irrelevant, so with regard to direct droplet infection it is not important whether the persons are outside or inside.

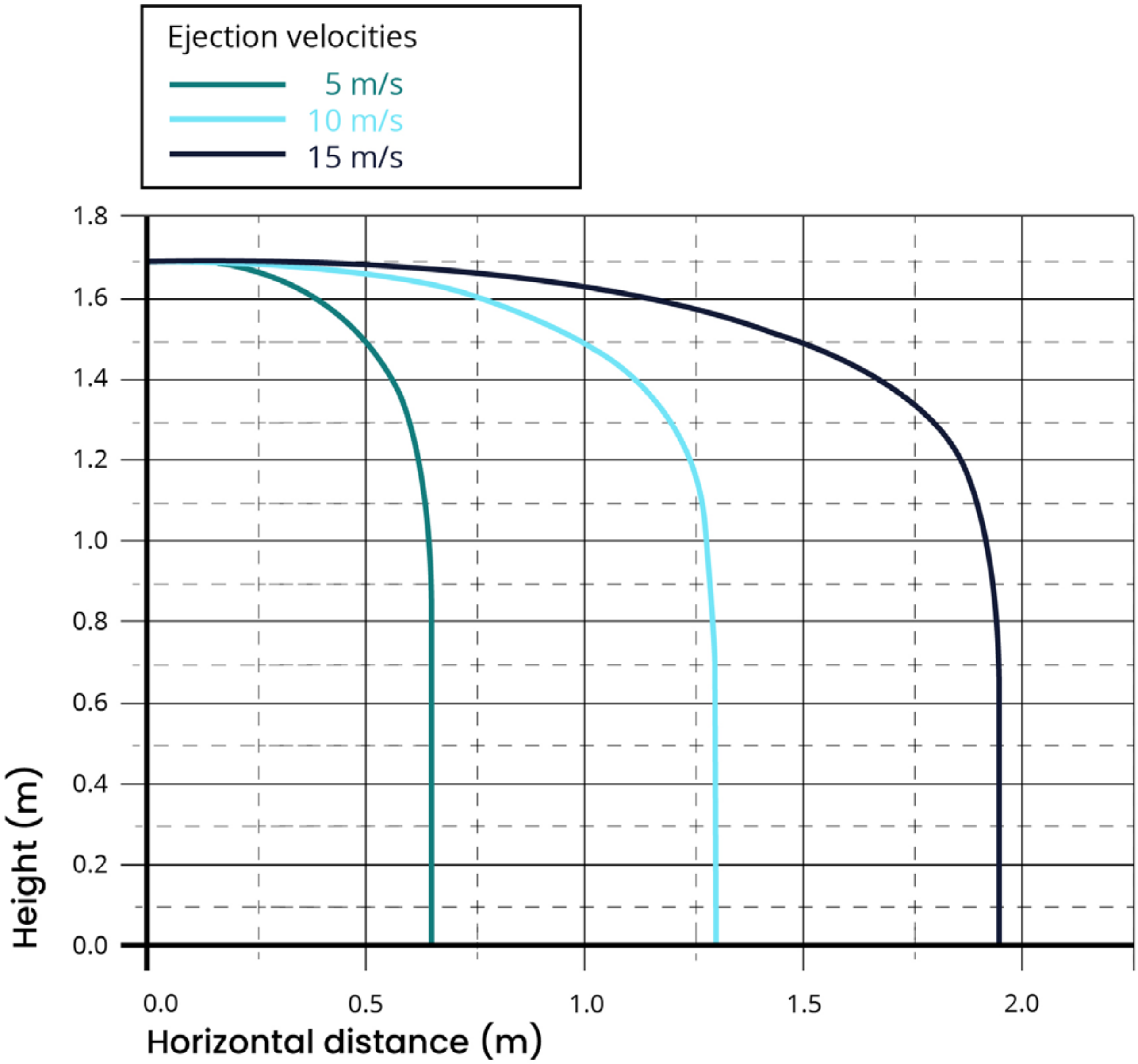

Figure 3: Trajectories of droplets with a diameter of 200 µm and the density of water ejected at different velocities at a height of 1.70 m (based on [57])

5. Ways to reduce the concentration of viruses in indoor air

There are various ways of reducing the concentration of viruses in room air. While measures such as ventilation and filtration aim to reduce the concentration of viruses, the irradiation of air or filters with UV light is used to inactivate viruses.

An effective process for reducing the concentration of particles in a room - and thus in a similar way to the concentration of virus-containing aerosol particles - is dilution with cleaner, less particle-laden, i.e. virus-free air. In outdoor areas, dilution takes place constantly through natural air movements. Indoors, dilution can be achieved by efficient ventilation. For this purpose, windows should be opened and air movement should be provided. The most effective way to do this is by airing the room from side to side, i.e. apart from the windows in the room, skylights and/or doors should be opened, as well as windows and doors in adjoining rooms. The ventilation time required depends on the size of the room, the number and size of the windows and the difference in temperature between inside and outside. If necessary, the exchange of air can be forced mechanically, e.g. by a fan. It should be borne in mind that although the outside air is virus-free as a rule, it is not free of other air pollutants. Although the concentration of viruses can be lowered by ventilation, the general air quality in the interior may even deteriorate.

The need for ventilation can be monitored, for example, by continuously measuring the carbon dioxide (CO_2) concentration in the interior. Sufficiently accurate CO_2 monitors (also known as CO_2 traffic lights) are commercially available at low cost. Since CO_2 is produced during respiration in the same way as virus-contaminated aerosol particles, the CO_2 concentration can, under certain conditions, also be taken as an indicator for the concentration of exhaled aerosol particles. However, this only applies in cases in which no active filtering of the indoor air, e.g. with air purifiers (see Section 5.2) or ventilation systems in recirculation mode (see Section 5.3), is performed. In these cases, aerosol particles are extracted from the air, but not the CO_2. This would mean that ventilation would tend to be too frequent, which can be unfavourable from an energy point of view. However, the risk of infection would tend to decrease. The CO_2 concentration at which ventilation should start is currently under discussion. According to the Commission on Indoor Air Hygiene of the German Federal Environment Agency, a CO_2 concentration of less than 1000 ppm (0.1 vol%) indicates hygienically adequate air exchange under normal conditions [58]. The German Social Accident Insurance (Deutsche Gesetzliche Unfallversicherung) advises that this value should be kept as low as possible in day-care centres [59]. The natural CO_2 concentration in outside air is approx. 410 ppm and cannot fall below this value indoors either.

Although ventilation can reduce the particle concentration and viral load indoors, it cannot prevent direct droplet infection between two people if the distance is too small.

Further possibilities for reducing the concentration of particles and viruses exist in filtration solutions, which are described below.

5.1 Fundamentals of air filtration

Particulate filters are usually made of *nonwovens*. According to EN 29092, nonwovens are networks of three-dimensionally arranged fibres. Aerosol particles are separated in filters by different mechanisms. The frequently encountered idea that particle filters function like “sieves” or “fishing nets” and thus only retain large particles is fundamentally wrong, because very small particles in particular can be filtered out with very high efficiency due to their Brownian molecular movement [60, 61]. If an aerosol flows through the open areas between the fibres in a filter, three different mechanisms lead to the separation of particles on the fibres [9]: Impaction, interception and diffusion [17], see Figure 4 and Section 3.2.

These three mechanisms have different effects on particles of different sizes. Impaction, i.e. inertial separation of particles, is the dominant separation mechanism for particles >1 µm. The influence of interception also increases with increasing particle size. The diffusion due to Brownian molecular movement, on the other hand, increases with decreasing particle size and is the essential and highly efficient separation mechanism in filters for particle sizes <0.1 µm. As soon as a particle hits a fibre, it sticks to it. It is largely impossible for particles separated in a filter or on other surfaces to detach again, as unrealistically high forces would be required to do so [62].

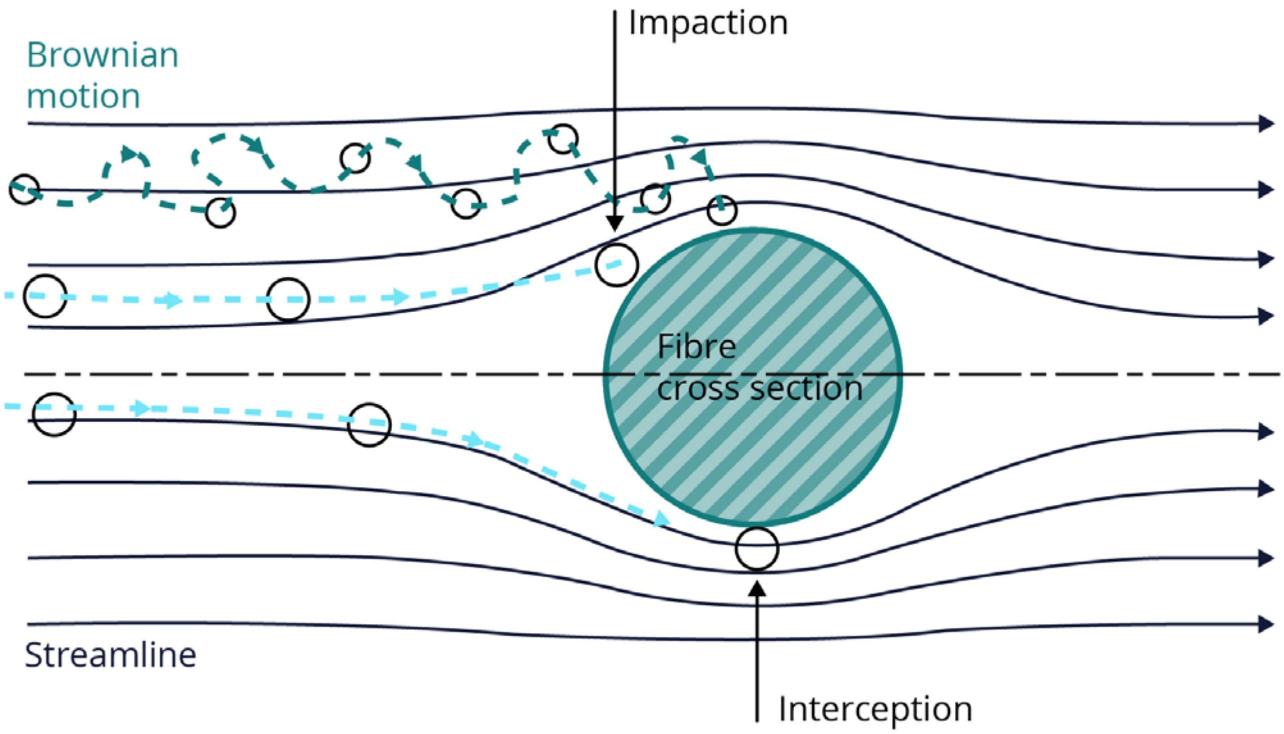

Figure 4: Particle collection mechanisms in a fibre filter (based on [61])

The superposition of these three separation mechanisms results in a typical U-shaped separation curve (see Figure 5). Depending on filter and inflow velocity, the resulting minimum separation efficiency (also known as *most penetrating particle size*, MPPS) is typically between 0.1 µm and 0.3 µm. Conversely, this means that particles of all other sizes, even very small ones, are separated even more efficiently. With conventional room air filters, the minimum efficiency is 30-90 % depending on the filter class. With highly efficient HEPA (*High Efficiency Particulate Air*) filters according to EN 1822-1 or ISO 29463, the minimum filter efficiency is at least 99.95 %, depending on the filter class. These standard-compliant specifications always refer to the nominal flow rate[4] of the filters. If a filter is operated with a lower volume flow, large particles are separated with lower efficiency due to decreasing impact, whereas small particles are separated with higher efficiency because they have more time for diffusive separation. The separation minimum therefore migrates to larger particles. When operating a filter with a flow rate higher than the nominal flow rate, the reverse is true.

In general, a denser, thicker or multi-layer filter medium is required to achieve a higher degree of separation. However, this also increases the flow resistance (pressure loss) of the filter [63] and thus, e.g. in the case of breathing masks, the breathing resistance and, when operating filters for air purifiers or ventilation systems, the energy requirement.

So-called electret filters are a special feature in this context. Their fibres are electrically charged during manufacture [64, 65]. Some airborne particles carry a natural electrical

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[4] *Flow rate for which this filter is designed. This is typically specified in the data sheet of the filter.*

charge [66] and can thus be removed from the air with greater efficiency than with purely mechanical filtration. However, uncharged particles are also polarised in the resulting electrical field within the filter and are thus also increasingly separated [64, 67]. These two electrical effects have different effects on different particle sizes, so that the separation curve of an electret filter usually has several local minima [68, 69]. Since the introduction of electrically charged fibres has no noticeable influence on the pressure drop, electret filters are particularly interesting for applications in which a high pressure drop is to be avoided, while at the same time achieving high separation efficiency [70]. They are used, for example, in breathing masks [71, 72] or for household room air cleaners [73].

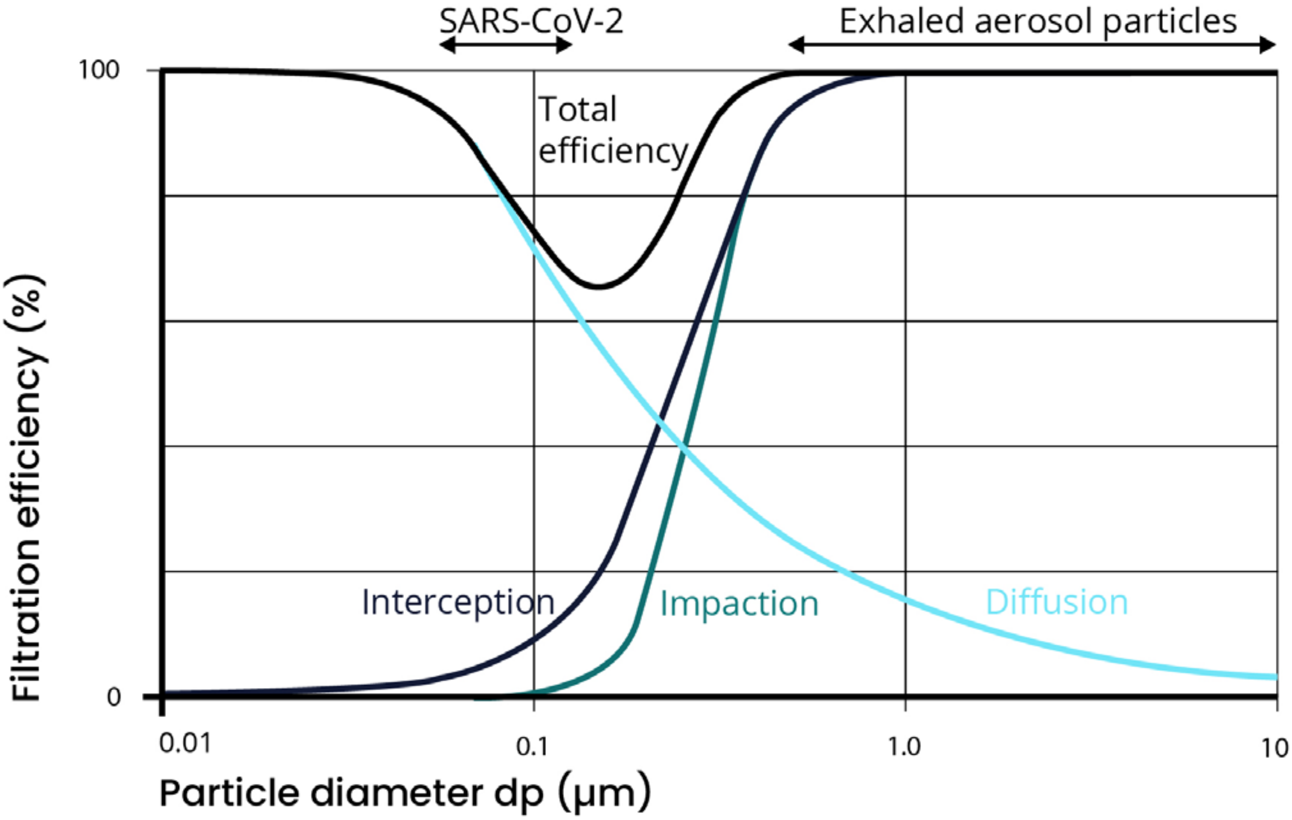

Figure 5: Filtration efficiency of a highly efficient air filter as a function of particle diameter (based on [60]); the total efficiency of the filter is determined by the separation mechanisms diffusion, interception and impaction; the course of the separation efficiency of filters with lower efficiency is similar, but lower and may not reach (almost) 100 % for very small and very large particles

During the operation of air filters, particles are deposited on or in the fleece, causing the free pore-like air volumes to narrow. Due to the denser filter medium, the filter efficiency increases with increasing operating time, but also the pressure drop [74] and thus the energy requirement and breathing resistance. In the case of electret filters, the loading of the filter is also accompanied by an electrical discharge of the filter [75, 76]. The influence of decreasing charge on the separation efficiency is generally greater than the increase in mechanical efficiency due to particle separation, so that the overall separation efficiency of electret filters decreases during operation [76]. The discharge of the filters is also accelerated by air humidity [77, 78] and especially by solvent vapours [79, 80, 81]. The storage and service life of electret filter is therefore more limited than that of non-charged filters. However, a possible discharge during storage is described in the scientific literature as low [82] to negligible [83]. Currently there is no technical solution to recharge electret filters after use.

5.2 Effectiveness of air purifiers

Air purifiers are mobile devices that can be positioned anywhere in a room. They are equipped with a fan that draws in the air from the room, passes it through filters and returns the cleaned air to the room. In terms of particle concentration, they thus have virtually the same effect as ventilation with clean outside air by reducing or keeping the particle concentration low over time [84]. Air purifiers have become increasingly popular as household appliances in recent years. In the context of the COVID 19 pandemic, larger air purifiers, often referred to as professional air purifiers, e.g. for classrooms or industrial workplaces, have also come onto the market. The advantages of air purifiers compared to ventilation are that no heat escapes from the room, especially in the cold season, and their effectiveness is independent of the particle concentration in the outside air. For this reason, air purifiers are regarded as an additional component for minimising the risk of infection, especially in rooms where regular ventilation is not possible [1]. Disadvantages of air purifiers are possible additional acquisition costs, power consumption and noise emissions of the fan. Noise emissions in particular can significantly reduce acceptance in everyday life [85]. Another disadvantage is that air is only circulated and not exchanged. However, this does not happen with closed windows either. In contrast to ventilation and the associated input of oxygen, the concentration of exhaled CO_2 therefore accumulates in the room. In addition, just as with ventilation, direct droplet infection between two people cannot be prevented if the distance is too small.

Most air purifiers have non-woven filters to separate particles [86]. In the case of household appliances, these are often electret filters to achieve a low flow resistance. This has the advantage that more air can be circulated with the same power consumption but lower noise emission. However, regular filter changes are necessary, as the initial efficiency can drop considerably due to discharge of the filters [81]. Newer "professional" air purifiers, on the other hand, often have highly efficient, but uncharged filters of HEPA classes H13 or H14[5] with correspondingly higher pressure drop. Many air purifiers also contain activated carbon to separate gaseous pollutants and

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[5] *The filter designations are taken from the European standard EN1822-1. According to the international standard ISO 29463, E11 filters are designated ISO 15 E, H13 ISO 35 H and H14 ISO 45 H*

odours [87]. However, the activated carbon has no significant influence on particle separation. In some cases, additional functions are also offered for the inactivation of micro-organisms by UV light, plasma or ozone. It has been known for decades that UV irradiation of viruses can lead to their inactivation [88] and is used in many air purifiers [89, 90]. The efficiency of UV irradiation to inactivate other corona viruses has already been demonstrated [91]. However, the studies listed in the review by Heßling et al. [91] were not carried out on airborne viruses but on viruses deposited on surfaces. The radiation dose is decisive for efficient inactivation. Heßling et al. assume that a dose of 0.0037 J/cm² is required to inactivate 90 % of the viruses. Hamzavi et al. [92] report that a dose of 1 J/cm² is required to inactivate 99.9 % of the viruses on respirators. While viruses deposited on filters with the aid of UV radiation can thus be efficiently inactivated, it is currently unclear whether the findings can be transferred to airborne viruses. The method also harbours potential risks: UV rays cause damage to human skin when irradiated directly. In addition, UV radiation can lead to the formation of ozone in the room air. Accordingly, such methods should not be used if there are people in the room who could be exposed to UV radiation or ozone.

Evidence provided by manufacturers on the effectiveness of their air cleaners should always be critically reviewed. Current testing standards for air purifiers, such as the Chinese GB/T 18801:2015 or the US ANSI/AHAM AC-1:2015, do not include standardised test methods for testing the effectiveness of UV radiation or the use of ozone or plasma. There is currently no European testing standard for air purifiers. An international IEC standard to replace the national standards is currently in preparation.

The effectiveness of air purifiers is usually assessed by means of the *Clean Air Delivery Rate* (CADR), which is determined in a standardised way by means of decay rates in a test chamber [93]. The CADR indicates how many cubic metres of cleaned air the air purifier provides per hour and thus corresponds to the product of filter efficiency and volume flow rate that the unit circulates. However, especially in the case of household appliances, the CADR is usually only given for the highest fan speed, which is usually not used at all or only for a short time due to noise. The corresponding information on lower fan speeds is often not available for these appliances. In addition to the manual setting of the fan speed, many domestic air cleaners have automatic modes that control the air flow independently based on particle concentration measurements taken by the unit. Since, in the case of typical particle pollution indoors, virus-containing particles make up only a small proportion of the total particles and the built-in sensors cannot distinguish between virus-containing and virus-free particles, the automatic mode should not be used when using air cleaners to prevent infections.

The decisive factor is therefore not only the highest possible filter efficiency, but always the combination with sufficient air turnover. For example, the same cleaning performance (CADR) can be achieved with an H13 filter with 99.95 % separation efficiency as with an E11 filter with 95 % separation efficiency at an air flow rate that is about 5 % higher. However, since the pressure drop of the H13 filter is typically about twice as high as that of the E11 filter [94], about twice as much power is required. In addition, an air purifier with an H13 filter is more complex and more expensive. If an H14 filter with a minimum efficiency of 99.995 % is used, this balance is even less favourable. The use of H13 and H14 filters therefore has no technical advantages and is neither economically nor energetically sensible. It can also be counterproductive to retrofit existing air purifiers with highly efficient filters, if the reduction of the volume flow rate due to the higher pressure drop exceeds the gain in filter efficiency and the CADR ultimately even decreases [95]. The use of highly efficient filters in air cleaners is therefore often at the expense of energy efficiency and noise emissions or at the expense of effectiveness and is therefore not generally recommended. Exceptions may be air purifiers that extract air in the direct vicinity of a (potentially) infected person and return the purified air back into the room. There are also more recent developments of highly efficient H13 filters made of PTFE membranes, which have a significantly reduced pressure drop compared to conventional non-woven filters, so that high air flow rates can also be achieved with an H13 filter.

Basically, two scenarios are conceivable for the operation of air purifiers: If, during operation, persons in the room (e.g. during school lessons or meetings), among whom an infected person is present, exhale viruses or virus-containing particles, an equilibrium concentration of viruses in the room is established over time, assuming a homogeneous distribution[6] [96]. The higher the CADR of the air purifier, the lower the equilibrium concentration, but it can never be exactly zero. If the viruses are evenly distributed in the room, the resulting equilibrium concentration depends only on the quantity of viruses exhaled (source) and the quantity of viruses removed per unit of time (sink). The latter depends only on the CADR, not on the room volume. Kriegel et al. [97] calculated that at a CADR of 750 m³/h, the risk of infection per hour of time spent in a room with an infected person can be reduced to 10 %. The risk of infection is thus minimised, but other protective measures, such as ventilation or wearing masks, must never be completely neglected [98]. On the other hand, air purifiers can be used, e.g. during school breaks or between meetings in an empty room, to reduce an existing initial concentration. The higher the air exchange rate[7], the faster this is achieved. This is the quotient of CADR and room volume. The test standards mentioned above recommend about three to six air changes per hour. The higher value is also currently recommended in the context of the COVID 19 pandemic [99]. For a 2.5 m high room with an area of 20 m² (50 m³ room volume), an air purifier with a CADR of 300 m³/h would be required. In principle, even higher air exchange rates result in an even faster decrease in particle concentration but are still associated with higher energy consumption and noise emissions. It is therefore always necessary to find a suitable compromise for the respective application.

When positioning air purifiers in the room, it should be ensured that they can freely draw in the room air and blow the purified air back into the room, otherwise the purified air cannot be distributed evenly throughout the room [100]. Accordingly, air purifiers should not be positioned behind objects or furniture or under tables. The decrease of the aerosol concentration over time strongly depends on the aerodynamic flow conditions in the room under consideration, the position of the installed unit in the room and its volume flow. In very large rooms, flow obstacles on the

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[6] *This assumption is not always given in reality, because in unfavourable flow situations it may not be possible to achieve homogeneous mixing in a short time.*

[7] *Strictly speaking, the term air exchange rate is not correct in this context because the air is circulated and not exchanged. Nevertheless, it is commonly used to describe this situation.*

ceiling can also have a negative effect on the uniform distribution of the air [99]. As an alternative to a single unit with high CADR, several units with lower CADR can be used [96], whereby care should be taken to ensure that one unit does not directly draw in the purified air discharged by another unit. The use of several air purifiers can also lead to the exhaled air of individual persons being sucked in more directly, thus reducing the distribution of viruses in the room.

5.3 Effectiveness of ventilation systems

In contrast to mobile air purifiers, ventilation systems are fixed installations installed in buildings to improve indoor air quality. They are often referred to as heating, ventilation and air conditioning (HVAC) systems. Depending on the design, HVAC systems can be designed as pure fresh air or circulating air systems or as a combination of both. In the case of a pure recirculating air system, the combination of volume flow and the filter used is always relevant for the effectiveness of the air purification (as with air purifiers), whereas for pure fresh air systems the efficiency of the filter is of greater importance, since the air passes through it only once and the purified air then displaces the indoor air. However, this only applies to general air pollutants. If, on the other hand, the virus concentration in the outside air is considered negligible, then the choice of filter for reducing the virus load in a room with a fresh air system is irrelevant. Fresh air systems have the advantage that gases emitted in the interior, such as exhaled carbon dioxide, are removed from the room. However, pure fresh air systems are less favourable from an energy point of view, since air drawn in from outside must be tempered to the indoor conditions, e.g. in a heat exchanger [101].

Filters used in HVAC systems are tested and classified according to the international standard ISO 16890. This classification into the filter groups ISO ePM1, ISO ePM2.5 and ISO ePM10 as well as ISO Coarse mainly aims at the separation efficiency for different fine dust fractions of typical urban or rural outdoor air. Filters classified as ePMx must have a minimum separation efficiency of 50 % for the respective fine dust fraction. The separation efficiency determined in standard tests is added to the respective filter class. An HVAC filter of class “ISO ePM2.5 65 %” separates at least 65 % of PM2.5. As electret filters are often used for HVAC systems, the minimum efficiency always refers to the average value of the charged and uncharged filter.

A combination of an ISO Coarse and a higher efficiency filter is often used, with the coarse dust filter protecting the fine filter. To supply rooms with particularly high air quality requirements, e.g. clean rooms or operating theatres, EPA (E10 - E12), HEPA (H13 or H14) or ULPA (U15 - U17) filters in accordance with EN 1822-1 and ISO 29463 standards can be used instead of ISO ePM filters, but their use is always associated with increased energy consumption due to the higher air flow resistance for the same air flow rate.

In the context of the current COVID 19 pandemic, ventilation systems are of particular importance. It has been known for some time that the recirculation of air in a ventilation system can lead to an accumulation of pathogens in a room if it is not adequately filtered [102]. In spring 2020, the outbreaks of COVID-19 in the Westphalian meat industry produced precisely this scenario, since the air for cooling was recirculated without filtration

[103]. The outbreak in a restaurant in Guangzhou, China, is also attributed to the air being circulated by an air conditioning system without filtration [104]. Similarly, on the cruise ship Diamond Princess, the corona virus is believed to have spread via the ventilation system with inadequate filtration, leading to high rates of infection, although passengers were quarantined in their cabins [105].

Based on these findings, the use of recirculation is now generally not recommended and instead the supply of 100 % fresh air with the highest possible volume flow and heat exchange is recommended [1]. Accordingly, on 20 October 2020, the German federal government launched a funding programme in which a total of 500 million euros will be provided for the conversion and upgrading of ventilation and air-conditioning systems in public buildings and places of assembly [106]. This programme explicitly calls for the conversion of air recirculation systems into air supply systems. From the point of view of GAeF, these measures make sense, but a sense of proportion should be maintained in the operation of the systems and in the selection of filters. The introduction of viruses or other pathogens with the outside air is unlikely, so that the use of highly efficient, e.g. H13 or H14 filters is not necessary and should be avoided from the point of view of energy saving and climate protection. In recirculation mode, a distinction must be made between whether the system supplies a single room or several rooms. For a single room the use of a highly efficient filter is not necessary (see discussion of air purifiers in Section 5.2). If, on the other hand, the system supplies several rooms, then the use of highly efficient filters can be useful to prevent the possible spread of viruses from one room to another. In hospitals, for example, there is usually a two-stage filtration system. The first stage usually separates mainly coarse particles. For all sensitive zones such as operating theatres and isolation rooms, there is then a second stage with stricter requirements, in which filters with higher efficiency are used for smaller particles.

An exhaust air system for classrooms recently developed by the Max Planck Institute for Chemistry in Mainz, which can be produced by the pupils themselves with quite simple means, provides for the extraction of air above the pupils' heads, since exhaled air rises due to thermal effects [107]. Fresh air is supplied directly using outside air. A comparable extraction system could also be useful for conventional ventilation systems. With this concept, very good values were achieved for the extraction of test particles with simulated heat convection at the point of generation at about two air changes per hour [78].

In general, ventilation systems require regular maintenance and filter replacement. As a rule, the filters are only checked via the pressure drop of the filters. In the case of electret filters, however, the pressure drop may not be the right measure for a filter change, but rather the loss of filter efficiency. Permanent monitoring of the filter efficiency can be achieved by means of low-cost dust sensors [108], which have been available for several years, but are not currently state of the art. Such a development is particularly desirable for large ventilation systems that supply rooms used by many people, such as hotels, exhibition centres or lecture halls.

6. Effectiveness of masks

The German Federal Institute for Drugs and Medical Devices (BfArM) basically divides masks into three categories [109]:

Filtering facepieces

which include FFP1, FFP2 and FFP3 respirators, but also equivalent half-masks such as KN95 from China and N95 from the USA

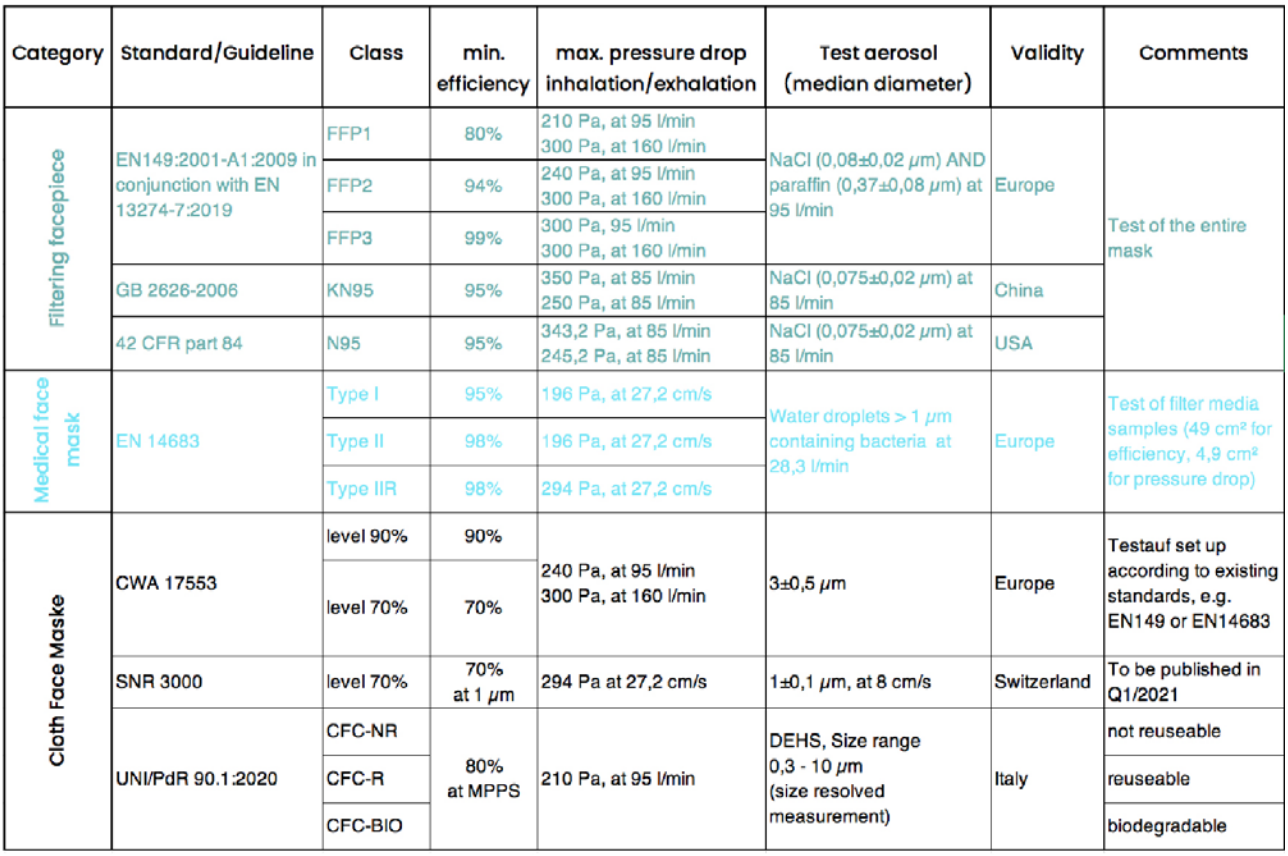
Medical face masks of classes Type I, Type II and Type IIR

hese include mouth and nose guards and surgical masks

Mouth and nose covers

which include so-called everyday fabric or community masks

The standards applicable to filtering facepieces and medical face masks are listed in Table 1 with the main test conditions. There are currently no testing standards for community masks, only proposals from various standardisation bodies. A selection is also listed in Table 1.



Category	Standard/Guideline	Class	min. efficiency	max. pressure drop inhalation/exhalation	Test aerosol (median diameter)	Validity	Comments
Filtering facepiece	EN149:2001-A1:2009 in conjunction with EN 13274-7:2019	FFP1	80%	210 Pa, at 95 l/min 300 Pa, at 160 l/min	NaCl (0,08±0,02 μm) AND paraffin (0,37±0,08 μm) at 95 l/min	Europe	Test of the entire mask
		FFP2	94%	240 Pa, at 95 l/min 300 Pa, at 160 l/min			
		FFP3	99%	300 Pa, 95 l/min 300 Pa, at 160 l/min			
	GB 2626-2006	KN95	95%	350 Pa, at 85 l/min 250 Pa, at 85 l/min	NaCl (0,075±0,02 μm) at 85 l/min	China	
	42 CFR part 84	N95	95%	343,2 Pa, at 85 l/min 245,2 Pa, at 85 l/min	NaCl (0,075±0,02 μm) at 85 l/min	USA	
Medical face mask	EN 14683	Type I	95%	196 Pa, at 27,2 cm/s	Water droplets > 1 μm containing bacteria at 28,3 l/min	Europe	Test of filter media samples (49 cm² for efficiency, 4,9 cm² for pressure drop)
		Type II	98%	196 Pa, at 27,2 cm/s			
		Type IIR	98%	294 Pa, at 27,2 cm/s			
Cloth Face Maske	CWA 17553	level 90%	90%	240 Pa, at 95 l/min 300 Pa, at 160 l/min	3±0,5 μm	Europe	Testauf set up according to existing standards, e.g. EN149 or EN14683
		level 70%	70%				
	SNR 3000	level 70%	70% at 1 μm	294 Pa at 27,2 cm/s	1±0,1 μm, at 8 cm/s	Switzerland	To be published in Q1/2021
	UNI/PdR 90.1:2020	CFC-NR	80% at MPPS	210 Pa, at 95 l/min	DEHS, Size range 0,3 - 10 μm (size resolved measurement)	Italy	not reuseable
		CFC-R					reuseable
		CFC-BIO					biodegradable

Table 1: Overview of common testing standards for different particle-filtering half masks and medical viewing masks, as well as documents from various standardisation committees for the testing of mouth-nose-coverings

The use of a mouth-nose cover is currently recommended in many areas and is compulsory in most European countries when using public transport and in many countries, e.g. in Germany and Austria (with interruptions) since spring 2020 also when entering a shop. If suitable masks are used properly and over a large area, they can effectively contain the spread of viruses via the air [110, 111, 112, 113]. Nevertheless, there is a great need among the population for more information on which mask type provides what protection against the transmission of the virus. At present, the three types of masks listed above are available to the public for protection against particles containing viruses. Particle separation in masks depends only on the particle size (see Figure 4), but not on whether the particles are biologically active or inactive [114]. It should be noted here that freshly exhaled aerosol may have a different size distribution from ambient aerosol due to the higher air humidity. It is therefore important to consider not only the self-protection provided by the individual mask, but also the external protection.

In general, any mask is better than no mask at all, especially with regard to the protection of others, i.e. the protection of fellow human beings [115]. It must be taken into account that masks are essentially designed to retain potentially virus-laden particles when exhaled. However, they also offer a certain degree of self-protection during inhalation, even if this is usually much less, because the liquid particles shrink between exhalation and inhalation. In order to ensure a high degree of protection when several people meet, it is very important that everyone uses the most efficient mask possible and wears it correctly, i.e. as close as possible to the mouth and nose. Figure 6 shows the deposition efficiencies of an FFP2, two medical type II masks and some fabric masks. It can be seen that an FFP2 mask has the highest efficiency and the fabric masks the lowest. The two Type II masks behave very differently for particles smaller than 0.3 µm. For micrometer sized particles, however, these masks are very efficient. Fabric masks, on the other hand, only show high separation efficiencies with a particle size of several micrometres.

In order to protect itself effectively against viruses, the mask must filter fine particles well and also fit tightly. At the same time, masks are not a panacea, but must always be used in accordance with the hygiene guidelines, which include keeping your distance and the usual hygiene measures. In addition, care should be taken not to touch the mask when removing it, as otherwise viruses may get onto the hands and spread via smear infection.

There are also face shields, but these have no filtering effect whatsoever and only stop particles of several micrometres in size, which are ejected at high speed when coughing or sneezing, for example, by impaction. Smaller particles, on the other hand, are retained inadequately or not at all [116]. Face visors are only used as protection against spitting and splashing of large droplets. These visors are therefore only recommended as an additional measure, e.g. for medical and nursing staff, to protect their own eyes from large, possibly infectious droplets [117, 118]. A similar effect could be achieved with protective goggles.

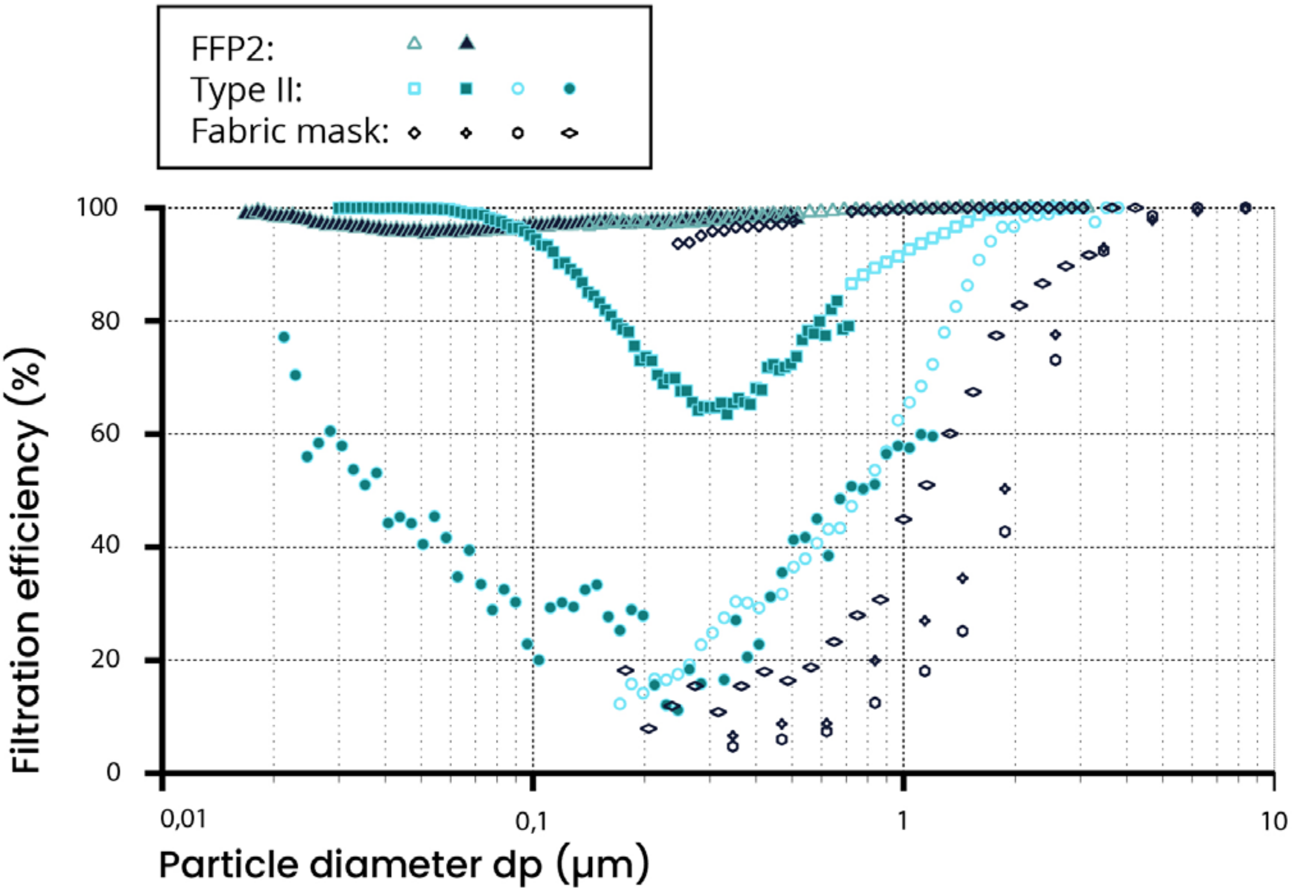


Figure 6: Separation efficiency of different mask types as a function of particle size, measured with optical aerosol spectrometers; the separation of very small particles in FFP2 and type II masks was also determined by means of electrical mobility analysis (filled symbols); data sources: FFP2 - Prof. Dr. H.J. Schmid, University of Paderborn, Type II - Prof. Dr. E. Weingartner, FH Nordwestschweiz and Dr. C. Asbach, IUTA, fabric masks: Prof. Dr. P. Tronville and Dr. J. Marval, Politecnico di Torino, Prof. Dr. E. Weingartner, FH Nordwestschweiz and Dr. C. Asbach, IUTA

6.1 Filtering facepieces

Filtering facepieces come from the field of occupational health and safety and are available, for example, to medical personnel for their work. They serve as self-protection against the inhalation of harmful particles, ranging from coarse dust to ultra-fine particles, depending on the protection level [119]. Masks certified accordingly must meet strict test standards that provide for different test aerosols (see Table 1). Viruses such as SARS-CoV-2 do not float through the air as free particles, but always with an envelope of lung fluid, saliva and/or mucus as exhaled droplets [120]. Even if this envelope shrinks over time through evaporation, the virus will not be completely exposed, even at low relative humidity. The diameter of these droplets is therefore much larger (see Section 4) than the diameter of the virus and also larger than the media diameter of the test mucus prescribed by the standards. It can therefore be assumed that the actual filtration efficiency for these particles is much higher than that of the MPPS of the applicable standard.

It is important that particle filtering half masks have a valid certificate. Manufacturers of FFP half masks must have their products tested in accordance with the mandatory EN 149:2001+A1:2009 standard before they are placed on the European market. Only test equipment that fully complies with all the requirements of the standard may be used to demonstrate compliance. This is important because, due to the shortage of masks in spring 2020, there are many falsely advertised or completely counterfeit products on the market that do not provide the specified protection. The user can recognise a tested and approved mask by the CE mark, the subsequent four-digit *Notified Body Number* (NBnr) of the testing laboratory and the mention of the applicable standard, e.g. EN 149:2001 on the product and packaging. A list of mislabelled masks has been published by the CDC on their website (https://www.cdc.gov/niosh/npptl/usernotices/counterfeitResp.html).

However, even the best respiratory masks with high separation efficiency only offer good self-protection against virus-containing particles if there is non-permeable contact between the skin of the person wearing them and the mask. However, people's faces differ considerably, for example in shape, size and nose type. As a result, not every respiratory protective mask will fit every person tightly and provide adequate protection [121]. In addition, there are many different models with different cuts, shapes and sizes in every protection level. A poor and insufficiently tight fit considerably reduces the protection of the wearer and can be responsible for illness despite a certified mask with high deposition efficiency. The ISO standard 16975-3 now exists for checking the seal of masks, and in some countries, such as the UK and the USA, a mandatory seal test is therefore required for all workers who have to wear a respiratory protective mask at work, e.g. in hospitals or nursing homes. Only a fit test can check whether a particular model and size of mask matches the individual face of the wearer and whether the mask can actually be used for self-protection. Specially adapted aerosol measuring techniques are used for this purpose. To pass this test, the mask must be put on correctly, the nose clip pressed on correctly and the appropriate mask shape and size must be selected. As an example, the British regulatory authority HSE created guideline INDG479 to be a national regulation for the tightness test for respiratory protective devices [122]. For extensive implementation, the accreditation programme "Fit2Fit" (https://www.fit2fit.org) was also developed there in cooperation with interest groups by HSE as proof of the competence of suppliers of fit testing to guarantee a particularly high safety standard.

Some breathing masks have a valve to facilitate exhalation. They do not filter the air as it is exhaled and therefore contribute to the spread of viruses. Although the valves are designed in such a way that the exhaled air is discharged downwards [123], small particles can still remain in the air for long periods of time, for example due to turbulent flow or Brownian molecular motion. Masks with exhalation valves are unsuitable for external protection and should therefore not be used in the context of pandemic control.

Although the maximum dust-holding capacity of the masks is typically not reached during normal use to protect against infection, the masks can be used for a wide range of applications. However, regardless of possible contamination of the mask, the useful life of the masks is limited, as they are usually made of electret filter material [75]. Accordingly, an expiry date for the maximum storage period is often indicated on the packaging of respiratory protection masks. When worn, the filter efficiency decreases over time as the filter material loses its electrical charge, e.g. due to the humidity of the exhaled air. At the same time, these masks cannot be reused, as the high efficiency of the mask with simultaneously low breathing resistance is only achieved by the electret material. Grinshpun et al. also found that sterilisation of masks both in autoclaves and with an ethanol solution significantly reduced filter efficiency and also increased breathing resistance [124].

6.2 Medical face masks

These disposable masks come from the medical sector and are subject to the Medical Products Act. According to EN 14683, “Type II” or “Type IIR” hygiene masks must achieve a minimum bacterial filter effect of 98 % and “Type I” masks 95 % (see Table 1). Since bacteria are relatively large compared to viruses (several micrometres in diameter), the filtering performance of hygiene masks for fine particles, e.g. viruses, is often lower than that of breathing masks. In addition, these masks do not seal tightly against the face, so that leakage flows occur during breathing which are not filtered. The effect of these leakage flows is not taken into account in the deposition curves in Figure 6, since these measurements were performed with tight filter holders.

If micrometre-sized virus-containing droplets are ejected by sneezing or coughing, hygiene masks retain a relatively large proportion of these, thus ensuring appropriate protection against foreign bodies. They thus help to reduce the risk of infection for people in the vicinity. In a study of 37 influenza-infected patients, Milton et al. [42] investigated whether respiratory masks retain particles that are produced during coughing. This was quite successful for the coarse aerosol particle fraction (defined here as >5 µm), because viral material was only detected in 4 of 37 patients when the patients wore surgical masks. This was not true for the fine aerosol particle fraction. In 29 of the 37 patients, viruses were still found even when wearing a respiratory mask. However, the amount of virus exhaled could be reduced by 55 % by wearing a surgical mask. In addition, wearing a mask, especially when coughing or sneezing, spreads the airflow over a larger area and reduces the speed of the exhaled particles and their range. A good fit of the mask on the face, i.e. over the mouth and nose, is crucial.

6.3 Mouth-nose-covers

Mouth and nose covers are fabric masks, also known as community or everyday masks, and consist of one or more layers of fabric with usually unspecified filter properties. The masks can be used several times and are partly washable. Measurements of the filtration efficiency on various commercially available fabric masks show a mixed picture: Only a few products have a comparable or higher efficiency than hygiene masks, while other fabric masks allow smaller particles between 0.1 and 0.5 µm to pass through to a high degree [125, 126]. It is only with very small particles (< 0.1 µm) that the filter efficiency of these substances also improves again due to diffusion separation (see Section 5.1). Drewnick et al. [126] investigated the suitability of different materials that can be found in the household as filter media for everyday masks. Of the textile materials investigated, silk was the least efficient and two-layer tricot fabric the most efficient. The two-layer tricot fabric achieved a separation efficiency of about 75 % at a particle size of 1 µm. The authors also tested the material of a vacuum cleaner bag, which showed by far the highest efficiency, in MPPS at approx. 0.1 µm of >90 %.

The efficiency of fabric masks cannot usually be assessed by the purchaser. In general, however, two or multi-layer masks show higher particle separation than single-layer masks, denser fabrics separate particles better than looser materials, and non-woven fabrics show better separation behaviour than woven fabrics. However, since thinner, looser materials have lower breathing resistance, the differences between the materials can be largely compensated for by increasing the number of layers of fabric, so that the deposition values of surgical masks can be achieved [126, 25].

Currently there are no valid standards on how to test and classify fabric masks. However, initiatives have been launched in Switzerland [127] and Italy [128, 129] to remedy this situation. The French standardisation authority AFNOR also recommends that fabric masks be tested according to EN149 in conjunction with EN 13274-7:2019, i.e. comparable to FFP masks [130]. At the European level, a workshop (CWA 17553) of the European standards authority CEN has reached a consensus on how to test fabric masks [131]. The criteria of these specifications are listed in Table 1.

7. Current research needs

From the point of view of the Gesellschaft für Aerosolforschung, there is an acute need for research in order to better understand infection via the aerosol path on the one hand, and to be able to take improved measures to contain the pandemic to protect the population from the pandemic on the other. Many of these research fields require the concerted cooperation of the different scientific disciplines involved.

The most urgent open research needs from the GAeF's point of view are:

- Cooperation between the aerosol research fields and medical-epidemiological research as well as ventilation technology and fluid mechanics should be promoted in order to combine expertise from all areas in the best possible way.
- In the course of these collaborations, parallel research into transmission paths is crucial, in addition to dealing with the consequences of the pandemic, since research can only be conducted „in situ" in a pandemic situation.
- Since the particle size distribution is relevant for almost all areas of transmission, it should be better recorded by suitable measuring methods and influencing parameters (e.g. relative humidity and temperature of the environment) should also be recorded. These data represent an important basis for computer-aided modelling of the infection process.
- For research in the period after the pandemic, suitable model systems must be found and the transferability of results with different virus strains investigated.
- Respiratory problems and reduced lung volume are often reported as symptoms and late complications of Covid-19 disease. The influence of air pollution on these symptoms and the general course of the disease needs further research.
- This should be supported by the use of theoretical simulation models and accompanying model experiments on the spread and transmission of aerosol-bearing viruses and other aerosol-borne pathogens to evaluate possible protection, hygiene, ventilation and air purification measures.
- More knowledge about the „acute phase" with the highest aerosol production and highest virus production would help to better adapt quarantine measures.
- The duration of infectivity of aerosol-carried viruses and other aerosol-carried pathogens has not been sufficiently researched so far. This probably also requires the development of new methods, in particular to be able to assess infectivity in comparison to other transmission routes. The latter also includes the question of the minimum virus doses required for infection.
- The effectiveness of UV radiation against airborne viruses has hardly been researched so far. In particular, there is a lack of information on the exposure required (intensity × exposure time) to inactivate airborne viruses. This is particularly

important in the context of air purifiers or ventilation systems without separating filters, where there are usually only very short residence times. Furthermore, possibilities to test this on a real scale are currently still lacking.

- Ventilation concepts, especially for schools but also for other public buildings and places of assembly, must be evaluated with regard to this and other aerosol-borne diseases, in order to minimise economic damage. Aspects of energy efficiency and, accordingly, climate protection must also be taken into account.

- Possible by-products of air purification systems such as ozone or volatile organic compounds and their effect on secondary aerosol formation in indoor spaces should be investigated both experimentally in laboratory studies and in real indoor spaces.

- Indoor air quality in general is an important field of research to be strengthened, in addition to outdoor air quality monitoring, as people spend a large part of their time indoors (typically over 90 % in Europe).

- Systematic investigations on the tight fit of masks of all mask types, in particular during exhalation, and under realistic conditions, are still largely lacking.

In order to be able to deal with these and other research topics in a timely and comprehensive manner, the efforts already undertaken should be expanded and research resources should be made available at short notice. The allocation of these research funds should be based in particular on interdisciplinary issues, with the aim of developing a congruent and continuous catalogue of measures for future pandemic situations. Measured against the global economic losses of the current pandemic, it should become clear what advantage early and broad-based scientific studies can offer for the future.

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