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Flow analyses to validate SARS-CoV-2 protective masks

About distance rules, mouth-nose protection, particle filtering respiratory protection, filter materials and mask manufacturing

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1. Introduction

For many weeks, doctors and virologists have been providing very competent information about the corona virus SARS-CoV-2 and the coverage of the pandemic is enormous. The worldwide spread of the virus is still in its infancy and if there is no vaccine, experts fear that in the long term up to 70% of the population in Germany alone will be infected, i.e. around 58 million people. The burden on medical staff is already enormous and therefore the government's top priority is to delay the spread of the virus so that the seriously ill people can continue to receive optimal treatment and the medical system is not overburdened. [1]

The concept of delay has already proved effective and proven itself in 1918 in St. Louis in the USA during the spread of the Spanish flu. Two main concepts are currently being pursued to achieve the desired delay:

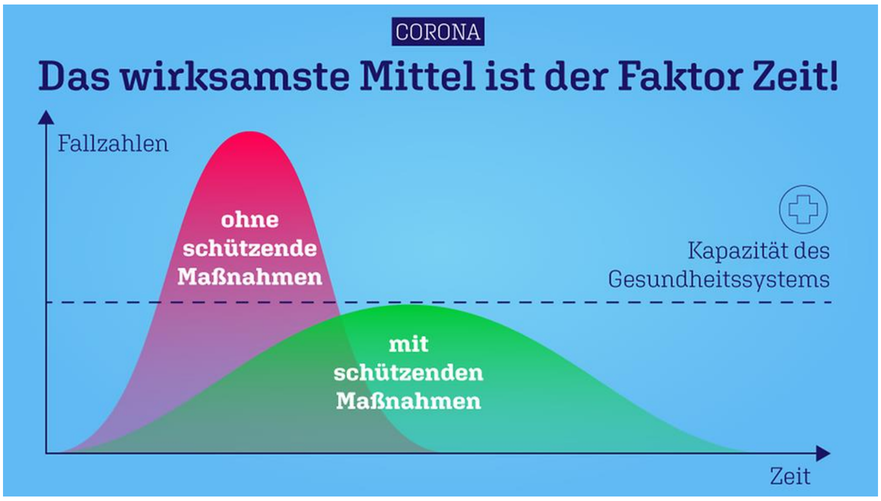
- Hygiene measures and
- Social distancing.

In order to achieve the latter, social and economic life was massively restricted, educational institutions were closed and lockdown were imposed.

It is easy to calculate that the current restrictions will have to be maintained for a very long time if hygiene measures and social distancing are the sole focus. If we start from the situation in Germany and assume that 70% of the population will be infected in the long term and 5% of those infected will require intensive care and respiration, the availability of 6800 ventilators and an average ventilation time of 6 days per patient will result in a necessary extension of the pandemic to almost 7 years!

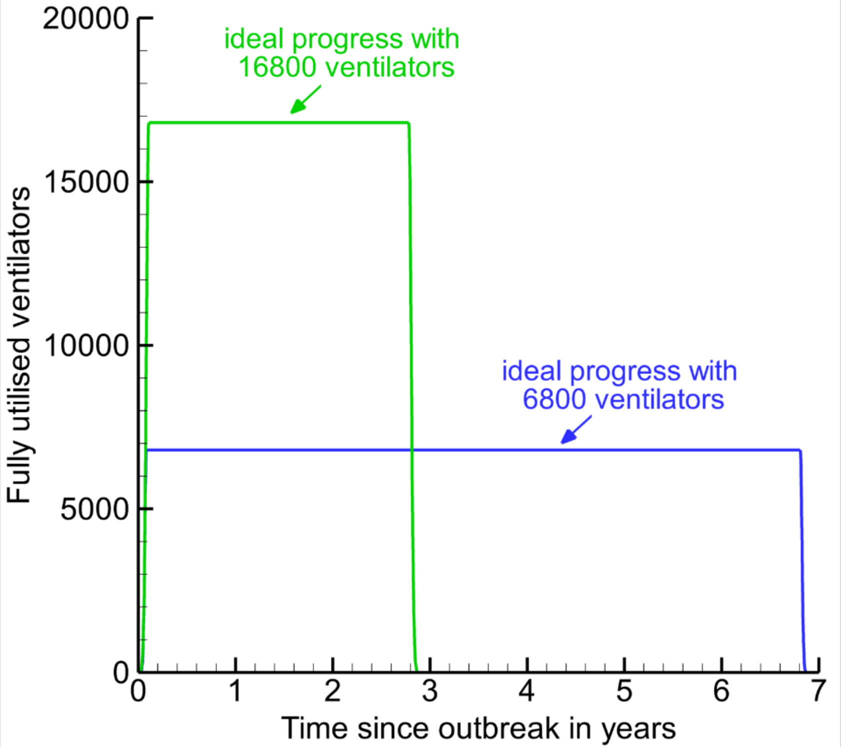
According to media reports 10000 new ventilators have been ordered, see [2]. This would reduce the duration of the measure to just under 3 years. To limit the duration of the pandemic to less than one year without overloading the medical system, more than 45000 devices would have to be available in Germany!

In the media, the benefits of the delay strategy are often illustrated with the following graphic, which is taken from the homepage of the German government



Source: https://www.bundesregierung.de/breg-de/themen/coronavirus/ausbreitung-coronavirus-1716188, called off on 04.04.2020

This graph, which is often shown in the media, is unfortunately misleading because the load limits of the medical system are drawn far too high and the course of the green function and the temporal stretching are shown unrealistically. With this curve, the available capacity is - apart from a single point in time - never used to capacity and therefore the time axis should cover many years. Correctly, the course for the two cases considered is as follows:



Time utilization of intensive care beds with ventilators at 6800 and 16800 available units. The function without measures (red graph in the first figure) is not shown, because it would result in a huge peak in the first 6 months, if 2.9 million patients have to be ventilated and a Gaussian-like pandemic course is assumed.

The longer the delay strategy continues, the more serious the consequences for the state, the economy and the population will be. Unemployment and insecurity among the people will increase, which in turn promotes radicalisation and can threaten democracy. It is therefore understandable that many are already calling for a relaxation of the restrictions.

The longer the pandemic lasts, the greater the risk that people will become accustomed to the threat and then fail to give it the attention, respect and resistance it deserves. Even now, many people regard the current coverage of the corona virus as excessive media hype and many consider the current political measures to be excessive. It is therefore possible that the spread cannot be delayed as desired. The pandemic would then run its course unchecked for several months, which would be devastating for the medical system, the risk groups, but also many other people. [1]

It is clear that the strategy of delay can only be implemented in the short term without posing a massive threat to the state, the economy and society. It is therefore necessary to consider other concepts as long as no vaccine or effective medication is available. It is simply not enough to find a possible way of countering the pandemic, but the way must be found which achieves the set goal at the lowest possible cost and with the minimum side effects for the state, the economy, social life and the people.

Two further ways are currently being discussed. The first provides for a controlled infection of the population. The aim of this strategy is to achieve herd immunity, where gradually around 70% of the population would have to be infected in order to stop the spread of the virus. In this scenario, the remaining 30% are largely spared from infection. How this strategy will work is not known at present.

The second approach relies on the use of technical aids, i.e. suitable respiratory masks, to ensure personalized isolation whenever protection is required. This approach aims to combat transmission where it occurs. It is clear that the virus could theoretically be completely eradicated within a few weeks if worldwide human-to-human transmission of the virus was completely prevented! In practice this is not achievable, but a real containment of the spread would be achievable with individual prophylaxis, even if the comprehensive restrictions are relaxed or lifted.

Strategy for controlled infection of the population (herd immunity)

The strategy of controlled infection it is extremely risky for the population. In the initial phase of the pandemic, it seemed that almost exclusively risk groups, especially elderly people with previous illnesses, had to expect death. In the meantime, however, the figures make it clear that this assessment is not correct. Even young people die significantly more frequently from Covid-19 than from influenza, see [3]. It is also possible that a serious infection with SARS-CoV-2 could have long-term health consequences, because, for example, a serious infection can cause the immune system to orient its defensive capabilities more strongly towards viruses and reduce its ability to protect against other diseases.

At present, it is approximately assumed that in Germany an average of one person dies with optimal medical care for every 100 infected persons, or 1.4 according to the Robert Koch Institute of April 3, 2020. The mortality rate is strongly dependent on the age structure in the countries, the quality of the medical system and the assumptions made in calculating the number. An evaluation of the data from the Chinese province of Hubei showed a mortality rate of 0.66% in the best case, see [3]. The WHO assumes an average mortality rate of 3.4% for all countries, see [4]. Should this risk be taken in view of the current situation for the economy? To answer this question, it is useful to consider where we run a comparable risk of death in daily life of around 1:100.

In 2018, the risk of a fatal plane crash was 1:7.7 million. This figure illustrates the reliability that technical systems in general must achieve in order to receive approval. The comparison also shows that a SARS-CoV-2 infection is statistically around 77,000 times more dangerous than travelling in a commercial aircraft. Even if one does not belong to a risk group, the fatal risk of infection is orders of magnitude higher than when using ordinary means of transport in everyday life. Therefore, the risk posed by the virus must be considered very high.

During the Apollo missions to the moon, a risk of 1:100 was accepted. Those who flew with the space shuttle were exposed to an actual mortal risk of 1:67. A risk of 1:67 was also taken by the allied soldiers in the Iraq war in 2003. For a possible mission to Mars, a risk of 1:75 is targeted. Dying from a SARS-CoV-2 infection therefore comes very close to the risks of manned space flight and war missions. Only very few people take such high deadly risks in full consciousness and without constraint. One must always be aware of this before exposing oneself or others to this deadly risk.

To allow a controlled infection of the population would be irresponsible in our view, given the figures. It is unimaginable what the 2.9 million patients who would have to be ventilated in intensive care units under this strategy would have to go through. We therefore very much hope that this strategy will not find a majority in parliament, because it is the task of the state to prevent harm to the people and not to sacrifice parts of the population. In my view, this path should only be taken if there is an effective drug that reduces the fatal risk in the event of infection by several orders of magnitude.

Strategy of personal isolation (protective masks)

What about the second way, which relies on suitable protective masks? There is an increasing debate in the media and the general public as to whether masks can provide effective protection against infection. The statements made by politicians and virologists are contradictory, as in some cases no differentiation is made between simple mouth and nose protection and a particle-filtering half mask, and because of the low protective qualities of the simplest masks, generalisations are being made in an inadmissible way about all masks. Furthermore, it is assumed that many people would not wear the masks correctly and consistently enough. It is also feared that wearing masks could lead to people no longer following the rules of hygiene and distance because the wearers of the masks might feel safe. Many citizens are therefore rightly feeling insecure and, due to the loss of confidence, are now beginning to help themselves by making masks from commercially available materials, in the hope that masks made by themselves will provide effective protection against the transmission of the infection via droplets.

In several epidemic-tested countries in Asia, the wearing of suitable masks is taken for granted. In Austria, people will have to wear a protective mask when shopping in future. In Germany, the discussion about compulsory masks is also slowly gaining momentum and it is to be expected that this culture will also soon find social recognition in our country. In the current emergency situation, masks appear to be the greatest source of hope, because the rapid development of effective medicines and vaccines is by no means guaranteed. But can this hope be fulfilled? This is the big question currently under discussion in the media. So far, there does not seem to be a clear answer. The only thing that is repeatedly pointed out is that there is no scientific evidence that masks can protect you, see [5]. Current analyses, however, indicate that suitable protective masks could have a positive benefit, see [6].

Can fluid mechanics contribute to the mask debate?

Interestingly, the discussion about the effectiveness of protective masks is being conducted by politicians, virologists and medical doctors. We think that fluid mechanics should also contribute to the debate on this topic. There are two reasons for this:

1. In order for the viruses to spread, they must be transported from the mucous membrane in the throat or lungs of an infected person by means of very small droplets through the nose or mouth into the free atmosphere, as this is the only way they can be inhaled by an uninfected person. The flow generated when breathing out therefore causes the droplets containing the viruses to be transported. The analysis and explanation of these processes require knowledge from the fields of fluid mechanics and aerodynamics.
2. In addition, the effective prevention of the spread from person to person by means of barriers or masks is also a research subject in fluid mechanics and aerodynamics. Therefore we take the liberty of taking a stand on this topic.

Aims of the investigations

It has been proven beyond doubt that suitable particle-filtering respiratory masks provide effective protection against the transmission of viruses by mouth and nose, and therefore it is also required by law that these masks must be worn as occupational safety equipment in hazardous areas. But what are hazardous areas in times of SARS-CoV-2?

In addition to hospitals, shops and public transport must certainly also be considered hazardous areas by now. If the initial restrictions were relaxed, many more areas would be added, because then the frequency of contacts would rise sharply again and the number of infections would increase rapidly without further protective measures.

The Bavarian State Office for Health and Food Safety writes that particle-filtering respiratory protection of protection class FFP2 or better is necessary to protect against infection by the corona virus SARS-CoV-2, see [7]. Unfortunately, these protective masks are currently available in all countries with difficulty or only at completely speculative prices, so that even the supply of medical personnel with masks cannot be guaranteed. It is therefore understandable that virologists have so far advised the population not to equip themselves with appropriate protective masks, as these masks are urgently needed in hospitals and medical practices.

However, since suitable particle-filtering masks, when used correctly, offer officially recognised protection against the spread of the infection via respiration, and since stopping the transmission from person to person is the most effective measure for slowing down the spread, the worldwide supply of people with these masks is also urgently needed as long as there is no vaccine or effective medication.

As these masks are currently not available, many people are asking themselves the following questions:

1. what is the point of respirators?
2. when should respirators be worn?
3. what filter material is appropriate to effectively filter out the droplets that transmit the viruses?
4. how must a respirator be manufactured and worn to provide effective protection?

These questions will be examined in this video from the perspective of fluid mechanics and aerodynamics. Since scientific experiments can better take into account the complexity of the real conditions than theoretical considerations and experimental results are also much more convincing than speculations and speculative discussions in the media, I have carried out many experiments in the laboratory together with my assistant in the last few days. I must admit that the results of the experiments have caused me to judge some things differently than before and therefore I consider the results interesting enough to share them here. This is the only way for everyone to form an opinion for themselves and, if necessary, to change their own behaviour.

In order to clarify what a mask has to do, which materials are suitable for manufacturing and how it is made and worn correctly, I will proceed in three steps.

In the first step I will first visualize how fast the droplets are spread by the flow from the mouth when breathing, speaking and coughing. These visualizations give a good impression of what the mask has to do and they answer the important question of what safety distances should be maintained in rooms when masks are not worn. For comparison, it is also demonstrated how the flow movement during breathing, speaking and coughing is influenced by a hygiene mask, a mouth-nose protection and a particle-filtering breathing mask. Sneezing is not explicitly considered, as this transmission path is of secondary importance in the current spread of the infection according to expert opinion.

In the second step, the filtering effect of a hygiene mask and a mouth and nose protection is analysed and it is shown which commercially available materials from the household provide good protection against small droplets and which do not. The last point in particular is extremely important when making masks in order to ensure that the mask really does protect against droplet infection.

Finally, the last part of the video shows how a particle-filtering protective mask can be manufactured very easily, quickly and inexpensively and how it must be worn in order to provide reliable protection. The material costs for such a mask are about 50 cents and the production takes about 5 minutes with some practice.

2. Experimental investigations

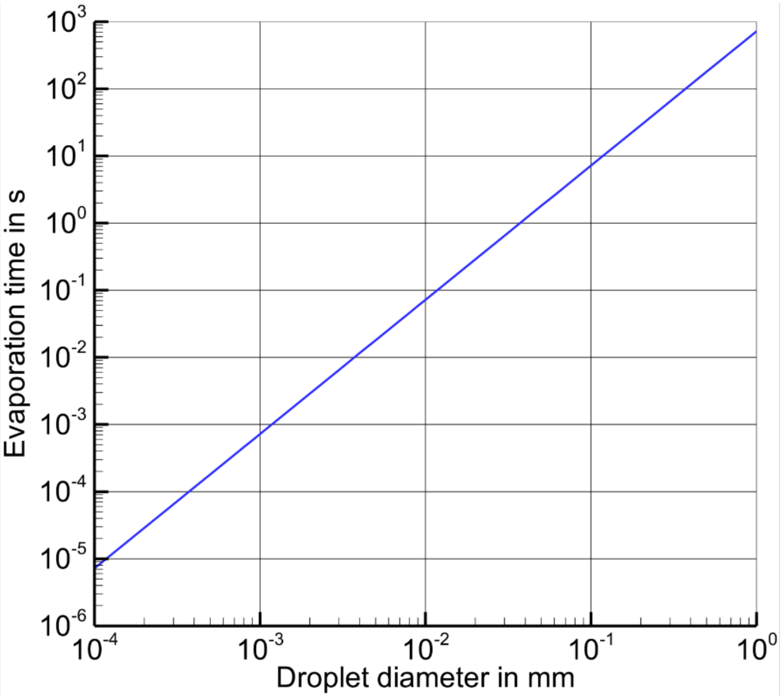
Since the viruses are transmitted via droplets, the first question is how big are the droplets that come out of the mouth when breathing, speaking and coughing. There are studies that show that droplets with a diameter of 0.1 µm to at least 0.9 mm are produced when coughing, see [8]. Sneezing also produces much larger droplets, which can be several millimetres in size, see [9]. However, the droplets, which can be up to several millimetres in size, can be reliably blocked by a simple mouth and nose protector or a cloth. The small particles, on the other hand, require materials with very good filtering properties.

Since the removal of the smallest droplets in an air stream is the greatest challenge in mask development, only droplets with a diameter of 0.1 – 2 µm are used for the flow experiments. For comparison, the SARS-CoV-2 virus has a maximum size of 0.16 µm. If these droplets can be filtered out effectively, then all droplets larger than 2 µm can be filtered as well. Droplets smaller than 0.1 µm are not explicitly considered because, on the one hand, they evaporate quickly and, on the other hand, the possible number of viruses they can carry is unlikely to lead to infection.

The desired size distribution of the droplets was generated with special aerosol generators (PIVpart45, PIVTEC GmbH and AGF 2.0, Palas GmbH). For the illumination of the droplets, powerful Nd:YAG double pulse lasers (SpitLight PIV 1000-15, InnoLas Laser GmbH and Evergreen 200, Quantel) were used, whose output beam was fanned out with some lenses to form light sections. In the first measurements, the light section plane was oriented perpendicular to the mouth and parallel to the spine of the test person. In the second investigations, the light section was located in the middle of the channel parallel to the flow. The visualization of the particles in the light section was done with highly sensitive sCMOS cameras (PCO edge 5.5, LaVision GmbH), which are able to register the scattered light of the particles. Carl Zeiss Distagon T* lenses with 25 mm and 35 mm focal length were used for the imaging.

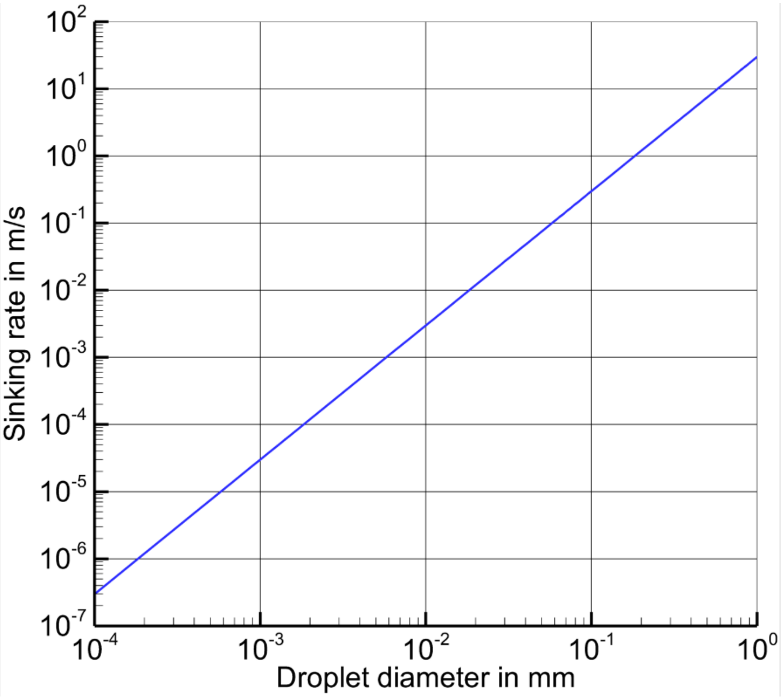
The first question to be answered is how large the distance between the donor and the recipient of the droplets must be in order to exclude an infection with a probability bordering on certainty even without a mask. This question has often been discussed in the media, but the statements vary widely. Some recommend a distance of 2 m. Others assume much smaller distances. However, there are also publications that show that much greater distances could be useful. To answer this question, the velocity field of the flow in the generated light section was determined with the Particle Image Velocimetry measuring technique, see [10].

If the velocity at a certain distance in front of the mouth is close to zero, the virus cannot spread further in space. This information is then used to make estimates for the safety distances, naturally taking into account a sufficient safety factor to allow for human differences. How long the droplets can be infectious in the contaminated area is of course not clear from these experiments. But it is a fact that droplets with a diameter of a few micrometers and smaller practically do not sink to the ground, so that they remain in the air until they have evaporated. In dry air it takes a few seconds for small water droplets to evaporate completely, so that the contaminated area can be re-entered after a short time. For example, a 100 µm drop of water evaporates after about ten seconds and a droplet with a diameter of one micrometer after only a thousandth of a second according to the figure, see [11]. In high humidity, however, the evaporation time increases strongly and in very humid environments the small droplets do not evaporate at all.



Evaporation time of small water droplets in dry air

Large droplets evaporate very slowly, but they sink to the ground quite quickly and can therefore no longer be inhaled after a few seconds. A 100 µm large water droplet, for example, has a fall speed of about 0.3 m/s in still air and a 300 µm droplet comes to a fall speed of about 1 m/s according to the following figure



Sinking speed of small water droplets in air

However, very large drops can of course contaminate the surfaces of objects and cause a smear infection through contact. For this reason, hygiene measures should not be dispensed with and wearing light gloves when shopping or using public transport seems sensible in order to minimise the risk of smear infection and to suppress the habitual grip on one's own face.

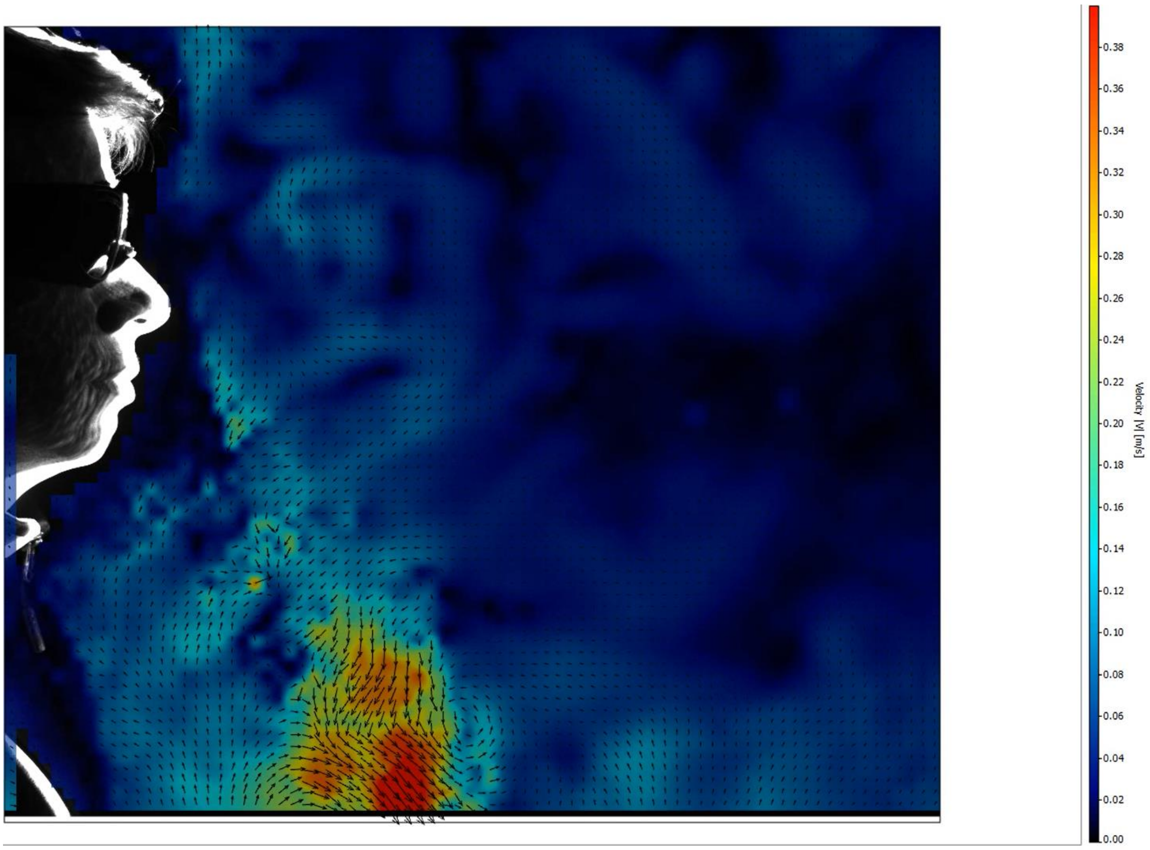
In order to carry out the experiments, the entire experimental room is first fogged with very durable DEHS droplets with an average diameter of one micrometer and then the air is set in motion by breathing, speaking and coughing. Between the individual experiments, it is necessary to wait quite a long time to ensure that the air movement has subsided.

We cannot conduct a strictly scientific analysis in the short time available. This would be very extensive and would have to be carried out several times with many test subjects and many more filter materials. For time and cost reasons, we limit ourselves here to a sensitivity analysis. This seems appropriate in view of the current urgency of the problem. If I were to try to apply for third-party funds for this research now, then we would be able to start work in a year at the earliest and that would of course be far too late to make a contribution in the current crisis. A short-term, unbureaucratic provision of research funds for such studies would certainly be desirable in view of the crisis.

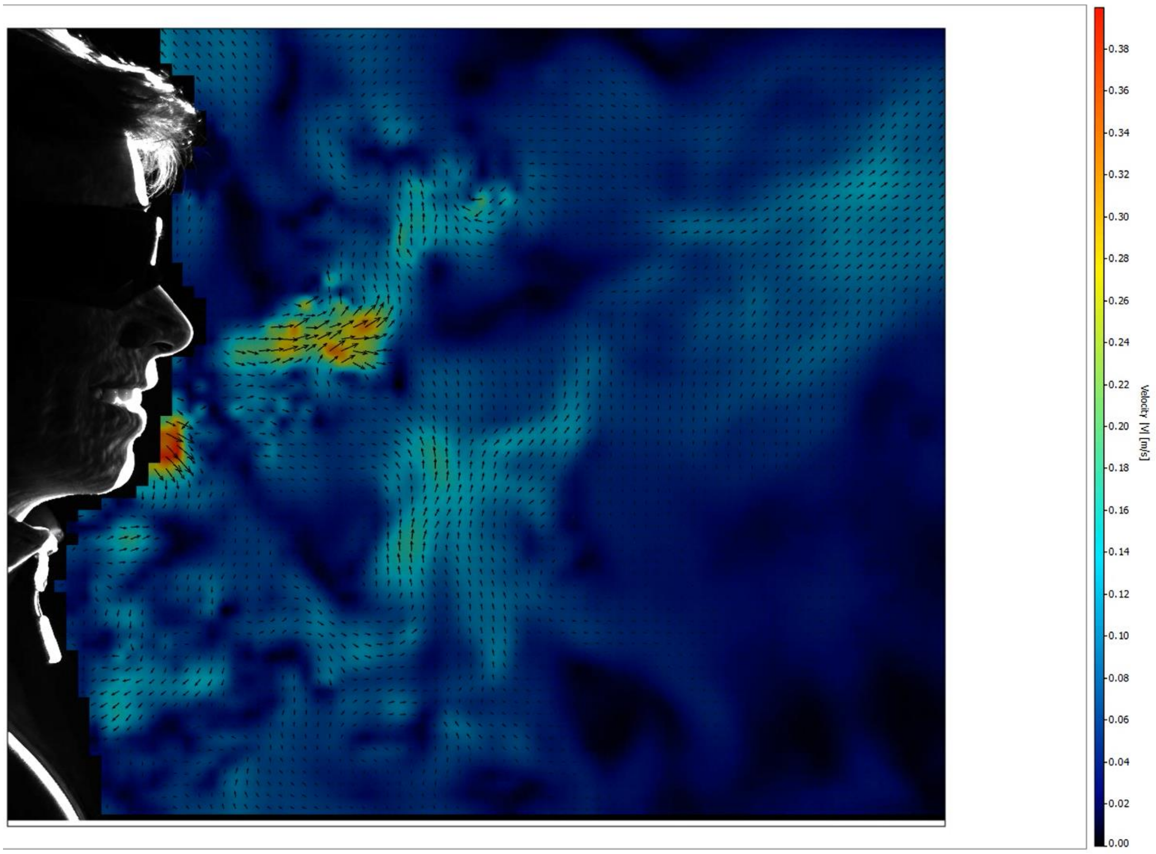
A: Breathing, speaking and coughing without masks

The evaluation of the measurement results shows that during normal unencumbered breathing through the nose the air is only slightly moved. The maximum exit velocity of the air is approx. 0.5 m/s and the area around the mouth where air movement can be detected is approx. 0.3 m. It is therefore unlikely to become infected if you are sitting next to an infected person on a bench, or at a table opposite a person who is infected. In this situation, protection with a mask is therefore not necessary if a safety distance of 1 m is maintained.

During normal speech, the air is also only slightly moved. The exit velocity is only about 0.3 m/s when speaking, because the mouth opening is larger than the nostrils. Due to the low exit velocity, the biased spatial range remains within 0.2 m, although more air escapes when speaking than when breathing calmly through the nose. Without a mask, a safety distance of one metre is completely sufficient to effectively protect against droplet infection during a normal conversation. A safety distance of 1.5 m should be maintained in heated conversations between two people or highly controversial meetings with several participants.

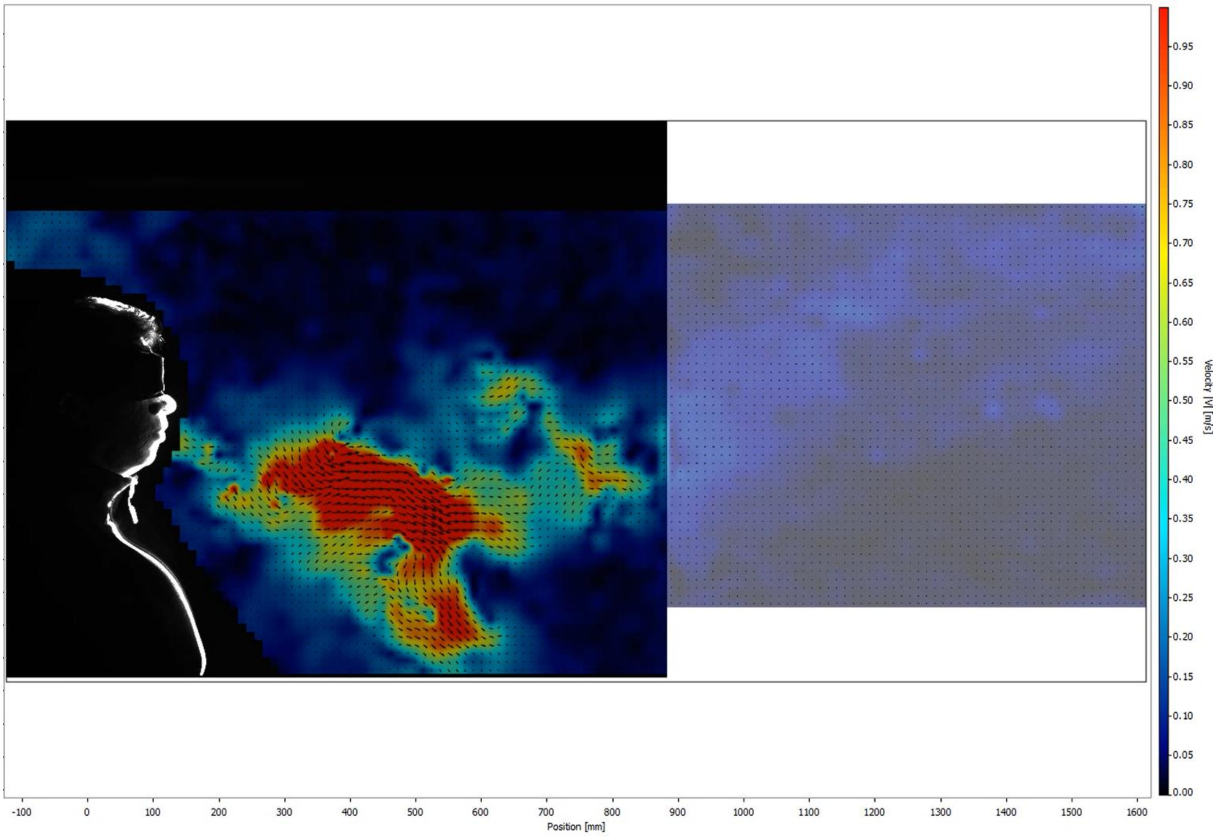


Flow field when breathing through the nose without mask



Flow field when speaking without mask

The situation is different in the case of an intermittent cough, as the air is pressed out of the lungs by the respiratory muscles much faster than when breathing or speaking. This is necessary because the greater the flow speed reached during coughing, the better the cleaning effect of the lungs. This is due to the fact that the shear stress acting on the particles adhering to the lungs and throat increases with the flow velocity. The greater the shear stress acting on the particles, the better the cleaning success. The measurements show that the exit velocity directly at the mouth opening can reach 4 – 5 m/s, which agrees well with literature references, see [12].



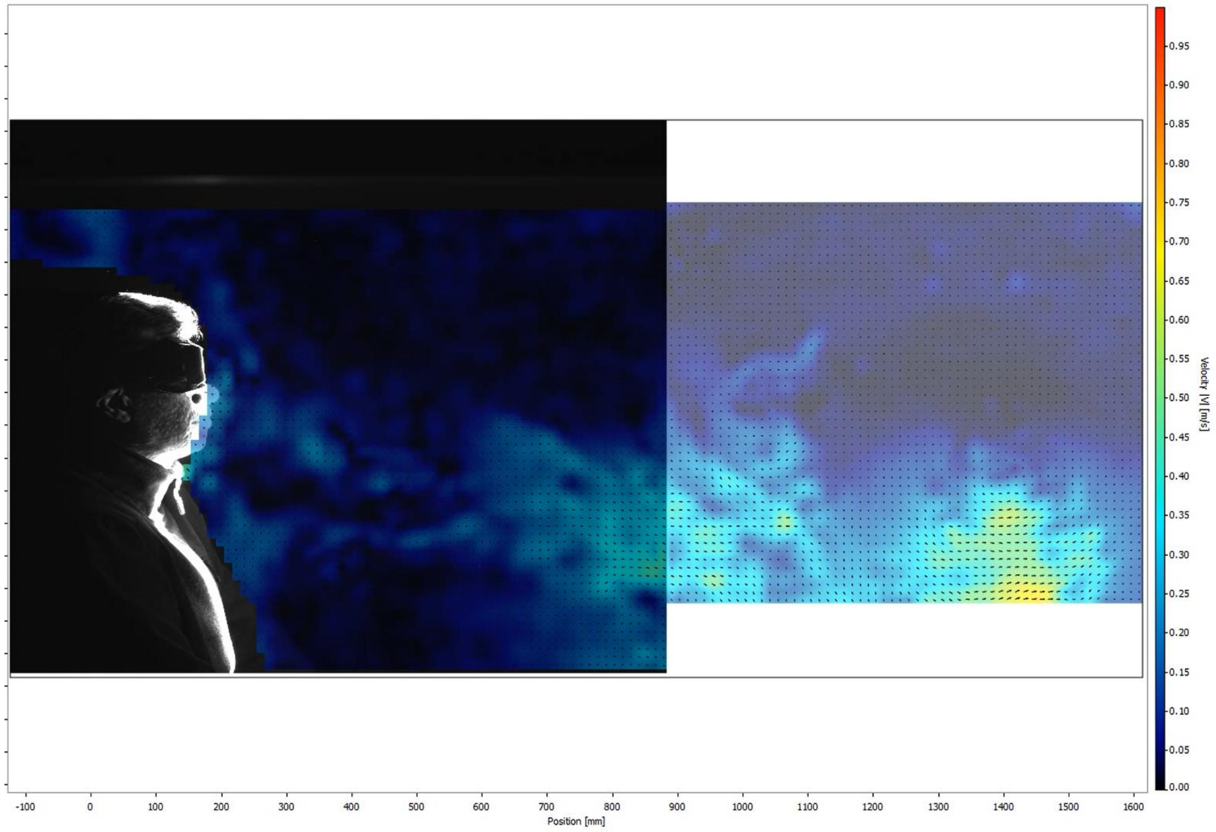
Flow field when coughing without mask (whooping cough over one breath)

The experiments make it clear that the area that is contaminated when coughing depends very much on two parameters:

1. The duration of the coughing process and
2. The angle to the horizontal at which coughing occurs.

If a lung filling is coughed out in a shock-like manner, a safety distance of 1.5 m is sufficient after these experiments, since the air volume in the lungs is not sufficient to set a larger area in motion at typical flow velocities.

However, in the case of a prolonged irritable cough, the contaminated area can also be 2 – 3 m. To contaminate this area, it is not only necessary to cough for a longer period of time, but also horizontally. This requires the head to be slightly tilted backwards. Since this position is rather uncomfortable when coughing, it will probably occur rather rarely, so that the contaminated air flows from the mouth diagonally downwards. This has also been observed in other studies, see [13]. However, this also means that even if an adult's head is no longer within the range of the contaminated air after only one metre, a small child standing three metres from the source or sitting in a stroller can still get contaminated air. Therefore, the safety distance to persons who cough for a long time should not be less than 3 m.



Flow field when coughing without mask (irritable cough over several breaths)

Due to the turbulent mixing, the diameter of the contaminated area increases rapidly with distance and thus the concentration of the droplets decreases, so that an infection becomes increasingly unlikely with increasing distance. In addition, the small droplets evaporate very quickly and the large droplets usually sink quickly if they do not fly ballistic, as they do when spitting or sneezing (see [14]). The ratio of the air flow velocity to the sinking velocity of the droplet is essential for the range. Therefore an infection is relatively unlikely from a distance of 3 m. Because several breaths have to be coughed out directly one after the other to reach these propagation lengths, there is usually enough time to move away from the coughing person with a few steps. This dynamic protection strategy is highly recommended if the recommended safety distances cannot be maintained or are not sufficient to protect oneself.

If a person sneezes in the immediate vicinity, it is recommended for your own protection to increase the distance to the person sneezing as soon as the sneezing process is registered visually or acoustically! As long as the droplets do not fly ballistically, as they do when spitting, there is enough time to take a few steps to safety.

In summary, from a fluid mechanics point of view, the following safety distances are recommended for the static distance rules:

- 1 m breathing through the nose
- 1 – 1.5 m Speaking

- 1.5 m whooping cough (one lung volume)
- 3 m chesty cough (several lung volumes)

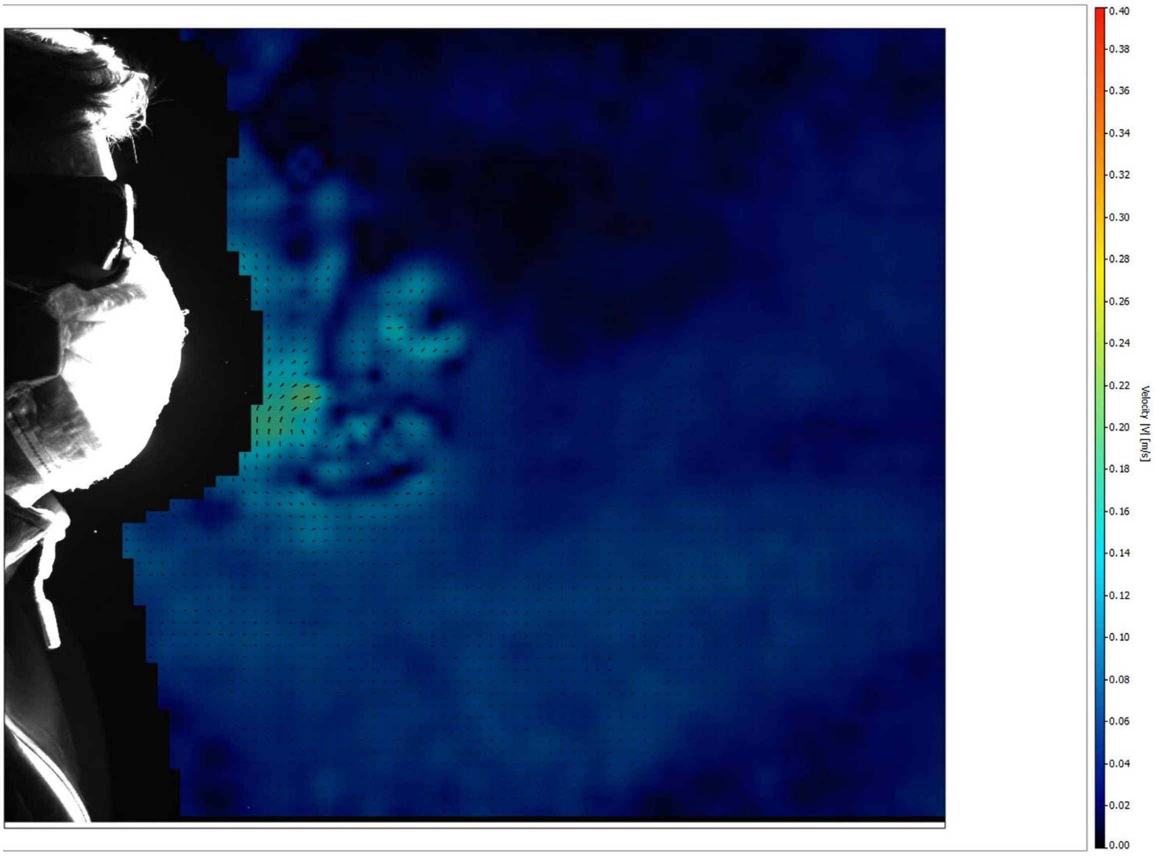
The data already take into account a safety factor, but it is nevertheless recommended to dynamically increase the distances depending on the situation as soon as possible contamination is imminent or the discharge has already started. After all, it is difficult to estimate how long the ejection will take place and since the length of the contaminated area is related to the ejection time, it is worthwhile to actively increase the distance. Outside, on the other hand, the distance rules can be reduced because of wind and turbulence. However, the wind direction must be taken into account. It is advisable to position oneself outdoors during conversations with a person in such a way that both are getting the wind from the side.

B: Breathing, speaking and coughing with masks

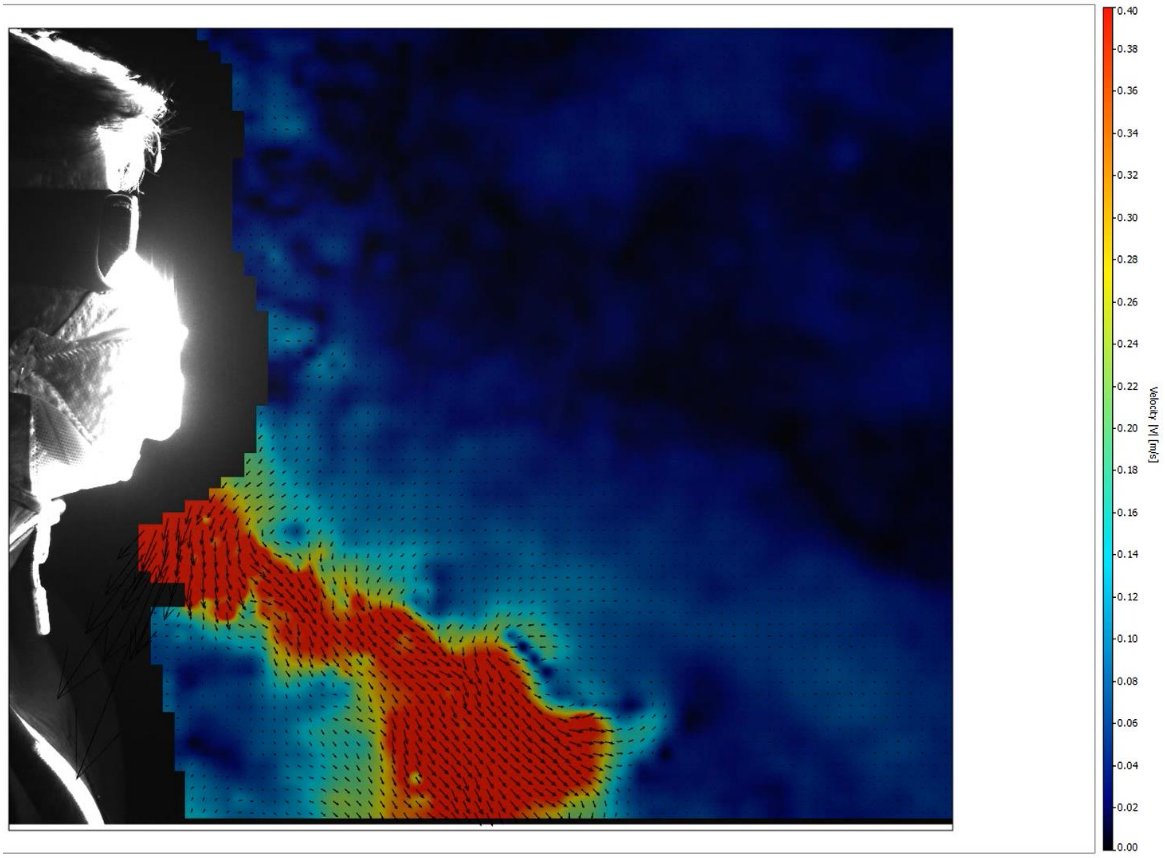
It is clear that the distances determined can often not be maintained in daily life. Therefore, the principle of social distance according to the distance rules will no longer work reliably in practice as soon as state restrictions are relaxed. Especially in shops and public transport, the distances between people will then become much smaller again, but also in working life and in leisure time at cultural or sporting events.

The following figures show that protective masks have a significant influence on the spread of the air we breathe when breathing, speaking and coughing. It can be clearly seen that even a simple mouth-nose protection effectively limits the spread of the air we breathe. The flow velocity behind the protection is negligibly small, so that even a large-scale spread is effectively prevented. However, since the pressure behind the mask increases when breathing out, speaking or coughing, the air can flow around the edge of the mask if it is not tight enough against the face. Wearers of these masks are therefore best met from the front. It should be noted, however, that although a loosely fitting mask can generally allow a lot of air to flow past, the larger the gap at the edge of the mask, the lower the exit speed will be. Therefore, even with an ill-fitting mask, the contaminated area is significantly reduced compared to the situation without the mask. With the particle filtering FFP2 protective mask, almost no air can escape at the mask edge. Therefore, positioning to a person wearing such a mask is not important. However, FFP2 masks with a valve allow exhaled air to pass through unhindered, see figure. Therefore, masks with a valve must never be worn by persons with an infection. Taking into account these experimental results, the above spacing rules can be modified as follows:

- 0.5 m breathing through the nose
- 0.5 m speaking
- 1 m whooping cough
- 1.5 m chesty cough



Flow field during coughing with mouth and nose protection



Flow field when coughing with FFP2 mask with valve

This makes it clear that even quite simple masks greatly limit the spatial spread of contaminated air if the material's tightness is at least equal to that of a surgical mask. Halving the safety distances already has a great effect on the capacity of public facilities. A stadium could accommodate 4 times more people without endangering the safety of the people if the safety distance were halved.

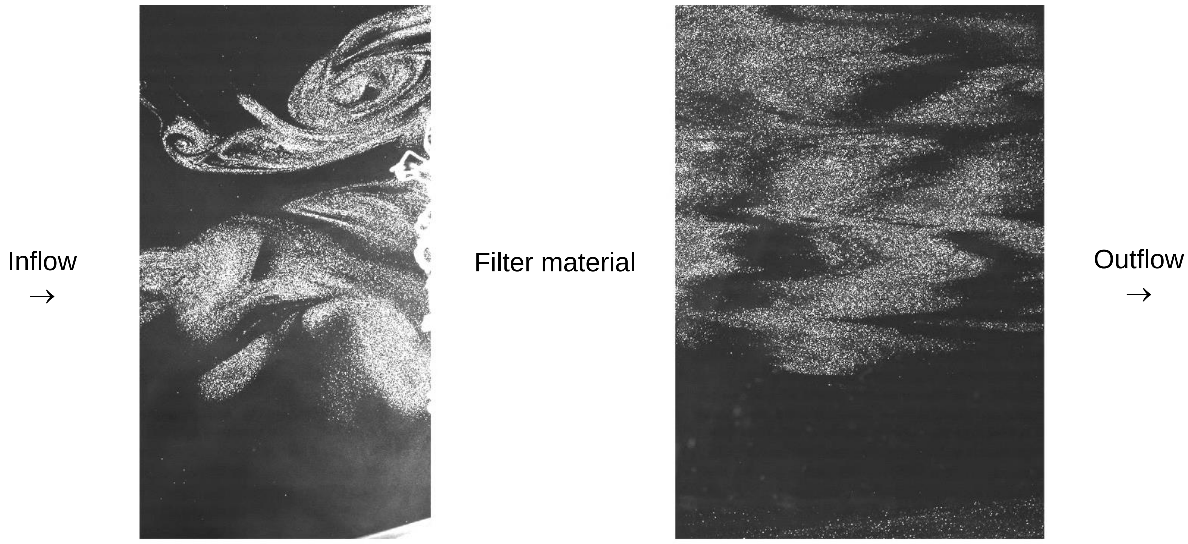
If someone is infected and wears such a mask, the transmission is effectively contained. It is therefore correct that infected persons wearing these masks effectively protect the non-infected people as long as the reduced distance rules are respected. On the other hand, if the infected persons do not wear a mask, then the non-infected people must protect themselves much better, since simple masks do not provide protection against infection! This is very important to consider when selecting a suitable protective mask.

C: Filter effect of masks and household materials

The question now is how non-infected persons can safely protect themselves if the distance rules cannot be observed and the infected persons are not wearing a mask and consequently the environment around them is contaminated with viruses. In this case, only FFP2 or even better respiratory masks offer effective protection, as they are only permeable to a very small fraction of tiny droplets. However, as these protective masks are currently not available, the question is whether there are commercially available materials that can effectively prevent the spread of the droplets.

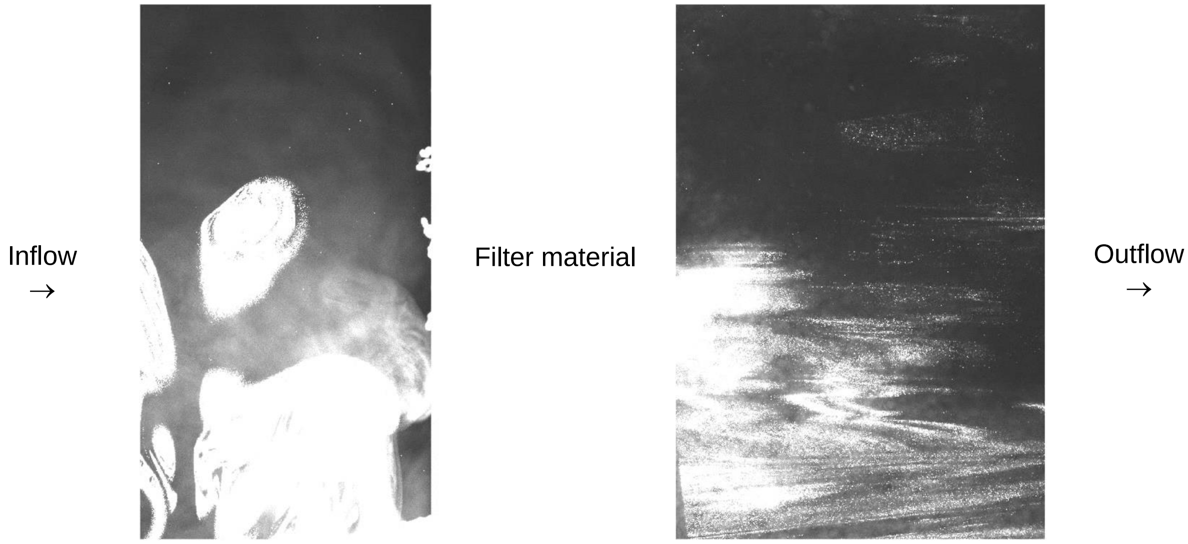
For this purpose, a test setup was used which largely complied with the official test conditions specified by the authorities (DIN EN 149). The droplets with a diameter of 0.1 – 2 µm were fed in before the filter materials. The materials were firmly mounted in front of the inlet of a flow channel. The intake speed of the droplets was based on the test standard. In addition to the volume flow and the pressure drop across the filter material, the movement of the droplets through the filter material was measured with Particle Image Velocimetry. With this measuring method, the movement of the droplets in front of and behind the filter material can be observed very precisely in a measuring plane, which was again generated in these experiments with a laser light-sheet. The area of the filters and the channel edges is not shown, since no relevant flow information is visible in these areas. The flow direction is from left to right. If the intensity of the scattered light emanating from the droplets is large in front of the filter material (left image) and close to zero behind it (right image), this shows that the droplets used are almost completely filtered out by the material. If, on the other hand, no reduction in intensity can be detected behind the filter material, there is no filter effect at all.

Initially, a commercial mouth-nose protector was investigated, which is used in clinics to protect staff. The comparison of the two pictures shows that almost all droplets pass the filter material unhindered. This means that this mouth-nose protector does not offer any significant protective effect compared to the droplets used. In addition, these masks do not seal tightly enough with the face, so that the droplets in the surrounding area can also flow unhindered past the edge of the mask when inhaled and reach the lungs. If the mask does not fit properly, this will even be the rule, as the air will largely follow the path of least resistance. Although the pressure loss of the mouth-nose protection tested is only about 70 Pa, it will still be sufficient to slow down the air sufficiently so that it flows into the lungs mainly around the edge of the mask. Therefore, these masks do not provide effective protection against the transmission of the virus via droplets when the ambient air is contaminated. It is therefore strongly discouraged to wear this mouth and nose protection in contaminated areas. If this protection is worn in such areas, it is essential that the distance rules are followed for your own protection.



Effectiveness of particle filtering (diameter approx. 0.1 – 2 µm) with the filter material of the mouth and nose protector

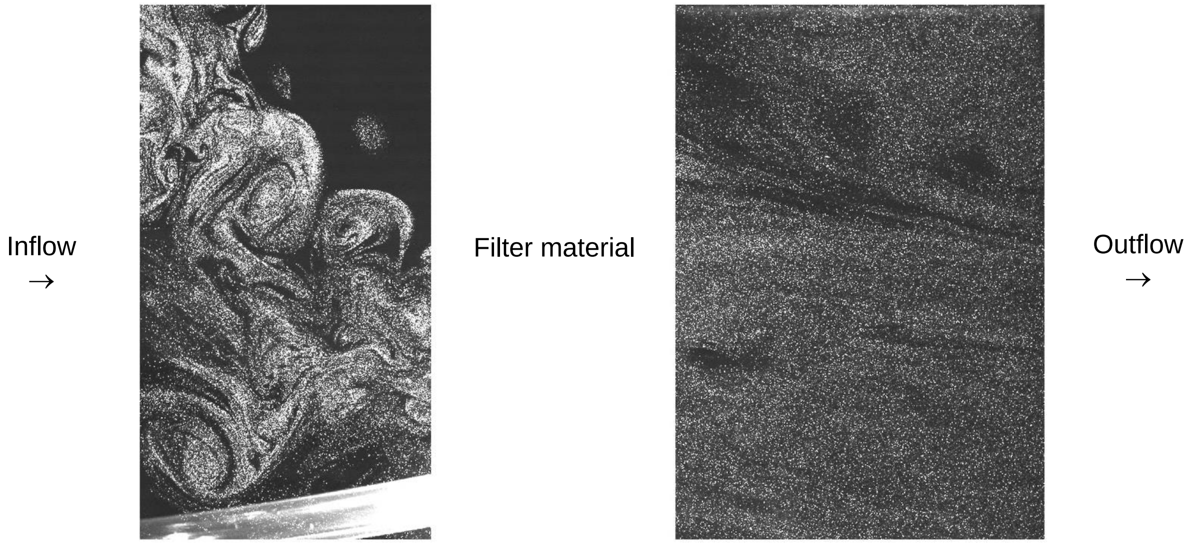
In the next experiment, the mouth-nose protector was sprayed with water intermittently to answer the question of whether the filter effect changes due to moisture. This case simulates a mask that was worn for a long time. It is shown that the already poor filter function is not significantly affected by moisture, see figure. Only wearing the mask becomes more uncomfortable and the flow resistance increases, so that more and more air will flow past the mask.



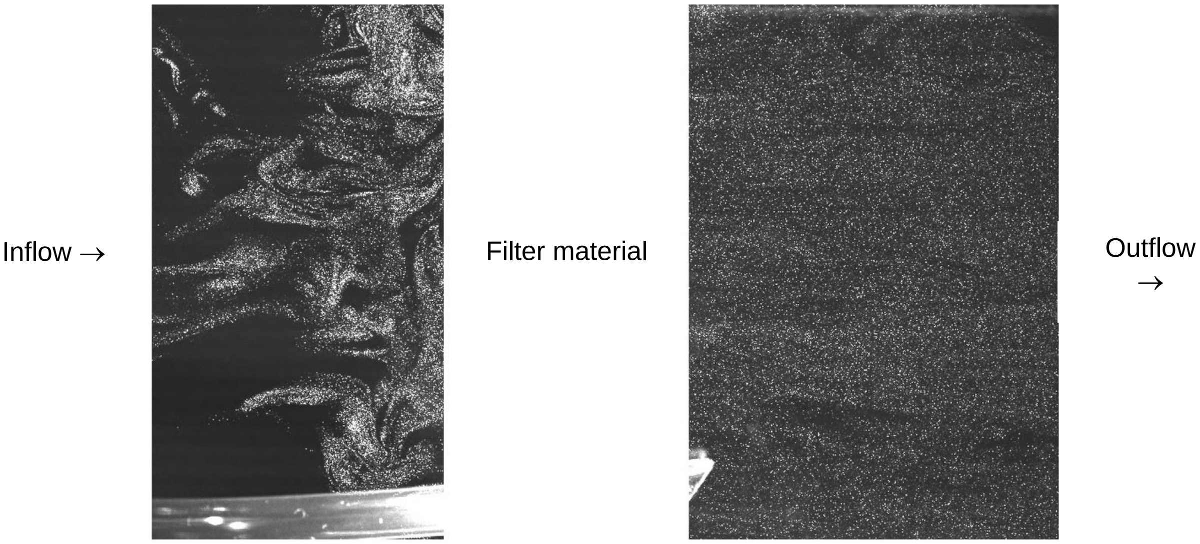
Effectiveness of particle filtration (diameter approx. 0.1 – 2 µm) with the filter material of a moist mouth and nose protector

Even worse than the mouth-nose protection is the hygiene mask, see figure. This is certainly suitable for catching larger objects such as hair, dandruff or similar, but droplets, such as those produced when talking, coughing and sneezing, cannot be filtered out of the air stream by the hygiene mask.

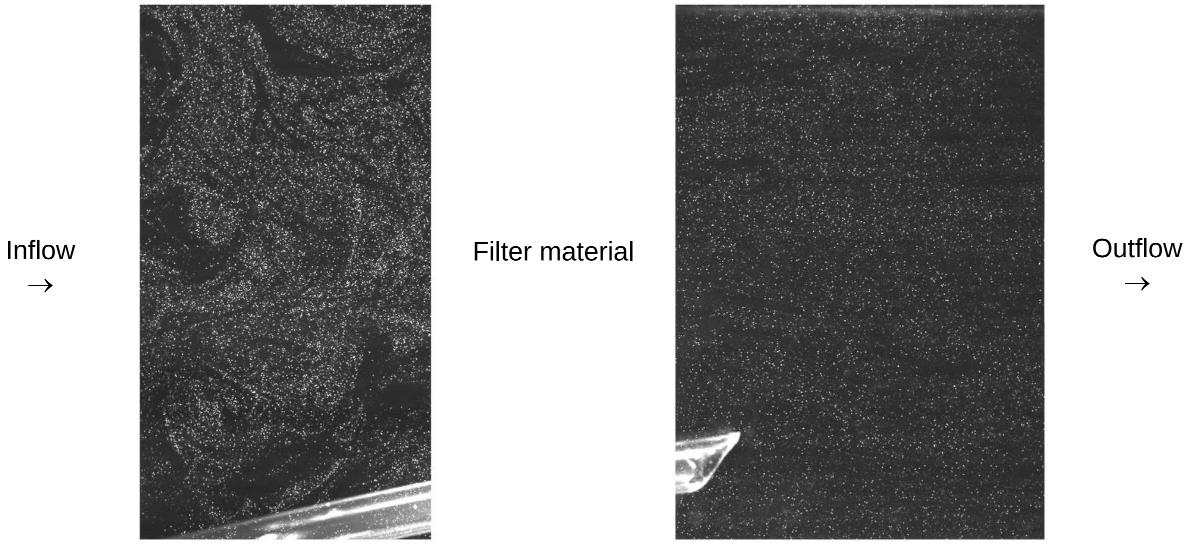
Materials such as paper towel, toilet paper with 4 layers, paper tissues, coffee filters also offer no protection at all against droplets in this size range. These materials are very well suited to homogenize the inhomogeneous droplet clouds but they do not show any filtering effect for the droplets used here. Only very large droplets are retained by these materials and therefore these materials are suitable for their intended use, which is stated on the packaging, but not as filter material for small droplets. It is therefore strongly discouraged to make masks from these materials. They offer no effective protection against droplet infection at all!



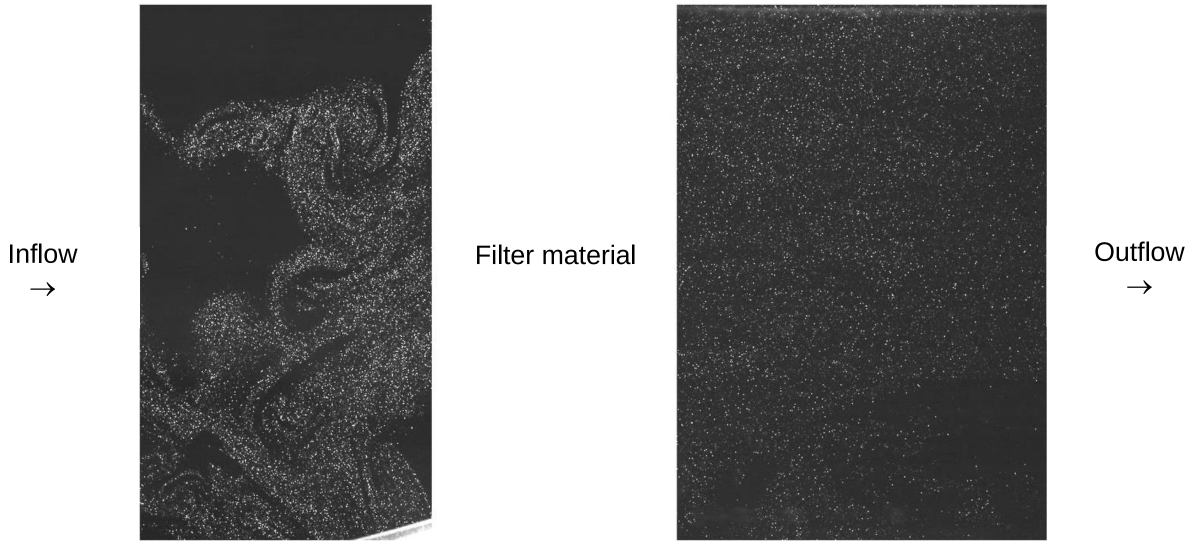
Effectiveness of particle filtration (diameter approx. 0.1 – 2 µm) of toilet paper



Effectiveness of particle filtration (diameter approx. 0.1 – 2 µm) of a paper kitchen towel

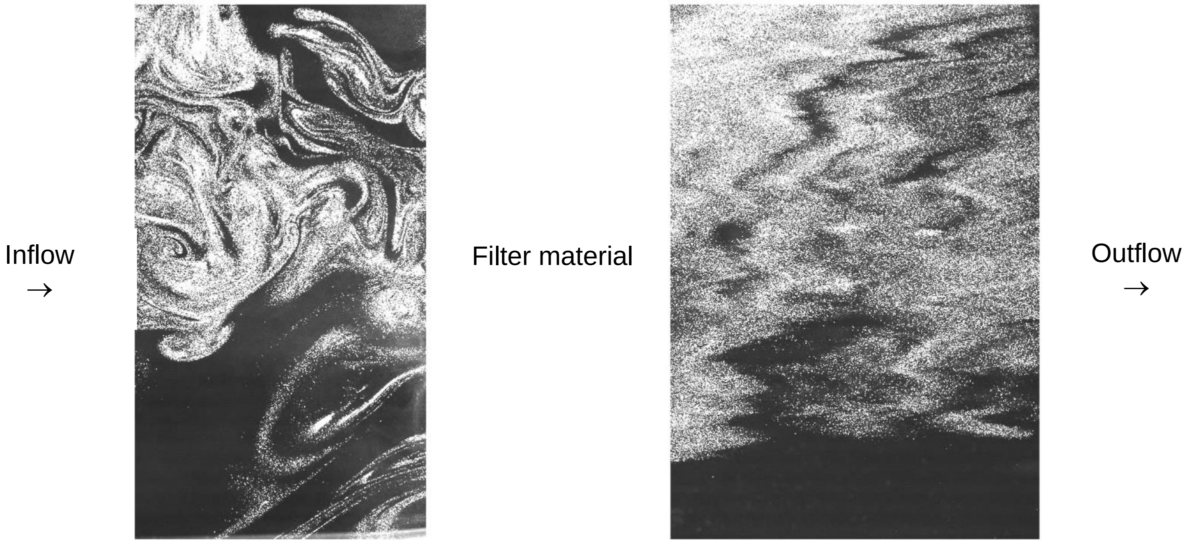


Effectiveness of particle filtration (diameter approx. 0.1 – 2 µm) of a coffee filter



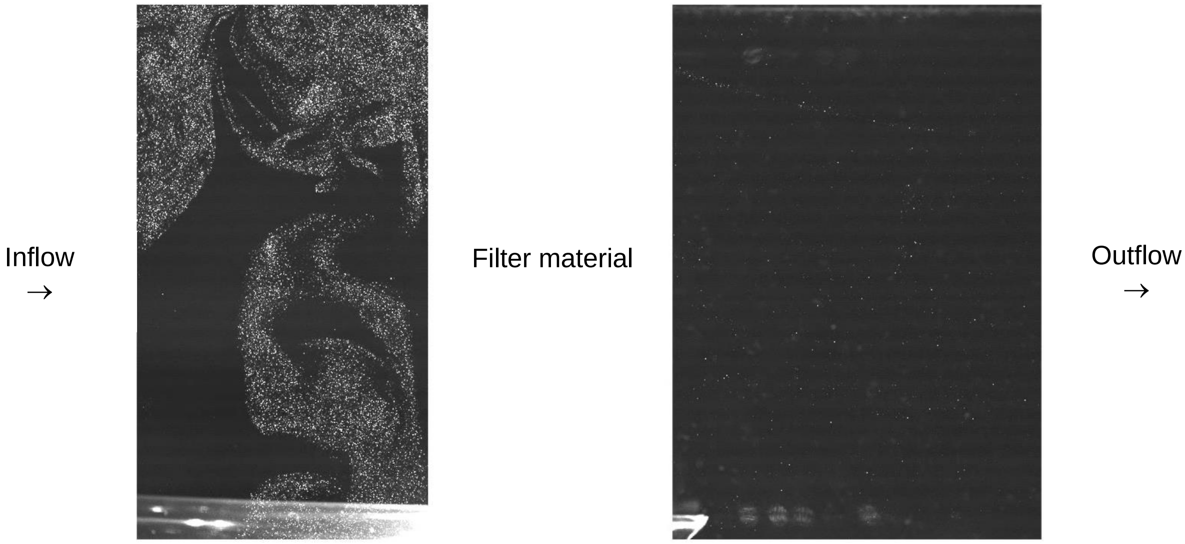
Effectiveness of particle filtration (diameter approx. 0.1 – 2 µm) of a microfibre cloth

Furthermore, a very strong fleece was tested, which serves as a protective coating on ironing boards. The material is 4 mm thick, completely opaque and has a pressure drop of about 35 Pa. However, the filter effect is close to zero even with this material. It can be clearly seen in the picture that the clouds of droplets flow through the fleece unfiltered. Only a certain redistribution of the droplets can be seen. In conclusion, it can be said that even quite thick and dense materials offer no protection against infection. Therefore, one should also not use these materials, fleeces and fabrics as mask material if one wants to protect oneself from a droplet infection. Even several layers of a dense material do not have a filtering effect on the droplet sizes that primarily escape when breathing, speaking and coughing.



Effectiveness of particle filtration (diameter approx. 0.1 – 2 µm) of a fleece

Good results could only be achieved with the material of a high-quality vacuum cleaner bag. Despite the small droplets used in these experiments, almost all droplets are reliably filtered out and consequently no larger droplets can penetrate the material. According to the manufacturer, the material filters 99.9% of the fine dust down to 0.3 µm. Simple vacuum cleaner bags had a better filtering effect than the mouth and nose protector and all other materials tested, but they could not come anywhere near matching the high-quality vacuum cleaner bags in terms of filtering effect. The material of high-quality vacuum cleaner bags with fine dust protection is therefore basically suitable as a starting material for the manufacture of a particle-filtering mask[1]. Tests with water have shown that the protective effect is largely maintained even when the mask material is dripping wet.



Effectiveness of particle filtration (diameter approx. 0.1 – 2 µm) of a high-quality vacuum cleaner bag

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[1] The manufacturers Swirl and DM expressly advise against using their vacuum cleaner bags for the production of breathing masks, see
https://www.melitta-group.com/de/Statement-der-Melitta-Group-zu-alternativen-Schutzmasken-3605,263.html, 11.04.2020
https://futurezone.at/science/drogeriemarkt-warnt-vor-masken-aus-staubsaugerbeutel/400809749, 11.04.2020

Whether a mask made of this material is comfortable to wear cannot be deduced from these experiments. Therefore, in the following we will analyze whether a mask can be made from this material that fits comfortably and makes breathing as little difficult as possible.

3. Manufacture of a mask

There are two important aspects to consider when manufacturing a mask.

First, the fit must be very well matched to the size and shape of the face. If the mask does not fit well and closely to the face, it will not only be uncomfortably to wear, but contaminated air can also flow in and out unhindered through gaps at the edge of the mask. It is important to remember that most air will take the path of least resistance. Therefore, most of the air will flow through the openings, if there are any. In this case the mask has no protective function. It is therefore very important to make sure that no openings are created at the edge of the mask, e.g. by a beard, long hair or jewellery. Furthermore, it is important to make sure that the mask fits tightly even when coughing and sneezing. When coughing and sneezing, the air escapes from the mouth very quickly and this increases the pressure inside the mask. If the pressure becomes too high, the mask can come off the face and the air can escape unfiltered. If you are not infected, this is irrelevant. But if you are infected, it would be fatal for the unprotected people around you. This must be prevented by a good fit and a solid attachment to the head!

Secondly, the size of the mask must be correctly dimensioned. If only the material usage is taken into account, a minimum solution would be aimed at in order to be able to produce as many masks as possible from the available material. But the commercial masks are quite voluminous and there is a good reason for this. The lungs need about 0.5 – 0.75 litres of air per breath without physical exertion. When doing sports or sneezing, the volume per breath naturally increases significantly and wearing a mask also tends to cause a little more air to be breathed in. This volume must flow through the filter material. The smaller the area of the filter, the faster the air must flow through the filter during a breath. However, the flow resistance, which is directly felt when breathing in and out, increases with the square of the speed. This means that if the surface of the mask is halved, the flow speed doubles and consequently the flow resistance quadruples. Since the smaller the flow resistance of the filter material, the easier it is to breathe through the mask, the larger the surface of the mask should be. Those who have difficulty breathing without a mask should not save on the material.

Now we come to the production. There are many possibilities to produce an effective breathing mask. But here we present only one very simple variant. During the production we pay attention to an optimal function, a minimal material requirement and a simple manufacturing without special tools (only scissors and punch). Concerning design and creative colour design, everyone can give free rein to their imagination.

First, a quarter circle is cut out of the vacuum cleaner bag[2] and turned inside out, so that the inner surfaces come out[3]. Now you can decide whether the seam should sit on the nose (shark shape) or on the cheek (duck beak shape). The open sides, which should sit on the nose and chin, are rounded off slightly to achieve a good fit. The area sitting on the nose is shortened more to avoid covering the eyes and to ensure that the metal strip sits well on the nasal bone.

The open mask edges are fixed with flexible adhesive tape[4]. Kinesiology adhesive tapes with a cotton surface are quite suitable, as they lie comfortably on the skin and stick very firmly. Furthermore they are made for the skin and therefore well tolerated. To ensure a good fit and a tight seal over the nose it is very important to glue a flexible metal strip in the nose area. The metal strip should be about 10 cm long and not too thin. Ready-dimensioned metal strips can be used in quick-fasteners or staples. Suitable metal strips can also be cut out of the sheet metal of cookie jars. The metal strip must sit on the outside of the mask and be firmly glued on. If it is attached to the inside, small metal tips and the edges can press against the nose. Furthermore, the seal of the mask in the nose area can be impaired. The strong adhesive tape that is also used for the mask edge is also suitable for gluing on.

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[2] If vacuum cleaner bags are used as masks because no FFP2 mask is available and suitable protection against droplet infection is urgently needed, a vacuum cleaner bag that is free of chemical additives should be used only temporarily and as a stopgap to prevent possible irritation. It is essential that the dust bag (or other material used to make a mask) is free from harmful substances that may be released into the skin, mucous membranes and respiratory tract when cut and worn.

The manufacturers Swirl and DM expressly advise against using their vacuum cleaner bags for the production of breathing masks, see

https://www.melitta-group.com/de/Statement-der-Melitta-Group-zu-alternativen-Schutzmasken-3605,263.html, 11.04.2020

https://futurezone.at/science/drogeriemarkt-warnt-vor-masken-aus-staubsaugerbeutel/400809749, 11.04.2020

[3] We strongly recommend using the outside of the dust bag as the inside of the respirator for the following reason. In order to obtain approval, the vacuum cleaner bags must not release any dust or parts of the bag itself (fleece, glass fibre, synthetic fibres or other filter materials and additives etc.) outside into the ambient air. Since the users of the mask do not want to inhale any of these substances either, we strongly recommend using the outside of the bag as the inside of the mask.

[4] It is very important to glue the cut surfaces of the bag with a strong adhesive tape so that nothing can be released from the inside of the bag material to the outside.

Materials required to manufacture a mask and the different manufacturing stages from top left to bottom right

To attach the mask to the head, tapes or better an elastic band is required. For attachment, two holes should be punched or perforated into the material on each side with a distance of a few centimetres to ensure a comfortable and airtight fit. The correct position of the holes can be determined by gently pulling on the presumed fastening points. If the mask fits comfortably when pulled at the presumed fastening positions and there are no gaps at the edge of the mask, the optimal fastening position for the elastic band has been found.

The length of the elastics must be adapted to the head size. To determine the correct length, the first elastic band is tied or stapled on one side of the mask and then the mask is put on. The elastic band is then passed around the head and held at the other fastening point of the mask so that the mask fits comfortably and without gaps. Now the mask can be taken off, whereby the fingers must remain at the correct position of the elastic to allow the correct attachment to the mask. The procedure is repeated to also determine the length of the second rubber band. It is important that one rubber band is above the ears and one below to ensure a firm fit even when looking up and down or when the mask is under load.

If the elastics are attached on both sides, the mask is ready in its simplest form and can be put on and tested. After putting on the mask, the noseband must first be bent with both hands into the appropriate shape. To check the tight fit of the mask, hold the mask lightly with both hands without changing the fit and breathe out strongly. If air flows through gaps at the edge of the mask, the noseband or elastic strap must be adjusted. If no seal can be achieved despite these measures, the mask is too large. In this case the mask can be cut open in the chin area a little towards the tip of the mask and the mask size can be adjusted by overlapping. Once the correct size has been found, the overlapping areas can be connected with the adhesive tape. If the mask gets wet during use, the breathing resistance increases or the mask is damaged, it must be replaced. To be on the safe side, you should always take several masks with you so that you always have a spare. A few masks can be given away on the way.

The particle filtering protective mask is ready and can be used in everyday life. A cloth can be pulled over the mask to embellish it.

When using the masks, the following points are very important:

1. To ensure effective protection against infection via the mouth and nose, suitable particle-filtering half masks must be used and not simple face masks, which only give a feeling of security but do not provide reliable protection.
2. Masks must be put on correctly with clean hands, otherwise they do not provide protection. Care should be taken to ensure good wearing comfort and to check for gaps and damage.
3. In order to effectively contain the spread of the virus, the masks must always be put on as soon as the distance rules can no longer be adhered to, whether at work, when shopping, when travelling, during cultural activities but also during leisure time.
4. Masks should only be worn when really necessary and never for more than 75 minutes at a time. Before putting them back on, a sufficiently long recovery period of about 30 minutes should be observed and they should be used for a maximum of 5 x 75 minutes per day.
5. If someone coughs on you directly, it is recommended to exhale slowly and immediately. This will increase the pressure under the mask and nothing can flow in from outside.
6. In addition to the mask, it is very important that the general hygiene measures and distance recommendations are followed. This is particularly important when eating and drinking, as the mask must be removed for this purpose. However, the hygiene measures also protect against smear infections, which can occur when putting on and taking off the masks, for example.
7. It is also recommended to wear protective goggles and light gloves to avoid infection via the eyes or hands. Especially when shopping, viruses can be transmitted via change or products that people check for quality by hand, such as fruit, and can lead to infection.
8. The masks have not been tested by any governmental authority and therefore they are of course not certified. The masks produced should therefore be seen as a sensible alternative until sufficient FFP2 and FFP3 masks are available again.

Conclusion

The results show that direct personal isolation with suitable respiratory masks is without doubt technically possible. Combating the transmission of the virus where it actually takes place therefore seems to be very sensible and appropriate.

If everyone consistently cooperates, the restrictions could be relaxed and life could continue to be largely normal without major restrictions. Instead of dissociating oneself from all people it would be much better to only distance oneself from those who do not wear suitable masks.

However, as there are other ways of transmission, it is essential to maintain the recommended hygiene measures. In the event of an accident in a car, the occupants are also protected by a variety of devices (seat belts, airbags, crumple zone, headroom, legroom, ...).

Experiments have also clearly shown that most household materials tested do not provide any protection at all and are therefore completely unsuitable as materials for protective masks. It is extremely important to acknowledge this! Only if the right material is used, the mask can offer effective protection! It is desirable that in a few weeks sufficient FFP2 masks will be available for the entire population. However, due to the limited production capacities and the great demand in hospitals and medical practices, this will probably not be achievable. It would therefore be advisable to provide the population with suitable filter material for mask production on a temporary basis so that they can protect themselves with suitable materials. At the latest when the number of SARS-CoV-2 infections reaches millions, this is absolutely necessary and vital for the survival of many people. If 10% of the population would agree to invest one hour to produce simple masks, there would already be 100 million particle-filtering protective masks for the population. The supply of the population with particle-filtering protective masks could thus be ensured on their own responsibility. The distribution problem could be solved very easily by giving the masks away to friends, neighbours and colleague.

If the government's comprehensive restrictions are lifted and the infection rate increases rapidly again, this enormous manufacturing capacity of the population should be mobilized for its own protection until sufficient commercial particle-filtering protective masks are available. However, the government would have to ensure that the population is sufficiently supplied with suitable filter material.

The technical solution to the pandemic problem with particle-filtering protective masks is not only possible, but also makes sense until an effective vaccine is found. The alternative solution, i.e. an uncontrolled or controlled infection of the population, would be a human tragedy in view of the deadly risk of around 1:100. A comparable risk is voluntarily taken only by astronauts and soldiers in war zones! This strategy would only be humane if a highly effective drug were available. It is to be hoped that the government will avert great harm to the people.

Literatur

[1] Ferguson NM et al. (2020) Impact of non-pharmaceutical interventions (NPIs) to reduce COVID-19 mortality and healthcare demand. Imperial College COVID-19 Response Team. https://www.imperial.ac.uk/media/imperial-college/medicine/sph/ide/gida-fellowships/Imperial-College-COVID19-NPI-modelling-16-03-2020.pdf, abgerufen am 04.04.2020

[2] https://www.welt.de/wirtschaft/article206603525/Beatmungsgeraete-Draeger-soll-10-000-Stueck-in-kuerzester-Zeit-bauen.html, abgerufen am 04.04.2020

[3] Verity R et al. (2020) Estimates of the severity of coronavirus disease 2019: a model-based analysis. Lancet Infect Dis, https://doi.org/10.1016/ S1473-3099(20)30243-7

[4] WHO Director-General's opening remarks at the media briefing on COVID-19 - 30 March 2020, https://www.who.int/dg/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19---30-march-2020, abgerufen am 04.04.2020

[5] Drosten broadcast 25, NDR Info Corona Virus Update from March 31st, 2020, https://mediandr-a.akamaihd.net/download/podcasts/podcast4684/AU-20200331-1323-5200.mp3

[6] Leung NHL et al. (2020) Respiratory virus shedding in exhaled breath and efficacy of face masks. Nature Medicine, https://doi.org/10.1038/s41591-020-0843-2

[7] https://www.lgl.bayern.de/downloads/arbeitsschutz/arbeitsmedizin/doc/merkblatt_mns_atemschutz.pdf, Bayerisches Landesamt für Gesundheit und Lebensmittelsicherheit, abgerufen am 04.04.2020

[8] Zayas G et al. (2012) Cough aerosol in healthy participants: fundamental knowledge to optimize droplet-spread infectious respiratory disease management. BMC Pulmonary Medicine 12:11, http://www.biomedcentral.com/1471-2466/12/11

[9] Han ZY et al. (2013) Characterizations of particle size distribution of the droplets exhaled by sneeze. J R Soc Interface 10:20130560, http://dx.doi.org/10.1098/rsif.2013.0560

[10] Raffel M et al. (2018) Particle Image Velocimetry. Springer Verlag

[11] Rensink D (2004) Verdunstung akustisch levitierter schwingender Tropfen aus homogenen und heterogenen Medien. Dissertation, Universität Erlangen-Nürnberg

[12] Nishimura H et al. (2013) A New Methodology for Studying Dynamics of Aerosol Particles in Sneeze and Cough Using a Digital High-Vision, High-Speed Video System and Vector Analyses. PLoS ONE 8:e80244, doi:10.1371/journal.pone.0080244

[13] Tang JW et al. (2009) A schlieren optical study of the human cough with and without wearing masks for aerosol infection control. J R Soc Interface 6:S727–S736, doi:10.1098/rsif.2009.0295.focus

[14] Lok C (2016) Where Sneezes Go. Nature 534:24-26