Experimental evaluation of the bidirectional filtration efficiency of respirators and face masks against airborne particles during cyclic breathing

Dennis Derwein[1], Tobias Maria Burgholz[2], Kai Rewitz[1], Dirk Müller[1,2]

1 RWTH Aachen University,
E.ON Energy Research Center
Institute for Energy Efficient Buildings and Indoor Climate
Mathieustraße 10
52074 Aachen, Germany

2 Heinz Trox Wissenschafts gGmbH
Mathieustraße 18
52074 Aachen

ABSTRACT

In this work we investigate the bidirectional filtration efficiencies of respirators, such as FFP2 masks and medical masks, under cyclic breathing and different fits. We developed a test bench, which consists of a test chamber with an artificial head, and which is connected to a specially developed artificial breathing function. The exhalation filtration performance of masks can be evaluated by exhaling particle-laden air into the test chamber. Similarly, the inhalation filtration performance can be evaluated by inhalation of particle-laden air from the test chamber. We compare four different types of masks (medical mask and three types of FFP2 masks). In addition, we investigate the influence of different mask fits (e.g., nose clip fitting) on the filtration efficiency of the masks, as a perfect mask fit cannot always be guaranteed in realistic scenarios and filtration efficiency may therefore be reduced. The results show that different maximum filtration efficiencies are achieved depending on the mask type. Only one of the three FFP2 masks can achieve filtration efficiencies above 89% while one only achieves a maximum of 59%. Depending on the fit, the medical mask can achieve up to 55% for self-protection. The fit of the mask has a major influence on the filtration efficiencies. If the mask is used without putting on the nose clip, a value of only 10 to 45% can be achieved, depending on the mask type and direction of protection. With two of the FFP2 masks, simply putting on the nose clip is enough to achieve filtration efficiencies of at least 75%. It was also shown that a medical mask with the best fit protects at least as well in both directions as the three FFP2 masks with the worst fit level. In addition, the fit of the mask and the filtration efficiency correlate very well with the measured pressure difference across the mask.

KEYWORDS

face mask, mask fit, filtration efficiency, airborne particles, infection risk

1 INTRODUCTION

Respirators, such as FFP2 masks and medical masks, are a widely used measure to reduce the airborne transmission of potentially viral particles between individuals. FFP2 masks promise a high level of self-protection. DIN 149 specifies that the total inward leakage of FFP2 masks must not exceed 11%, which corresponds to a total filtration rate of 89% (DIN EN 149). If a high level of protection must be guaranteed, so-called fit tests can be carried out. Qualitative fit tests according to DIN ISO 16975-3 even specify fit factors of at least 100, which corresponds to a filtration rate of around 99% (ISO 16975-3).

Such tests are only common in work areas where a high level of protection must be guaranteed, for example in medical facilities (Regli et al. 2021). During pandemic situations, common people need to be protected by FFP2 masks, who are not trained in the correct use of FFP2 masks and do not have access to fit tests in everyday situations. It can therefore be assumed that in everyday situations, FFP2 masks are more likely to be worn imperfectly, so that the protective effect is reduced (Knobloch et al. 2023). To evaluate the effectiveness of masks in containing infectious diseases, such as during the COVID-19 pandemic, it is therefore essential to consider reduced filtration efficiency due to imperfect use.

One method of determining the filtration efficiency of masks is to use test benches that evaluate the filtration efficiency of masks by measuring particles using an artificial head and inhaled or ambient air contaminated with artificial particles (Tcharkhtchi et al. 2021). Previous studies have shown with these kind of test benches that the masks should be accurately evaluated under cyclic breathing (Mahdavi et al. 2014) and that the filtration efficiency varies depending on the direction of filtration (self and external protection) (Berger et al. 2023). While several studies have evaluated filtration efficiency for self-protection under cyclic breathing (Balazy et al. 2006; Mahdavi et al. 2014), there are few studies on the evaluation of filtration efficiency during cyclic breathing for external protection (Lindsley et al. 2023) or in both directions (Koh et al. 2022). A bidirectional evaluation should be carried out in a comparable setting, as both directions of filtration are relevant to the overall assessment of the effectiveness of masks in reducing the transmission of particles between individuals. In addition, there are no studies yet that have dealt with reduced fit. In those studies mentioned above, the fit of the mask is not further specified or, in some cases, an optimized fit is simulated by gluing the mask seal to the manikin (Berger et al. 2023; Mahdavi et al. 2014).

The aim of this study is to determine the bidirectional filtration efficiencies of different shapes of FFP2 mask types and medical masks and the reduction of these efficiencies due to imperfect mask fit. To achieve this, we have developed a test stand in which the masks can be measured on an artificial head under cyclical breathing.

Firstly, the design and functionality of the test bench is presented. Then the analysed masks and boundary conditions of the test plan are explained. The resulting filtration efficiencies are then presented and subsequently discussed. Finally, an outlook and conclusion are given.

2 TEST BENCH DESCRIPTION

A sketch of the mask test bench is given in Figure 1. The mask test bench consists of two main components: the test chamber (as seen on the left of Figure 1) and the artificial lung (as seen on the right of Figure 1). These two components are described below.

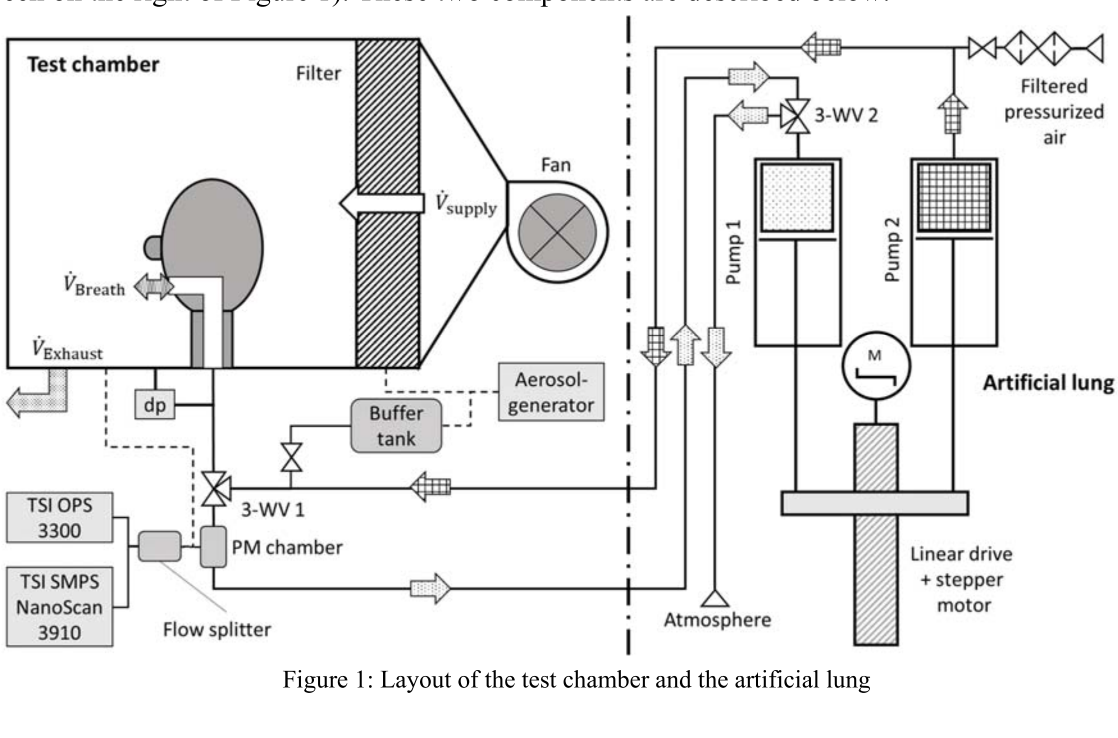

Figure 1: Layout of the test chamber and the artificial lung

2.1 Test chamber

The test chamber consists of a rectangular chamber with the dimensions of 1000 x 700 x 700 cm^3, thus amounting to a volume of roughly 490 litres. The side walls and the top wall are made of glass to ensure transparency and the front consists of a glass door to allow access into the test chamber. The base plate, which is made of a plastic plate, holds the artificial head and is used for power, data and hose connections. An F9/ePM1 and HEPA/H14 two-stage filter installed at the rear enables particle-free supply of air into the chamber through the entire cross-section. The supply air is delivered into the test chamber by a centrifugal scroll housing fan of the type “RadiCal G3G133-RO15-11” manufactured by “ebm-pabst” with an integrated constant air flow controller. The exhaust air is routed via a hose connection on the front side of the base plate, thus creating a mean flow from rear to the front of the chamber. In addition, five computer cooling fans are installed in the chamber to ensure well mixing and thus an equal distribution of particles in the chamber.

An artificial head is installed in the centre of the base plate. This artificial head is part of an "Airway Management Trainer" from "Laerdal Medical GmbH" and is connected to the artificial lung via tubes. We measure the pressure drop over the masks with an “SDP810-500Pa” differential pressure sensor by the company “Sensirion AG”, which is marked as “dp” in Figure 1.

Two particle analysers from “TSI Inc.” are used to measure the particle concentrations: an “SMPS NanoScan 3910” scanning mobility particle sizer measures the particles in the range from 10 nm to 420 nm while the optical particle sizer “OPS 3300” covers particle sizes from 300 nm to 10 µm. The two particle analysers are connected via a flow splitter (“FS” in Figure 1) of the type “3708” by the same manufacturer to the test chamber. The particles are generated by a portable test aerosol generator of the type “3073”, also from “TSI Inc.”, by atomisation of “Di-Ethyl-Hexyl-Sebacate (DEHS)” as the particle generator liquid. This enables the evaluation of a wide range of particle sizes between 87 nm and 2 µm, thus covering the "most penetrating particle sizes" of FPP2 masks (approx. 50–100 nm) and medical masks (approx. 300 nm) (Tcharkhtchi et al. 2021).

In the mode in which the particle filtration efficiency for the external protection is evaluated, the particle generator is connected to the exhalation pipe through the buffer tank and the exhaled air is loaded with particles. In these cases, the particle concentration is measured in the test chamber. In the mode in which particle filtration is assessed for the self-protection, the particle generator is connected to the test chamber and the test chamber air is loaded with particles. In these cases, the particle concentration is measured in the measurement chamber in the neck area.

2.2 Artificial lung

We use an artificial lung to mimic a cyclic breathing process through the artificial head. The artificial lung was firstly used for investigating exhaled air distributions in car cabin environments (Nabilou et al. 2023). The main part of the test stand consists of two spirometer calibration piston pumps from the manufacturer "Vitalograph GmbH", which are moved in parallel by a linear drive. The pumps each have a volume of 3 litres. During the breathing cycles, their volume can be adjusted using the stroke pathway of the pump. The volume flow profile of the breathing cycle can be controlled by applying a velocity profile of the stepper motor. The linear drive is driven by a stepper motor of type “AS2041-1H10” by the company “Beckhoff Automation GmbH & Co. KG”. The stepper motor and the valves are controlled by a programmable logic controller (PLC) from the same manufacturer. The use of two piston pumps allows the inhalation and exhalation process to be separated so that an air exchange can be guaranteed. The process works as follows. During the inhalation, the pumps are moved downwards by the linear drive. 3-way valve 1 (“3-WV 1”) and 3-way valve 2 (“3-WV 2”) open the path between “Pump 1” and the artificial head. “Pump 1” draws in the air from the test chamber through the artificial head and the two 3-way valves, thus creating an inhalation flow. Pump 2 draws in filtered compressed air. In the application where filtration efficiency for external protection is to be analysed, aerosol is also injected from the buffer tank during the inhalation phase into the pipe between “3WV-1” and “Pump1”. When exhaling, the two 3-way valves are switched, so that the pathway between “Pump 2” and the artificial head as well as the pathway between “Pump 1” and the exhaust opening to the atmosphere are opened. The linear drive moves upwards so that the inhaled air in “Pump 1” is released into the atmosphere and “Pump 2” pushes air through “3WV-1” and the artificial head into the chamber, thus creating the exhalation flow.

3 EXPERIMENTAL DESIGN

The experimental investigations are carried out according to a fully factorial test plan, whereby 3 factors are analysed: Mask type, mask fit, and filtration direction. There are various forms of FFP2 masks. The designations of the forms in this paper are based on the designations of Knobloch et al. (Knobloch et al. 2023). We analyse three different forms of FFP2 masks in this work. FFP2_1 corresponds to a so-called "coffee filter" shaped mask, FFP2_2 corresponds to a so-called "three-folded" mask, and FFP2_3 to a “rigid dome” shaped model. FFP2_1 is fixed to the head by ear loops, while FFP2_2 and FFP2_3 are fixed to the head by loops around the head. A medical mask is also analysed as a comparison, which is also fixed to the head by ear loops.

Table 1: Overview over the investigated masks

Mask	Manufacturer	Name	Type	Shape	Fixation
med. Mask	Unknown	OP-Mundschutz “SOFT PROTECT GERMANY” blau–BASIC	EN 14683 Typ II R	Medical mask	Ear loop
FFP2_1	Unknown	Atemschutz - Faltmaske FFP2 NR “Komfort20“	FFP2 NR	Coffee filter	Ear loop
FFP2_2	3M	Aura 9320D+	FFP2 NR D	Three-folded	Head band
FFP2_3	3M	8810	FFP2 NR D	Rigid dome	Head band

The mask fit is varied in 3 stages. In the first stage (Fit1), the mask is placed on the face and fixed in place by the loops, but no further measures are taken to optimise the fit. Furthermore, the nose clip is not fitted, so that the overall aim is to imitate a very careless wearing of the mask. In the second stage (Fit2), the mask is also put on without optimisation measures, but the nose clip is fitted around the nose. In the third stage (Fit3), a careful mask fit is imitated by applying the nose clip and optimising the mask fit so that possible leakage via the face seal is avoided as far as possible, thus attempting to imitate a "fit-tested mask". As a medical mask cannot be fitted anyway, only Fit1 and Fit2 are used when analysing the medical mask. Based on the three factors and considering that the medical mask is not examined in Fit3, this results in a fully factorial test plan of 22 tests, where each test point is carried out three times. A sinusoidal breathing profile is used as the breathing profile, which corresponds to the sinusoidal breathing profile A from EN 13274-3 with a breathing frequency of 10/min, a respiratory volume of 1 litre and a peak air flow of 34,2 litres/minute (DIN EN 13274-7). As pressure equalisation must still take place when switching between the inhalation and exhalation process and between the exhalation and inhalation process, pauses of 250 milliseconds are set in each case. The test procedure for each test point is as follows: First, a reference point without a mask is determined. After stable constant particle concentrations have been established, the particle concentrations are measured for 20 minutes, so that a total of 20 samples with a sample duration of 1 minute each are recorded for the two particle measuring devices. The three repetitions of the measuring point are then carried out by putting on the mask and measuring for 30 minutes. Experience has shown that a constant concentration is then established after about 10 minutes, so that 20 samples are also recorded for each repetition. The particle size-dependent filtration efficiency $\eta_{i,j}(d_{\mathrm{Particle}})$ for test point i and repetition j is calculated using Formula (1). Here, $c_{\mathrm{mean,i,j}}(d_{\mathrm{Particle}})$ corresponds to the particle concentration averaged over the 20 samples for test point i and repetition j and $c_{\mathrm{mean,ref}}(d_{\mathrm{Particle}})$ corresponds to the particle concentration of the reference measurement averaged for the test point i over the 20 samples, both measured in the measuring chamber in the neck area:

$$\eta_{\mathrm{in},i,j}(d_{\mathrm{Particle}}) = \left(1 - \frac{c_{\mathrm{mean},i,j}(d_{\mathrm{Particle}})}{c_{\mathrm{mean},i,ref}(d_{\mathrm{Particle}})}\right) * 100\ \% \qquad (1)$$

The differential pressure over the artificial head is measured in a frequency of 5 Hz, so that the differential pressure curve over time during the breathing cycle can be clearly recorded. The peak-values of the differential pressures for both inhalation and exhalation are averaged for the reference points and the test points. The mean mask differential pressures for inhalation and exhalation are then determined by subtracting the mean differentials pressures of the test points and mean differentials pressures of the reference points without a mask.

4 RESULTS

Figure 2 shows the particle size averaged filtration efficiencies for the 22 test points in the form of a grouped bar chart, whereby the particle size-dependent filtration efficiencies have been averaged over the particle sizes from 86 nm to 1023 nm. The bars are sorted into four groups, each representing the six test points for each mask type. For the medical mask, the external filtration efficiencies for the external protection are 10% to 41% for Fit1 and Fit2. For self-protection, the filtration efficiencies are at 21% and 53%. For the FFP2_1 mask, the filtration efficiencies for the external protection are at 15%, 40% and 56% and for the self-protection at 35%, 43% and 50%. For the FFP2_2 mask, the external filtration efficiencies are at 24%, 89% and 96% and for the self-protection at 35%, 86% and 98%. For the FFP2_3 mask, the external filtration efficiencies are at 41%, 75% and 91% and for the self-protection at 46%, 77% and 88%. The medical mask provides a higher self-protection than external protection. We also see that fitting the nose clip has a large impact and leads to a large increase in filtration efficiencies. FFP2_2 shows similar values for external protection for Fit1 and Fit2 as for the medical mask. Furthermore, the differences between Fit1, Fit2 and Fit3 in terms of self-protection are only very slight. It should also be noted that in this study, FFP2_1 can only achieve a level of self-protection that is way below the minimum filtration efficiency of 89% as specified in the DIN EN 149 standard (DIN EN 149) in this case, even performs worse than the medical mask. For the FFP2_2 mask, Fit2 already achieved comparatively high filtration efficiencies of over 80% for both directions, which are further increased by Fit3. FFP2_3 already achieves comparably high values for both directions in Fit1, but for Fit2 and Fit3 lower filtration efficiencies compared to FFP2_2 are achieved and furthermore for Fit3 only an average value slightly below the required minimum value of 89% could be achieved.

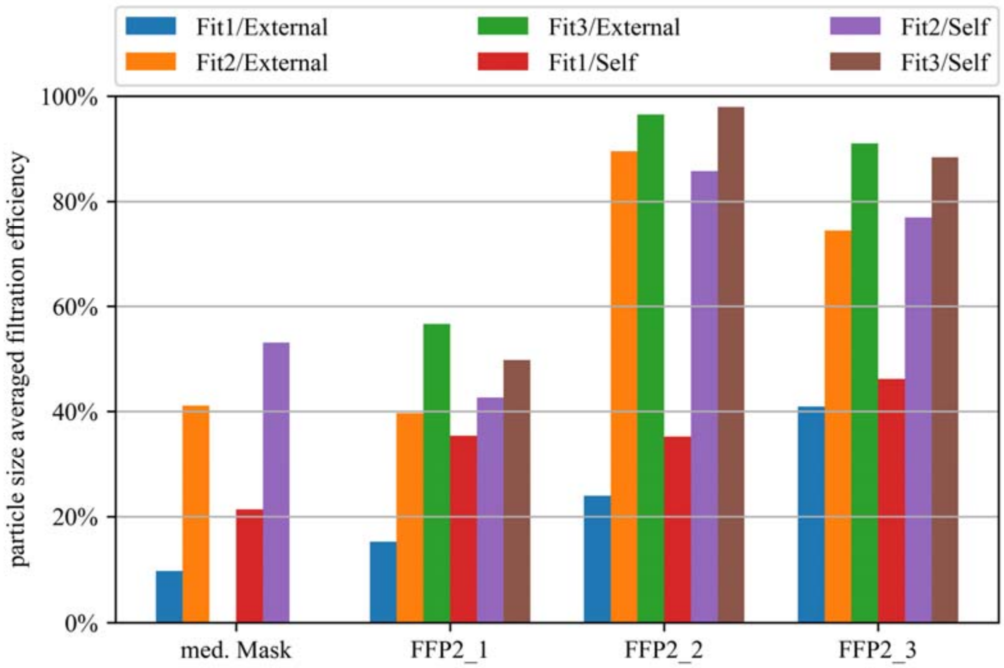

Figure 2: Overview over the particle size averaged filtration efficiencies for the investigated test points.

Furthermore, the differences between Fit1, Fit2, and Fit3 in terms of self-protection are only marginal. With this mask, we have found that the nose clip cannot be completely fitted to the nose, so that leakage still occurs in the nostril area. This may be due to the mechanical properties of the nose clip, as it is not very rigid compared to those of FFP2_2 and FFP2_3, and always springs back a little after fitting. With FFP2_2, very high filtration efficiencies of over 80% could already be achieved with Fit2, which shows that the design in this case also achieves a good fit without great effort. With Fit3 filtration efficiencies for self-protection are achieved that are clearly above the minimum requirements specified in DIN EN 149. FFP2_3 shows slightly lower filtration efficiencies for Fit2 and Fit3 than FFP2_2 and here, too, the minimum requirement from DIN EN 149 is slightly undershot. However, this mask shows the highest filtration efficiencies for Fit1 compared to the other three masks. Quite comparable filtration efficiencies for self- and external protection are achieved for all test points.

To gain further insights into the fit of the masks, the pressure differences over the tests are analysed. In Figure 3, the particle size averaged filtration efficiencies are plotted over the mean mask differential pressures. In this case, we analyse the repetitions of each test point instead of the mean values for each test point. The fit levels are marked with the shapes and the masks with the colours. A clear correlation between the filtration efficiency and differential pressure can be derived from this diagram. It is notable that the points for the medical mask, FFP2_2 and FFP2_3 for external protection and the self-protection cases are each in very similar ranges. It should be noted that the points for the medical mask are in similar ranges to those of FFP2_2 and FFP2_3, despite the much thinner mask material. The points for FFP2_1 are substantially lower and achieve much higher differential pressures with similar filtration efficiencies. Based on this observation, a further hypothesis can be put forward for the lower filtration efficiencies of FFP2_1. It can be assumed that the mask material of FFP2_1 generates a far higher flow resistance than that of the other three masks. In combination with the poor fit of the nose clip, far more air flows through the leaks in the nose wing area, which is not filtered.

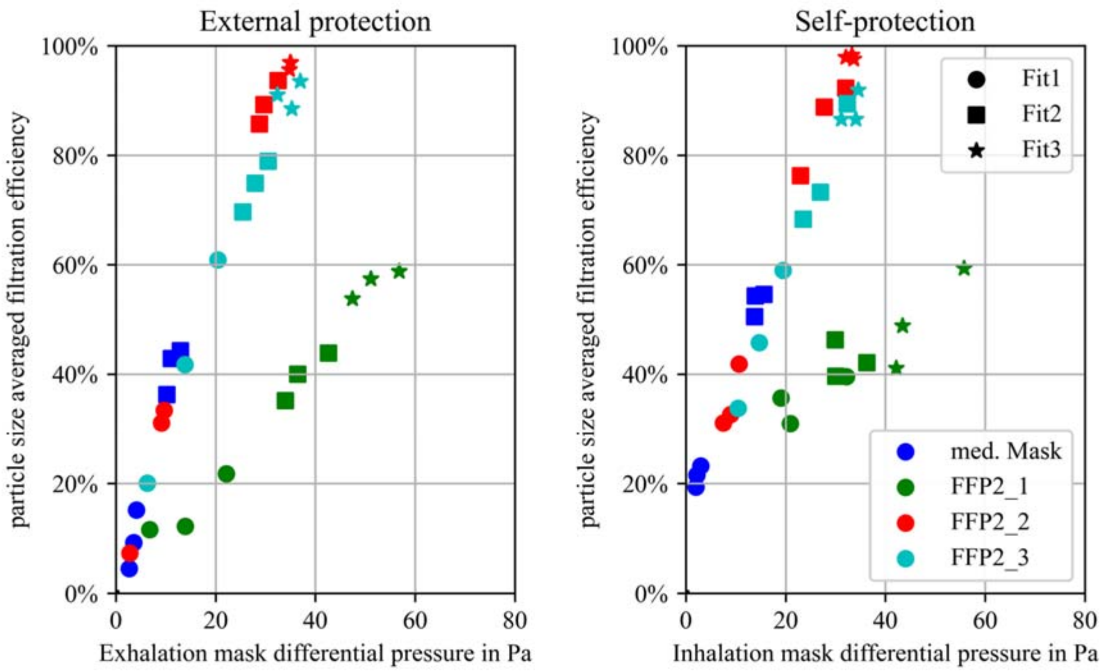

Figure 3: Filtration efficiencies for each test point repetition over the mask differential pressures

5 CONCLUSIONS

The results show that, both the mask type and the mask fit have clear influence on the filtration efficiencies. For instance, the fitting of the nose clip already has a big impact on filtration efficiency. The minimum filtration efficiency for self-protection off FFP2 masks specified in the standard DIN EN 149 could only be achieved with the "three-folded" FFP2 mask. Furthermore, the “coffee filter” shaped FFP2 mask only achieves a filtration efficiency that is way below the minimum requirements. This result is consistent with the findings of a literature review, in which a poor performance of such FFP2 mask types was determined in quantitative fit tests (Knobloch et al. 2023). Furthermore, the results show that a correctly worn medical mask performs at least as well as a poorly fitted FFP2 mask in this investigation. In addition, all masks show similar results depending on the direction of protection (external and self-protection). It was also shown that the fit-dependent filtration efficiencies correlate very well with the measured pressure difference. Far higher pressure differences were determined for the “coffee filter” shaped mask than for the other masks, from which can be concluded that the material may be responsible for the low filtration efficiency, among other things.

In future studies, the influence of the respiratory volume flow can additionally be investigated, and other mask types or different models of the same mask shape can be analysed. In this way, it can also be determined whether the “coffee filter” shaped mask also has similar problems for other models. The results can, for example, be used in model-based infection risk calculations in the future to determine the influence of imperfect fit on the risk of infection (Müller et al. 2021).

6 ACKNOWLEDGEMENTS

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