

Accumulation of water in face masks during respiration

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Abstract. Human exhalation releases droplets and aerosols primarily composed of water, which can contain bacteria and virions. This study measured water absorbed from exhaled breath (in vivo, 3 adults and 2 children) by three types of face masks (FFP2/N95, surgical, and cloth) intended to protect from SARS-CoV-2 (virion diameter: 0.06-0.14 μm). Absorption was compared to estimated mask pore volumes, and a physics-based model predicted absorption rates and durations. Results show minuscule to no water absorption by masks, with only 1.3% of the exhaled humidity being absorbed (until saturation after about 25 minutes), challenging the notion that water-bound virions are effectively filtered. A proposed shrinkage mechanism highlights discrepancies between observations and the accepted view of mask filtration. Energetic considerations suggest that one-fold positively charged particles $\geq 0.7 \mu\text{m}$ evade electrostatic attraction due to their kinetic energy during quiet breathing (air stream velocity $1 \frac{\text{m}}{\text{s}}$) surpassing the mask's surface electrostatic energy ($6.4 \cdot 10^{-17} \text{ J}$). The findings reveal a lack of empirical evidence and mechanistic understanding of virion-mask interaction supporting filtration of smaller particles by face masks. This underscores the need for further research to provide empirical evidence for an underlying filtering mechanism and to evaluate the harm-to-benefit ratio of mask-wearing in mitigating SARS-CoV-2 transmission.

Keywords: aerosol, particle, virion, shrinkage, filtration efficacy, electrostatic attraction

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1. Introduction

Face masks, after an initial period of being recommended *not* to wear [1–3], have been a staple of public health interventions against the spread of CoViD-19 in the years 2020 through 2023 [4]. After recommending cloth and surgical masks for the public [5], face coverings adhering to standards like EN 149 (Europe [6]), or NIOSH-42 CFR 84 (US [7]), commonly referred to as FFP2 masks or N95 respirators, have been widely mandated [see overview at 4]. According to the institutions, who suggested these mandates – like national and international health organizations – as well as according to those in political power to set and enforce these mandates, FFP2 masks are 94% and N95 respirators 95% effective in preventing the transmission of CoViD-19 infections serving two distinct purposes: 1) protecting the wearer from ambient infectious particles as well as 2) protecting others by filtering infectious particles from the exhaled breath of an infected mask wearer [8]. Surgical masks were deemed sufficient in less critical situations, such as during phases of low SARS-CoV-2-positive rates [3, 5]. In early 2021, cloth masks got banned (at first on airlines and in public spaces in Germany and Austria), because they are not subject to any standards with regard to their efficacy [9]. The Select Subcommittee on the Coronavirus Pandemic of the U.S. House of Representatives, in its report dated December 4, 2024—published just days ago as of this writing [10, p.206]—found that “The [U.S.] Administration Exceeded its Authority by Mandating Masks.” Criticizing *unclear* and *inconsistent* messaging, the report relied on a correlative meta-study [11] and ascertained a general lack of compelling evidence, both of which it identified as contributing to “Officials Flip Flopping on the Efficacy and Use of Face Masks” [10, p.204].

Triggered by the oftentimes conflicting announcements, we attempted to track down and collect relevant published literature for the communicated claims, specifically for the capture of virions in exhaled breath. The surprising lack of empirical evidence (even standards like EN 149 are misleading) led us to perform the simplest conceivable experiment to test capture capacity of face masks.

Breathing, talking, coughing, sneezing are sources for humans discharging liquid particles containing solid components from their mucous membranes of mouth and nose. Subsequently, these droplets (larger in size) and aerosols (smaller in size) containing germs, fungi, bacteria, metabolites, or virions may travel through the air to areas prone to infection like open wounds or the mucous membranes of others.

Surgical masks are usually intended for surgeons and other health professionals to use in operating rooms to prevent infections of open wounds. However, overall there is a lack of substantial evidence to support claims that face masks protect either patient or surgeon from infectious contamination [12, 13]. Among individuals in non-healthcare settings, surgical mask wearing has not been found to significantly reduce association with the incidence of acute respiratory illnesses [14]. The bacteria filtration efficacy of Type II (Europe: EN 14683 [15]) or Level 2 (USA: ASTM F2100-23 [16]) certified surgical masks is 98% in an *in-vitro* setting, meaning that 98% of a predefined *technical* test

aerosol is blocked by the mask material in a lab situation. It is important to note that the median size of particles in this test aerosol is determined to be $3.0 \pm 0.3 \mu\text{m}$, with the smallest size at $0.65 \mu\text{m}$. Also important, there is no leakage testing done with human subjects wearing surgical masks, meaning it is unknown how many particles actually find their way around the mask, which, of course, is highly dependent on the mask's fit over mouth and nose of the subject [17–20]. Beyond EN 14683 and ASTM F2100-23, no comparable EN or ASTM standardised testing and certification for filtration of viruses by masks are required by European or US authorities. In an investigation [21] that exposed human subjects to NaCl particles of sizes encompassing those of bacteria and viruses, the filtration efficacy of surgical and N95 masks was generally better for bigger, bacteria-sized particles ($0.5\text{-}5.0 \mu\text{m}$), and worst for exactly the size range of Corona and Influenza viruses ($0.04\text{-}0.2 \mu\text{m}$).

FFP2/N95 masks were originally designed for construction workers in dusty environments to block micro-particles from being inhaled. Later on, they were accredited the capability to also attract and block viruses [22, 23]. Taking a closer look at the standards these masks adhere to, we found a surprising discrepancy between the claims made by health and public authorities and the properties actually certified by the relevant standards. The European standard EN 149 classifies particle filtering face pieces (FFP) by 1) their particle filtration efficacy and by 2) their total inward leakage. Particle filtration efficacy of the filter medium (a piece cut from an FFP mask) is tested against a test aerosol in a specific setup to mechanically remove particles with a count median diameter between 0.06 and $0.1 \mu\text{m}$ [24] (in N95 respirators $0.075 \pm 0.02 \mu\text{m}$ [7]). This size range closely corresponds to the size of a SARS-CoV-2 virion [$0.06\text{-}0.14 \mu\text{m}$, 25–29]. EN 149 provisions for FFP2 masks that maximally 6% of all particles pass the filter medium, with in fact particle concentrations in front of (functionally: outside the mask) and behind (inside) the tested material probe being measured in a steady air stream (thus 94% filtration efficacy). It further determines the limit for total inward leakage in worn FFP masks. Specifically, tests with subjects wearing a well fitted FFP2 mask have to exceed 89% (not 94% anymore) filtration efficacy, this time using a test aerosol of particles with a count median diameter of $0.6 \mu\text{m}$ – for all leakage directed from the outside to the inside of the mask. This size range now is a whole magnitude larger than the typical size of a SARS-CoV-2 virion. Outward leakage testing for exhaled breath, i.e. flow directed from the inside to the outside of a mask, is not mandatory for any kind of aerosol. The only test considering exhalation for the EN 149 standard needs to demonstrate that CO_2 concentrations inside the mask do not exceed 1 vol% on average, i.e. 25 times the CO_2 concentration as compared to normal air in the open ($0.04 \text{ vol}\%$, [30]), and 5 times the CO_2 concentration declared as barely acceptable in closed rooms ($0.2 \text{ vol}\%$, [30]).

The *mechanism* of filtering and *permanently absorbing* infectious particles (whether exhaled or inhaled) remains unclear, as given standards only test for mechanical filtering properties of air enriched with *technical* particles (polystyrene, mineral dust, castor oil), with ‘filtering’ meaning the attenuation of a certain particle density in a steady stream.

Any specific probing of, for example, the role of electrostatic properties in particle capture, is not part of the standard testing. As a consequence, the void of knowledge about mechanisms of, in particular, absorption and adhesion of infectious particles to mask material is implicit to the remainder of this paper.

Basic and thorough experimental work on how efficacious polystyrene filter materials are in absorbing either electrically neutralized or charged *technical* aerosols has been performed by Fjeld & Owens already in 1988 [31]. For neutral particles of size $0.5 \mu\text{m}$, they found a substantial decrease in filtration efficacy as the airflow speed increased (investigated up to $0.2 \frac{\text{m}}{\text{s}}$, [31, fig.4]). The same decline in filtration efficacy was noted for electrically charged particles, when present at all. A highly significant decrease in electrostatic effect (filtration efficacy) with increasing airflow speed was also reported by Sanchez et al. [32], for speed values examined in the range $0.5\text{-}2.7 \frac{\text{m}}{\text{s}}$, in particular for (technical) particle sizes around $0.1 \mu\text{m}$. Recently, these experimental findings have been thoroughly enhanced by Zangmeister et al. [33]. They measured the efficacy of an extensive selection of over 40 textile materials (including layered specimens) to potentially filter out (electrically neutralized) aerosol particles (NaCl) in the size range of $0.05 \mu\text{m}$ to $0.825 \mu\text{m}$, however, exclusively at an airflow speed as low as $0.06 \frac{\text{m}}{\text{s}}$. Other than that, to the best of our knowledge, no substantially novel information has been added to the literature, since 1988, regarding quantitative measurements on how filtration by textile materials depends on the degree of *technical* particles being electrically charged; let alone of *naturally* occurring particles in exhaled human breath. There is, in general, a lack of data on the electrostatic charge of particles in human breath. Literature also lacks studies on quantitative measurements of the dependency of mask filtration on humidity (air and mask) and airflow speeds that actually reflect human breathing, not to speak of the combination of all of the aforementioned basic physiological particle as well as environmental parameters.

Consequently, using plain and simple measuring technology, we attempt to elucidate, experimentally, how much moisture from exhaled breath is absorbed by face masks. In our study, we acknowledge that infectious particles present in exhaled human breath are primarily composed of water [34, 35], bound in either droplets or aerosols, and are supposed to get caught in a mask's pore space while being attached to the fibers. Therefore, to find out how well face masks capture (potentially virus-laden) water, we measure the amount of absorbed moisture from exhaled human breath, *in vivo*, as well as moisture from hot steam employing a steam generator. Additionally, we use a simple physics-based model to predict how much water can theoretically be absorbed by a face mask.

2. Methods

We determined, experimentally, the accumulation of water in different types of face masks worn by the authors and their children (3 adults, 2 children) at low physical activity in everyday situations. For this, a mask was taken off by its user repetitively,

every few minutes, to measure the mask's current weight with a precision scale displaying grams [g] exact to 2 decimal places (Sartorius Master-Serie, LC-98648-004-02, Göttingen, Germany), i.e. at 0.01 g weight resolution. The experiments took place in late August 2022 at premises spanning approximately 100 m² located in Munich, Germany. The windows were open at moderate summer temperatures of about 25°C and air humidity of about 60%. We also experimentally measured the accumulation of water in the same face masks exposed to steam from a pot of boiling water. But before explaining the experimental procedures in more detail, we first present a simple physics-based model to predict how much water can be absorbed by a face mask and how much time this absorption process will take.

2.1. Simple a priori model estimation: a thought experiment

The geometric dimensions and other parameters of selected off-the-shelf and custom-made face masks are given in Table 1. Two questions are of interest: (i) How much of a mask's volume \mathcal{V}_{mask} is taken up by pores, which are, in the unused condition, filled with air? (ii) How does this pore volume \mathcal{V}_{pore} compare to the tidal volume \mathcal{V}_T (i.e. the volume of one breath) of an average human adult, particularly to the water content of one normal breath exhaled from the lung? The ratio $\frac{\mathcal{V}_{pore}}{\mathcal{V}_T}$ will return an estimate of how many breaths need to be taken until saturation of \mathcal{V}_{pore} with water absorbed from exhaled air. Assuming that a mask's fiber volume \mathcal{V}_{fib} complements \mathcal{V}_{pore} (i.e. $\mathcal{V}_{mask} = \mathcal{V}_{fib} + \mathcal{V}_{pore}$), the fiber ratio (equivalent to material solidity or packing density $\eta = \frac{\mathcal{V}_{fib}}{\mathcal{V}_{mask}}$) complements the pore ratio ($\chi_{pore} = \frac{\mathcal{V}_{pore}}{\mathcal{V}_{mask}}$). For example, data from the Leikang FFP2 mask, noted in the first row of Table 1, result in a pore ratio of

$$\chi_{pore} = \frac{\mathcal{V}_{pore}}{\mathcal{V}_{mask}} = 1 - \eta = \frac{\mathcal{V}_{mask} - \mathcal{V}_{fib}}{\mathcal{V}_{mask}} = \frac{(33.1 - 4.9) \text{ cm}^3}{33.1 \text{ cm}^3} = 0.85 \quad , \quad (1)$$

with a fiber volume of

$$\mathcal{V}_{fib} = \frac{\mathcal{M}_{mask}}{\rho_{fib}} = 4.9 \text{ cm}^3 \quad , \quad (2)$$

where the mask's mass (without straps) $\mathcal{M}_{mask} = 4.9 \text{ g}$ and the fiber density (whether polyamide, fleece, polyester, or cotton) $\rho_{fib} \approx 1 \frac{\text{g}}{\text{cm}^3}$ [31, tab.2] are given as directly known numbers. The mask's volume (fibers plus pores) is calculated from the geometric mask dimensions (Tab. 1) length $\mathcal{L}_{mask} = 15.6 \text{ cm}$, width $\mathcal{W}_{mask} = 10.6 \text{ cm}$, and thickness $\mathcal{D}_{mask} = 0.2 \text{ cm}$ as

$$\mathcal{V}_{mask} = \mathcal{L}_{mask} \cdot \mathcal{W}_{mask} \cdot \mathcal{D}_{mask} = 33.1 \text{ cm}^3 \quad . \quad (3)$$

According to these calculations, the pore volume takes up more than three quarters (here: 85%) of the volume of a typical FFP2/N95 mask.

The volume of one breath exhaled by an average human adult, who respire at low activity, is about half a liter of air ($\mathcal{V}_T = 500 \text{ cm}^3$). Exhaled air typically contains water vapor that is dissolved, reaching near-saturation levels of humidity, namely 99% of the relative humidity. At 35 °C (typical temperature of exhaled air), the relative humidity,

i.e. the maximum amount of water vapor that air can hold before it starts to condense into liquid water, is 0.004% [36, p.118, tab.8]. Thus, the corresponding water volume in one exhaled breath during low activity comes to $500 \text{ cm}^3 \cdot 4 \cdot 10^{-5} = 0.02 \text{ cm}^3$, i.e. a mass of 0.02 g of water. If this amount of water were *entirely* absorbed during each respiratory cycle, as conceived in our thought experiment, then the above-calculated pore volume ($V_{pore} = 28.2 \text{ cm}^3$) in the given example would be saturated with exhaled water after 1370 cycles. Given that one respiratory cycle takes approximately 4 s (15 cycles per minute), saturation would be reached within 90 min of low activity.

2.2. Absorption of humidity during human respiration

Each tested mask was freshly unwrapped from its original packaging, touched only at its straps, placed on the precision scale to measure its initial weight, \mathcal{M}_{mask} , and was then put over mouth and nose. If present, the locking clamp above the nasal bridge was adjusted by pressing briefly with a finger and thumb once. The correct fitting of the mask was checked by the experimenter. After that, the clock was started and slight activity was executed via typical daily routines, like playing a board game, doing the dishes, or working on a computer, for half an hour. To simulate a realistic activity level, a distance of about 10 m had to be walked every 5 min, to descend 7 steps (17.5 cm high and 27.0 cm deep), turn around, climb back up, and return 10 m. This walk-and-stairs task took about 30 s (10 s for each 10 m walking distance and 10 s for walking down and up the stairs). Continuously wearing and, consequently, inhaling and exhaling through the mask was only interrupted very briefly every 5 min, for about 5 s, to take off the mask, again only touching it at its straps, and place it on the precision scale for a mass reading ($\Delta\mathcal{M}_{abs}$). This reading was always taken directly after the walk-and-stairs task. In some cases, the measuring period was extended by another 30 min to confirm the observed mass increase or saturation (see Experiment 1: Fig. Appendix A.1E and Experiment 3: Fig. Appendix A.3E, F).

2.3. Absorption of steam from a boiling pot, or water when submerged

To assess the potential accumulation of water in different types of face masks in a more rigorous humidity environment than human breath, we exposed six different face masks to steam coming from a pot of boiling water. The pot's diameter was modified such that a face mask would cover its opening similar to covering a human face. For that we used a plastic, funnel-shaped attachment (flower pot), which we fixed to the pot with wire and then sealed the construction with aluminum foil and duck tape. The diameter of the so constructed steam outlet was 9.4 cm.

At the beginning of each experiment, a mask was taken freshly from its original packaging and weighed on the precision scale. The mask was then positioned over the steam outlet leaving a small gap between mask and steam generator to avoid water absorption from condensed water on the plastic surface. To stabilize this desired position, a thread was tightened horizontally underneath the mask at a respective height

Table 1. Mask parameters. FFP2 (EN 149) and N95 (NIOSH-42 CFR 84) are equivalent norms. Surgical IIR (EN 14683) and Surgical ASTM3 (ASTM F2100-23) are equivalent norms. The pore volume (p. vol.) $\mathcal{V}_{pore} = \mathcal{V}_{mask} - \mathcal{V}_{fib}$ (\mathcal{V}_{mask} : Eq. 3; \mathcal{V}_{fib} : Eq. 2) is the estimated volume of free space between the fibers within a mask’s volume. Hypothetically, filling \mathcal{V}_{pore} with water will increase the mass of a mask by $\Delta\mathcal{M}_{abs,max} = \mathcal{M}_{pore} = \mathcal{V}_{pore} \cdot \rho_{water}$, with density $\rho_{water} \approx 1 \frac{g}{cm^3}$. The pore ratio (p. ratio) indicates how much of a mask’s volume is taken up by pores (i.e. free space).

mask	source	type	layers	size	clamp	mass*	length	width	thickn.	p. vol.	p. ratio
						\mathcal{M}_{mask}	\mathcal{L}_{mask}	\mathcal{W}_{mask}	\mathcal{D}_{mask}	\mathcal{V}_{pore}	χ_{pore}
Leikang		FFP2/									
LK-008	[37]	N95 [†]	5	adult	yes	5.7	15.6	10.6	0.2	28.2	0.85
Mivolis		FFP2/									
Osvirol 8000	[37]	N95 [†]	4	adult	yes	4.1	16.0	10.6	0.13	18.5	0.84
Vitalis		Surgical									
Easy Fit	[38]	(IIR) [‡]	3	adult	yes	3.1 [#]	17.3	16.4	0.07 [#]	17.1	0.86
Sky Rabbit		Surgical									
Rabbiter	[39]	(ASTM3) [‡]	3	adult	yes	3.6 [#]	17.5 [#]	15.0 [#]	0.06 [#]	12.5	0.79
Rösch		Cloth									
Cotton	[40]	(Cott./Flc.)	3	adult	no	11.4 [#]	18.2 [#]	14.5 [#]	0.12 [#]	21.8	0.69
Adidas		Cloth									
Face Cover	[41]	(Polyester)	2	adult	no	10.0 [#]	17.0	15.3	0.19 [#]	40.9	0.83
Crom Cr2		Surgical									
Kids	[42]	(IIR) [‡]	3	kid	yes	2.6 [#]	14.4 [#]	16.0 [#]	0.07 [#]	13.8	0.86

* including straps (note: Mass of straps (0.6 - 1.5 g) is subtracted to calculate \mathcal{V}_{fib} in Eq. 2.)

measured (as not given in the manufacturer’s data sheet)

above the steam outlet. Two 1 liter water bottles were placed left and right of the steam generator to serve as anchors for the horizontal thread. Continuous steaming into the mask was only interrupted very briefly every 4-10 min by lifting the mask off of the thread, touching it only by its straps, and placing it on the scale to take a mass reading. The experiment was terminated when water accumulated on the mask’s surface in a

way that droplets of water remained on the scale after putting the mask back on the thread. Thermal imaging (CAT S62 pro, Bullitt Mobile Limited, Reading, England, UK) showed a temperature of 99°C at the pot’s opening, and temperatures of around 73°C on the outsides of the masks.

Finally, each mask was soaked with water to determine the mask’s mass when completely wet, \mathcal{M}_{soak} . For that, the mask was submerged in a basin of lukewarm water and all air was squeezed from the pores. Then, the mask was taken out and shaken carefully a few times until no more water dripped from the mask when held still, and no more water drops remained on the scale after weighing.

2.4. Data processing

Data were processed and analyzed using custom software (MATLAB R2023a, The MathWorks, Inc., Natick, MA, USA). The mass of absorbed water in a mask, $\Delta\mathcal{M}_{abs}$, at each reading was determined by the current weight of the mask, \mathcal{M}_{abs} , minus the mask’s initial weight, \mathcal{M}_{mask} . Analogously, the mass of water soaked up by a mask in a basin of water was determined by $\Delta\mathcal{M}_{soak} = \mathcal{M}_{soak} - \mathcal{M}_{mask}$.

For the steam generator experiments, pore volume saturation, i.e. saturation of $\Delta\mathcal{M}_{abs}(t) = \mathcal{M}_{abs}(t) - \mathcal{M}_{mask}$, was determined through fitting (by use of the MATLAB routine *lsqnonlin*) the time-dependent exponential function

$$\Delta\mathcal{M}_{abs}(t) = \Delta\mathcal{M}_{abs,end} \cdot \left(1 - e^{-\frac{t}{\mathcal{T}_{abs}}}\right) \quad (4)$$

across the mass data measured every 5-10 min, with $\Delta\mathcal{M}_{abs,end}$ the theoretically extrapolated, asymptotic limit of water (mass) absorption and \mathcal{T}_{abs} the characteristic time for exponential absorption. For the fitting procedure, we chose parameter bounds to be within $[2 \dots 100]$ g for $\Delta\mathcal{M}_{abs,end}$, and within $[0 \dots 0.1]$ min⁻¹ for $\frac{1}{\mathcal{T}_{abs}}$, with a function tolerance of 10^{-10} .

3. Results

3.1. Absorption of water during human respiration

The water masses ($\Delta\mathcal{M}_{abs}$) absorbed over time during human respiration for all tested face masks are presented in Figs. [Appendix A.1-Appendix A.5](#). Interpretation of these data yields a simple (and the key) result of our measurements: Only the cotton/fleece mask (Rösch) absorbs a measurable amount of water, albeit minuscule as compared to the available pore volume \mathcal{V}_{pore} . The amounts of water mass absorbed over time for the Rösch cloth mask, are compiled in Fig. 1: At maximum, after about 25 min of breathing while wearing the mask, 0.1 g of water is absorbed, which is equivalent to the amount of humidity contained in about 5 breaths. Given that 15 respiratory cycles occur in one minute, a total of 375 breaths are taken over 25 minutes. Consequently, 0.1 g of water divided by 375 yields $2.66 \cdot 10^{-4}$ g of water absorbed per exhalation. Considering that the mass of water in the exhaled humidity of one breath is 0.02 g, only 1.3% (calculated

as $\frac{2.66 \cdot 10^{-4}}{0.02} = 0.013$) of the exhaled humidity is absorbed. This holds only for non-laminated cotton-based face masks, where an outside hydrophobic layer is missing. All other tested masks (surgical and FFP2) do not absorb water at all. The mass quantity absorbed scatters by ± 0.02 g, which lies within the amount of water contained in one breath, and represents twice the resolution (0.01 g) of the measuring device (precision scale).

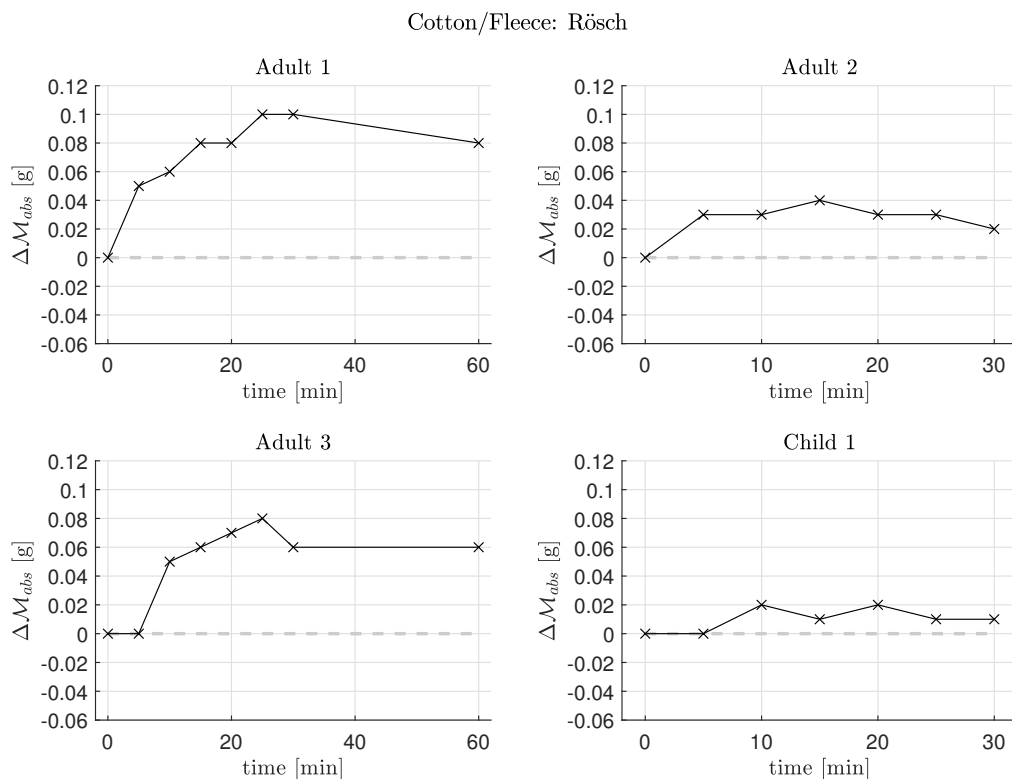


Figure 1. Courses over time of water mass absorbed ΔM_{abs} during breathing when wearing the Rösch cloth mask, one panel for each subject (three adults, one child). At maximum, 0.1 g of water is absorbed, which is equivalent to about the humidity contained in 5 breaths.

3.2. Absorption of steam from a steam generator, and of water when submerged and squeezed

The results of our steam generator experiments letting the masks absorb water when situated above a pot of boiling water are shown in Fig. 2. Only two of the six tested masks manifestly demonstrate saturation tendencies in absorbing water (steam, 73–99°C), both of the type ‘cloth’: the cotton/fleece mask (Rösch, panel E) and the polyester mask (Adidas panel F), with characteristic absorption times \mathcal{T}_{abs} of roughly an hour (67 min and 38 min, respectively), and predicted saturation values $\Delta M_{abs,end}$ clearly lower than the respective equivalent pore mass \mathcal{M}_{pore} . One FFP2 mask (Leikang, panel A) also demonstrates a slight saturation tendency, with \mathcal{T}_{abs} at about 120 min and $\Delta M_{abs,end} < \mathcal{M}_{pore}$. The remaining three masks, FFP2 (Mivolis, panel B),

surgical (Vitalis, panel C), and surgical (Rabbiter, panel D), demonstrate practically no saturation tendency, which is quantitatively indicated by $\Delta\mathcal{M}_{abs,end} > \mathcal{M}_{pore}$, with fitted characteristic absorption times \mathcal{T}_{abs} moderately (Rabbiter, 153 min) or clearly (Vitalis, 261 min; Mivolis, 478 min) higher than in the ‘household’ masks, i.e. cloth masks (cotton/fleece and polyester). Furthermore, only these cloth masks, made of materials ‘naturally’ soaking up water, performed in steam as would be expected, namely, showing saturation values of, at maximum, the water mass we found in our submerge experiment, i.e. $\Delta\mathcal{M}_{abs,end} \leq \Delta\mathcal{M}_{soak}$. All tested masks not falling in the ‘cloth’ category showed water absorption from hot steam increase linearly, and not exponentially, over time. Evidently, these masks do not only absorb water that is drawn into the pores, but also, upon saturation, additionally adsorb water onto their surfaces, which is reflected by the fitted parameter $\Delta\mathcal{M}_{abs,end}$ fulfilling $\Delta\mathcal{M}_{abs,end} > \Delta\mathcal{M}_{soak}$ and in three masks (FFP2 Mivolis, surgical Vitalis, and surgical Rabbiter) even $\Delta\mathcal{M}_{abs,end} > \mathcal{M}_{pore}$.

It is important to note, that all results on water absorption dynamics received from our experiments under artificial conditions (steam generator and submerging) are fundamentally different from the results received from our in-vivo experiments with humans actually breathing through a mask.

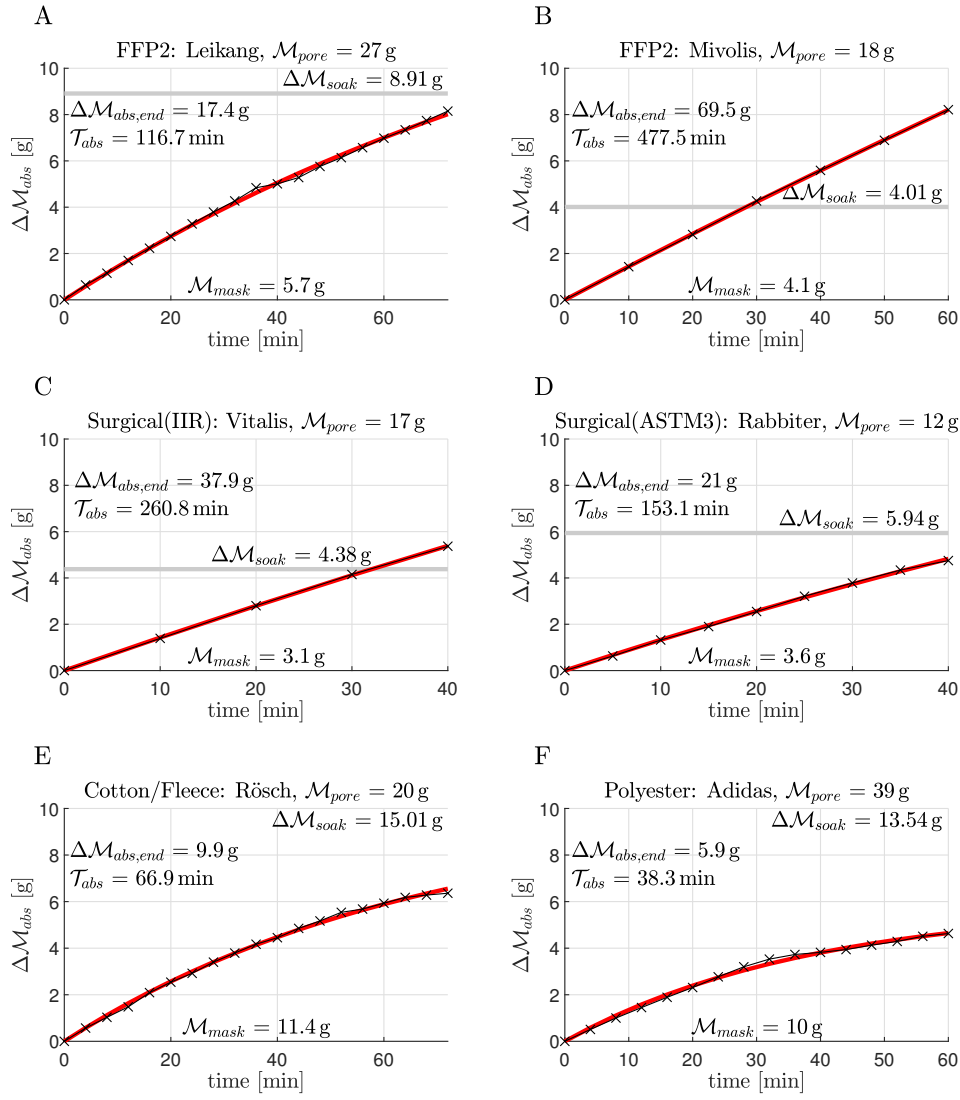


Figure 2. Measured and fitted courses over time of water mass absorbed, $\Delta\mathcal{M}_{abs}$, from steam (see Sec. 2.3), one panel for each tested mask. Mask type, mask name, and pore mass \mathcal{M}_{pore} ($= \mathcal{V}_{pore} \cdot 1 \frac{g}{cm^3}$: water mass equivalent to the pore volume, see Eqs. 2 and 3) are given in the panel titles. Initial weight (product information or measured when freshly unpacked) \mathcal{M}_{mask} is given at the bottom of each panel. $\Delta\mathcal{M}_{soak}$ corresponds to $\Delta\mathcal{M}_{abs}$ for the condition of a wet (non-dripping) mask after it had been submerged in a basin of water and all air squeezed from the pores. The measured data points of absorbed water masses are exponentially fitted according to Eq. 4. The function's (i.e. the mask's) two parameters, the saturation value $\Delta\mathcal{M}_{abs,end}$ and the characteristic absorption time \mathcal{T}_{abs} , are given in the upper left corners. Only two of the six tested masks manifestly demonstrate saturation tendencies in absorbing water (steam, 73-99°C), both of the type 'cloth'.

4. Discussion

The reason we actually looked at water absorption of face masks was because it appears to be established that virions in human breath are generally bound to water [34, 35]. Meaning, where there’s a virion there’s water. When humans exhale, they discharge liquid particles containing solid components. These droplets and aerosols are primarily composed of water, along with various biological substances such as cellular remnants, bacteria, and viral particles [34, 35]. Although at least two-thirds of a face mask’s volume consists of air (Table 1), all of the masks investigated—except for one—exhibited negligible or almost no water absorption. The only cotton-based mask examined (Rösch) absorbed a maximum of 0.1 g, equivalent to the water content of five breaths, over the course of 25 minutes (see Figure 1). This amounts to only 1.3% of any exhaled humidity. Similar results have been shown for cloth face coverings by Zangmeister et al [43, fig. S1]. It is not surprising that surgical and FFP2 masks are less effective at absorbing water, as two or more of their layers are typically composed of a hydrophobic non-woven polypropylene sheet [44]. However, it is striking that, generally, just a tiny portion of the theoretically available volume of a face mask, \mathcal{V}_{pore} (Table 1), is filled with water.

Basic physics may provide a potential explanation for this absence of water absorption. Breathing is convection of particle-laden air volumes into and out of the lung, which is induced by cyclic muscular contraction in the trunk. At the instant of exhalation, air is water-saturated, and particles mainly consist of water [34, 35]: they shrink drastically by evaporation with decreasing air humidity, and there are empirical indications that the characteristic shrinkage time scales in proportion to the square of the particle radius [45, 46]. That is, a breath particle’s water loss after exhalation is proportional to its surface area, yet also depending on surrounding humidity [45]. Exhaled particles seem to exist down to at least $0.5 \mu\text{m}$ [47] if not anything like $0.2 \mu\text{m}$ [48] or even just $0.02 \mu\text{m}$ [49]. Some water may still remain adhering to solid particle parts, i.e. the remaining biological material (such as virions) [35, 50] after having shrunk in diameter by a factor of 2.5 (at about 95% relative humidity, [45]) to 4 (below 40% relative humidity, [46]). For example, a virion of size $0.1 \mu\text{m}$ could have been bound in a particle of size $0.4 \mu\text{m}$ at the instant of exhalation (100% humidity). Then, within 0.3 ms [fig. 4 in 45] this particle would have shrunk to the size of $0.13 \mu\text{m}$ at about 90% humidity behind a mask [tab. 1 in 51].

Thus, a shrinkage mechanism could potentially resolve the conflict between our observation that practically no water is absorbed by face masks, and the widely accepted belief that FFP2/N95 face masks are capable of ‘filtering’ virions.

Looking into fluid mechanics, the Weber number is a critical parameter in understanding the behavior of droplets in fluid flows and their interaction with adjacent materials. In a simple fluid mechanics model of breathing through a face mask, the Weber number $We = \frac{\rho_{fib} \cdot v_{fluid}^2 \cdot d_{droplet}}{\sigma_{fluid}}$ describes the attraction of droplets within exhaled breath (fluid flow) by mask fibers (adjacent material). Attraction is indicated by We exceeding the critical value of 1. To calculate the relevant Weber number, the following

parameters are assumed: the particle size ($d_{droplet} = 1 \mu\text{m}$), the surface tension of water at body temperature ($\sigma_{fluid} \approx 0.07 \frac{\text{N}}{\text{m}}$), the surface tension of mucus ($\sigma_{fluid} \approx 0.01 \frac{\text{N}}{\text{m}}$), the breath flow velocity ($v_{fluid} = 1 \frac{\text{m}}{\text{s}}$) [52, 53], and the mask density ($\rho_{fib} = 1150 \frac{\text{kg}}{\text{m}^3}$) [31, tab. 2]. For the surface tension of water, $We \approx \frac{1}{60}$; for mucus, $We \approx \frac{1}{8}$. Therefore, aerosol particles of diameters below $1 \mu\text{m}$ are not attracted to mask fibers while flowing or flying past them because We decreases with droplet size. For reasonable assumptions, $We = 1$ would only be reached for mucus composed of particle sizes of at least $8 \mu\text{m}$. Accordingly, the mechanism considered in this thought experiment does not appear to be a good candidate to explain particle capture. Considering that above mentioned shrinkage would leave very small, rather dry particles for the filter material to capture, this further supports the notion of virions adhering to mask material through electrostatic attraction.

Following these hypotheses on particle properties, we first take a closer look at basic, energetic, considerations on electrostatic attraction between mask material and charged particles. In a second step, we attempt to put electrostatics into context with what literature reflects as the current state of knowledge on physical properties of particles in exhaled human breath.

4.1. Particle attraction by face masks? An energetic back-of-the-envelope calculation

To conduct a quantitative check of the theory that face masks ‘filter’ or ‘capture’ particles, we compare a particle’s kinetic energy and a mask’s ‘capturing’ electrostatic potential energy. We consider an exhaled breath particle of diameter $0.4 \mu\text{m}$ (in the *dried* state), which is the most prevalent (dry) size in the sub-micron range [49], taking further into account that the particle size in 90%-saturated air of exhaled breath behind a mask is not significantly different from the dry condition [49]. Note that a particle of this size is only three times the diameter of a SARS-CoV-2 virion. We estimate the volume of our example particle by treating it as a sphere with radius $0.2 \mu\text{m}$. After calculating the volume of this sphere, which amounts to $3.4 \cdot 10^{-20} \text{m}^3$, we can determine its mass, assuming a density similar to that of water, which is approximately $1000 \frac{\text{kg}}{\text{m}^3}$ (holds true for virtually any biological material). Consequently, the particle’s mass (m) is calculated to be $3.4 \cdot 10^{-17} \text{kg}$. The velocity of particles carried by the flow of exhaled air (mass transport by convection) at a mask’s distance away from the mouth (about 5 cm) varies within the range of 0.5 to $1.5 \frac{\text{m}}{\text{s}}$ during breathing at low physical activity [52]. At an average velocity of $v = 1 \frac{\text{m}}{\text{s}}$ [53], the kinetic energy of our spherical example particle of radius $0.2 \mu\text{m}$ amounts to $1.7 \cdot 10^{-17} \text{J}$ ($= \frac{1}{2} \cdot m \cdot v^2$).

The electrostatic surface potential of a freshly unwrapped surgical mask has been determined to be about $U = 400 \text{V}$ [54]. The corresponding potential energy at the surface of the mask for a particle carrying a single elementary charge ($q = 1.6 \cdot 10^{-19} \text{C}$) is then $6.4 \cdot 10^{-17} \text{J}$ ($= q \cdot U$). Hence, any one-fold positively charged spherical particle of radius $0.2 \mu\text{m}$ that comes into contact with the mask’s surface within the exhaled airflow is likely to be captured by the charged mask material.

Nevertheless, we have not come across any literature source that indicates the

presence of electrically charged particles in exhaled air. On the contrary, the aforementioned study by Morozov et. al. [49], which stands out for directly investigating human breath aerosols rather than using proxy particles, suggests that particles present in exhaled breath are typically uncharged. This can be inferred from the fact that counting the particles by an electrostatic collector (a measuring device using this mechanism) seems to require both drying the particles and running them through a corona charger. Also, the electrostatic attraction by (commonly pre-charged) mask material diminishes with manipulations of any kind, as its customary initial surface voltage attenuates with any touching, wearing (sweat and saliva), folding, moisturizing, or washing [54].

In our example, the very small spherical particle will no longer be captured once the voltage of the mask surface has dropped to one-fourth of its initial value (100 V). Numbers are practically the same for FFP2/N95 masks [55]: A freshly unwrapped FFP2 mask exhibits a surface potential of 500 V, while losses in voltage have been measured to be even greater than in surgical masks, with potential values dropping as low as 20V.

It should be noted that, with convection velocity given as $1 \frac{m}{s}$ in quiet breathing (Sanchez et al. [32] have examined this speed exactly in their tested speed range), kinetic energy goes linearly with particle mass, and mass goes cubically with radius (size). That is, we can now easily predict that all exhaled particles with radii greater than $0.35 \mu\text{m}$ (particle size above $0.7 \mu\text{m}$) will inevitably escape ($\frac{1}{2} \cdot m \cdot v^2 > q \cdot U$) any face mask, even when freshly unwrapped. The fraction of *uncharged* particles, which is highly likely to be extensive, will escape anyway, regardless of the voltage state of any mask considered.

4.2. Literature and its voids: mechanistic modeling and experimental determination of crucial physical parameters—or, how many mosquitoes are caught by a charged wire-mesh fence?

It is a justified question to ask how masks, designed to filter particles as small as $0.6 \mu\text{m}$, are able to block virions of size $0.1 \mu\text{m}$. To answer this question, a popular expert virologist drew the analogy of a mosquito trying to fly through a charged wire-mesh fence [56]. The reassuring answer focused on electrostatically charged mask fibers (the fence) allowing to attract, and thus filter, virions (the mosquitoes) potentially embedded within aerosols or droplets. Unfortunately, no literature references were provided alongside this assertion. When pursuing the question of how important electrostatic effects are in filtering *virions* (whether SARS-CoV-2 or others) from breath, we were surprised to find that no such estimates exist. This particularly pertains to the potential differences between the physical properties and material compositions of virion-laden droplets and aerosols in exhaled breath as compared to technically generated particles in test aerosols. Quite simply, the possible effectiveness of all types of filtering mechanisms [57], interception, impaction, diffusion, gravitational settling, and electrostatic attraction, in relation to virions are rather unknown as of today.

To the best of our knowledge, there has not been a single study that combined

experiments on humans, in which breathing through a mask constitutes the source of (possibly charged) virions, with theoretical, mechanistic modeling of the filtering process by mask material, or, beyond, entire face masks *in situ*. Further, no research could be found, in which a theoretical, mechanistic model has predicted and thus explained the filtering process(es) of virions being captured by mask material (the ‘fence’). The characterization as ‘mechanistic’ implies that model predictions are required to be based solely on empirically known properties assigned to both, mask material *and* (model) virions, as well as physical characteristics of the interactions (force laws) between the virions, their solvent (water), and possibly virion-and-water-adherent biological material (like lipids, proteins, fat, etc.). Regrettably, the existing literature lacks a strictly physical model of virion-mask interaction that could mechanistically elucidate the hypothesized filtration of virions by face masks in humans. Consequently, there is also no quantitative experimental evidence validating such mechanistic model that could demonstrate the capture *and accumulation* by mask material.

We are aware of three [58–60] studies experimentally proving presence of virus material on the surfaces of face masks. Chughtai et al. [58] designed a study for health workers to test for virus material present on the outer surfaces of face masks during inhalation. Kim et al. [59] tested for presence of SARS-CoV-2 virus material on the outer and inner surfaces of masks worn by symptomatic patients. However, the statistical evidence in those two studies is utterly meager, *plus* they both did not perform calibrated determinations of virus material *concentrations*, much less a quantification of potential concentration increases over time (accumulation).

Allegedly protective effects of face masks are exclusively *inferred* from incomplete studies, such as (i) purely theoretical modeling, see e.g. [61] for a recent review, (ii) PCR tests for virus material present on mask surfaces after their use by symptomatic persons in a hospital setting [58–60], or (iii) surrogate airflow experiments, in which breathing is substituted by (technical) aerosol generation and convection of non-human ‘charged dust’ (breath particle proxies) [54, 62]. A causal mechanism (instead of mere correlation [54]) between electrostatic charges on masks and its filtration efficacy has not been convincingly formulated, while changes of electrostatic properties (mask surface potentials), due to *actual* all-day use, of several common face masks have all right been quantified [54, 55].

An eminently meticulous article from 1988 by Fjeld & Owens [31] already combined points (i) and (iii). They measured the quantitative impact, by systematical variation, of several physical properties of aerosols (technical: polystyrene), the mask material (electret: thermoplastic polymer), and their potential adherence interaction under varied airflow velocity conditions. As a major downside, the air humidity in their experiments was not controlled or even reported, and they only probed particles of one size (0.5 μm). But they properly investigated the impact of both convection velocity of the airflow and charge levels of the mask material as well as the particles (each down to completely uncharged). Addressing point (ii), their work should have long set the stage for further, analogous, experimental setups to investigate potential mask filtration of human breath

particles by ‘simply’ replacing a technical aerosol generator with human subjects. While basic electrostatic properties of human-exhaled particles are seemingly still unknown and a validated method to identify the particles’ “pathogenic agents” [35] is still missing, fairly detailed data on particle size distribution in various exhalation conditions [47] as well as on airflow (convection) velocities [52] are now available.

Since 1988, considerable advances have been made in understanding the process of exhaled particle shrinkage by evaporation [46, 63]. The degree of shrinkage seems to strongly and primarily depend on the level of air humidity [45], which has been measured behind masks ($> 85\%$ as a rule) [51, tab. 1]. Experimental findings on human saliva droplets of sizes ranging within $120\text{-}300\ \mu\text{m}$ suggest a shrinkage limit of about one fourth in diameter when the humidity is below 40% [46]. Calculations performed by Pöhlker et al. [45] employed a theoretical model that assumed the shrinkage to be independent of initial size, even down to droplets measuring $0.8\ \mu\text{m}$. This finding aligns reasonably well with the observations of Papineni et al. [63], who reported a shrinkage factor of approximately 3.5 for $1\ \mu\text{m}$ particles, as well as with the shrinkage factor of about 4 observed by Stiti et al. [46] in particles two orders of magnitude larger.

Morozov et al. [49] seem to have encountered another interesting property of the smallest exhaled particles. In their experimental study, they observed that *dried* particles at sizes below $0.5\ \mu\text{m}$ (with an average size of $0.37\ \mu\text{m}$) did not exhibit any increase in volume when exposed to 100% humidity, but rather decreased in volume by approximately 10% as a result of voids escaping the particle’s core. In contrast to this experimental observation, the authors estimated a shrinkage factor of 2.7 for initial lung droplets exhaled, which is in good accordance with the previously mentioned range of 3.5-4. These findings suggests a high level of irreversibility in the shrinkage of breath particles. Quite the opposite is discussed by Zangmeister et al. [43]. The authors argue that hygroscopic particles (e.g. salts like NaCl, which is contained by saliva, mucus, and breath) take up water and increase in diameter when exposed to a high relative humidity environment ($> 85\%$). Under the physiological conditions mimicked in their study (back to 99% relative humidity, the near-saturation level of breath at the instant of exhalation), a dry $0.3\ \mu\text{m}$ particle grows to $1.3\ \mu\text{m}$ and the largest dry NaCl particle studied ($0.825\ \mu\text{m}$) grows to over $3.6\ \mu\text{m}$. Here, reversibility of shrinkage would be given, however, the initially dry particles had been generated technically as opposed to the dehydrated ones from exhaled human breath. Finally, we would like to point out two more papers: Work done by Morawska et al. [64] is a concise plea for the very topic we have emphasized in this section, which is the crucial need for profound, physical modeling of breathing, i.e. exhalation and its intricate interplay with obstacles such as masks, as well as inhalation involving particle deposition. The authors subsequently provided a comprehensive review [50], which complements the current state of research in the field of breathing.

To conclude this section in view of our results, particularly with regard to the contribution of electrostatic attraction in filtering SARS-CoV-2 from exhaled breath, we concur with the assessment provided by the German Respiratory Society (DGP)

[65]: “Whether this principle also applies in the moist environment of exhaled breath has not been investigated so far.” Thus, according to the scientific state of the art, when asked how many mosquitoes are caught by a charged wire-mesh fence, the answer should be: “All of them—provided the mesh’s aperture size is sufficiently small, and the mosquitoes are electrically charged and the wire voltage is adequately high.” However, as of today, it is simply unknown whether face masks capture virions from human breath or the surrounding air, let alone how many.

5. Conclusion

As of this writing (2024), there is, to the best of our knowledge, no *direct empirical proof* that virions are *accumulated over time* in face masks, whether surgical or FFP2/N95, whether for inhalation or exhalation. Our study clearly shows, that at least the virions’ constant companion, water, is definitely *not* accumulated in these masks during exhalation. We ascribed this fact to particle shrinkage via evaporation and then followed the idea of electrostatic attraction to preserve possible filtering of virions all the same. We inferred from energetics that particles of diameter $0.7\ \mu\text{m}$ or larger are out of the question for electrostatic attraction as their kinetic energy would just whip them through the mask or let them bounce off the mask’s fibers. While it is plausible that smaller particles could potentially be captured through electrostatic attraction, there is currently no empirical evidence or mechanistic understanding of virion-mask interaction that supports the filtering of particles of such size. Also, fluid mechanical attraction as indicated by the Weber number is incapable of explaining the capture of small particles ($< 8\ \mu\text{m}$).

Water, acting as the solvent or carrier of *any exhaled* virion, does not accumulate in surgical or FFP2/N95 face masks during human breathing. The lack of *direct* evidence regarding the accumulation of virions in face masks, coupled with our observation that masks do not absorb water, leads us to the following compelling conclusion: Based on the current state of research, it can only be inferred that face masks, whether surgical or FFP2/N95, do not have a substantial impact on the airborne (ambient) spread of viruses, as they are not suited for permanent capture of virions. This conclusion is supported by best-quality controlled clinical trials demonstrating minimal impact of masks (making “little to no difference” [11, p. 22]) in reducing respiratory viral infections [11, 66, 67].

Any assertion to the contrary necessitates the provision of unambiguous, quantitative measurements demonstrating a verifiable increase in the concentration of virions within the fabric of a face mask over time. Furthermore, if the accumulation of exhaled viral material within face masks were to be experimentally confirmed, or if their efficacy in preventing inhalation from the surrounding air were established, it would be imperative to subsequently determine the *quantitative* (physiological or epidemiological) significance in terms of reducing transmission or infectivity. Last but not least, it would be scientifically (and legally) mandatory to consider the potential benefits of such effects in relation to the established harms experienced by the wearer of a

mask [68–78]. These potential harms would encompass the possibility of increased viral loads (if indeed present in masks) and undoubtedly other pathogenic burdens constantly encountered by individuals wearing masks, as noted in previous research [72].

Given our inability to identify any substantial water absorption in commonly used face masks from different manufacturers, coupled with the fact that the certification process does not specifically evaluate their ability to capture bio-active materials (particularly not viruses), we are consequently prompted to raise the following questions: (1) What exactly is the underlying filtering (particularly adhesion) *mechanism* responsible for the reduction in transmission of SARS-CoV-2, influenza and other pathogens, as consistently claimed by authorities (e.g. [22, 23])? (2) To what extent *can* face masks reduce transmission? (3) What is the *harm-to-benefit ratio* when considering the prolonged exposure of individuals, especially vulnerable populations such as children [70, 74], pregnant women [74], and the elderly, to significantly elevated concentrations of CO₂, increased breathing resistance [76, 77], higher concentrations of (re-)inhaled pathogens [72] and other toxic or carcinogenic substances [75], and impaired recognition of facial expression [78]?

Author contribution statement

Susanne Lipfert: Methodology, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing. **Michael Günther:** Conceptualization, Methodology, Formal Analysis, Writing – Original Draft, Writing – Review & Editing. **Robert Rockenfeller:** Validation, Writing – Original Draft, Writing – Review & Editing. **Daniel Renjewski:** Validation, Writing – Original Draft, Writing – Review & Editing.

Ethics statement

Part of the experiments in this study involved self-experimentation, which is not commented on in the Declaration of Helsinki. Therefore, the requirement for ethics approval does not apply. However, the study followed ethical principles such as informed consent from the participant, protecting their privacy and confidentiality, and minimizing potential harm or discomfort. The study was conducted in compliance with all applicable laws and regulations. There was no institutional involvement, and there was no possibility of coercion.

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Declaration of competing interests

The authors declare no competing interest.

References

- [1] Netburn D 2021 A timeline of the CDC’s advice on face masks Los Angeles Times, 27 July 2021 <https://www.latimes.com/science/story/2021-07-27/timeline-cdc-mask-guidance-during-covid-19-pandemic> (accessed 02-16-2024)
- [2] Die Bundesregierung 2020 Mund-Nase-Schutz bei Coronavirus – Sich selbst und andere schützen, 3 April 2020 Die Bundesregierung <https://www.bundesregierung.de/breg-de/themen/coronavirus/corona-schutzmasken-1737518> (accessed 02-16-2024)
- [3] World Health Organization 2020 Advice on the use of masks the community, during home care and in health care settings in the context of the novel coronavirus (2019-nCoV) outbreak: interim guidance, 29 January 2020 World Health Organization <https://www.who.int/docs/default-source/documents/advice-on-the-use-of-masks-2019-ncov.pdf> (accessed 02-16-2024)
- [4] in Data O W 2023 Data Page: Face covering policies during the COVID-19 pandemic Data adapted from Blavatnik School of Government, University of Oxford <https://ourworldindata.org/grapher/face-covering-policies-covid> (accessed 10-28-2024)
- [5] World Health Organization 2020 Advice on the use of masks in the context of COVID-19: interim guidance, 5 June 2020 World Health Organization <https://apps.who.int/iris/handle/10665/332293> (accessed 02-16-2024)
- [6] Committee CEN/TC 79 “Respiratory protective devices” 2009 DIN EN 149: Respiratory protective devices – filtering half masks to protect against particles – requirements, testing, marking; German version EN 149:2001+A1:2009 DIN Standards Committee Optics and Precision Mechanics (NAFuO) <https://www.din.de/en/getting-involved/standards-committees/nafuo/publications/wdc-beuth:din21:118506130> (accessed 02-16-2024)
- [7] The National Institute for Occupational Safety and Health (NIOSH) 2023 Code of Federal Regulations: Title 42 Chapter I Subchapter G Part 84 – Approval of respiratory protective devices The Electronic Code of Federal Regulations (eCFR) <https://www.ecfr.gov/current/title-42/chapter-I/subchapter-G/part-84> (accessed 02-16-2024)
- [8] Prather K A, Wang C C and Schooley R T 2020 Science **368** 1422–1424
- [9] Mackintosh E 2021 European countries mandate medical-grade masks over homemade cloth face coverings CNN, 22 January 2021 <https://edition.cnn.com/2021/01/22/europe/europe-covid-medical-masks-intl/index.html> (accessed 10-28-2024)

- [10] Wenstrup B 2024 After Action Review of the COVID-19 Pandemic: The Lessons Learned and a Path Forward United States House Committee on Oversight and Accountability, 4 December 2024 <https://oversight.house.gov/report/after-action-review-of-the-covid-19-pandemic-the-lessons-learned-and-a-path-forward> (accessed 12-08-2024)
- [11] Jefferson T, Dooley L, Ferroni E, Al-Ansary L A, van Driel M L, Bawazeer G A, Jones M A, Hoffmann T C, Clark J, Beller E M, Glasziou P P and Conly J M 2023 The Cochrane Database of Systematic Reviews **11** CD006207
- [12] Da Zhou C, Sivathondan P and Handa A 2015 Journal of the Royal Society of Medicine **108** 223–228
- [13] Burdick H N and Maibach H 2021 Clinical Infection in Practice **12** 100087
- [14] Wang M X, Gwee S X W, Chua P E Y and Pang J 2020 Frontiers in Medicine **7**
- [15] Committee NA 176-04-07-01 AK “Infection protection masks” 2019 DIN EN 14683: Medical face masks – requirements and test methods; German version EN 14683:2019+AC:2019 DIN Standards Committee Health Technologies <https://www.din.de/en/getting-involved/standards-committees/nagesutech/publications/wdc-beuth:din21:311258244>(accessed 02-16-2024)
- [16] Subcommittee F2340 on Biological 2023 ASTM F2100-23: Standard specification for performance of materials used in medical face masks ASTM Volume 11.03: Occupational Health And Safety; Protective Clothing <https://www.astm.org/f2100-23.html> (accessed 02-16-2024)
- [17] Drewnick F, Pikmann J, Fachinger F, Moormann L, Sprang F and Borrmann S 2021 Aerosol Science and Technology **55** 63–79
- [18] Shah Y, Kurelek J W, Peterson S D and Yarusevych S 2021 Physics of Fluids **33** 073315 ISSN 1070-6631
- [19] Viola I M, Peterson B, Pisetta G, Pavar G, Akhtar H, Menoloascina F, Mangano E, Dunn K E, Gabl R, Nila A, Molinari E, Cummins C, Thompson G, Lo T Y M, Denison F C, Digard P, Malik O, Dunn M J G, McDougall C M and Mehendale F V 2021 IEEE Open Journal of Engineering in Medicine and Biology **2** 26–35
- [20] Knobloch J, Franke G, Knobloch M, Knobling B and Kampf G 2023 Journal of Hospital Infection **134** 89–96
- [21] Lee S, Grinshpun S A and Reponen T 2008 The Annals of Occupational Hygiene **52** 177–185
- [22] Pinning J 2021 FFP2-Masken – Hinweise des Arbeitsausschusses NA 027-02-04 AA “Atemgeräte für Arbeit und Rettung” zur DIN EN 149 DIN press release, 27 January 2021 <https://www.din.de/de/din-und-seine-partner/presse/mitteilungen/ffp2-masken-787882> (accessed 02-16-2024)
- [23] CDC 2021 Types of Masks and Respirators Centers for Disease Control and Prevention <https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/types-of-masks.html> (accessed 02-16-2024)

- [24] Committee CEN/TC 79 “Respiratory protective devices” 2019 DIN EN 13274-7: Respiratory protective devices – methods of test – Part 7: Determination of particle filter penetration; German version EN 13274-7:2019 DIN Standards Committee Optics and Precision Mechanics <https://www.din.de/en/getting-involved/standards-committees/nafuo/publications/wdc-beuth:din21:303320253> (accessed 02-16-2024)
- [25] Ksiazek T G, Erdman D, Goldsmith C S, Zaki S R, Peret T, Emery S, Tong S, Urbani C, Comer J A, Lim W, Rollin P E, Dowell S F, Ling A E, Humphrey C D, Shieh W J, Guarner J, Paddock C D, Rota P, Fields B, DeRisi J, Yang J Y, Cox N, Hughes J M, LeDuc J W, Bellini W J, Anderson L J and null null 2003 New England Journal of Medicine **348** 1953–1966
- [26] Zhu N, Zhang D, Wang W, Li X, Yang B, Song J, Zhao X, Huang B, Shi W, Lu R, Niu P, Zhan F, Ma X, Wang D, Xu W, Wu G, Gao G F and Tan W 2020 New England Journal of Medicine **382** 727–733
- [27] Bar-On Y M, Flamholz A, Phillips R and Milo R 2020 eLife **9** e57390
- [28] Varga Z, Flammer A J, Steiger P, Haberecker M, Andermatt R, Zinkernagel A, Mehra M R, Scholkmann F, Schüpbach R, Ruschitzka F and Moch H 2020 The Lancet **395** e100
- [29] Menter T, Haslbauer J D, Nienhold R, Savic S, Hopfer H, Deigendesch N, Frank S, Turek D, Willi N, Pargger H, Bassetti S, Leuppi J D, Cathomas G, Tolnay M, Mertz K D and Tzankov A 2020 Histopathology **77** 198–209
- [30] Lahrz T, Bischof W, Sagunski H, Baudisch C, Fromme H, Grams H, Gabrio T, Heinzow B and Müller L 2008 Bundesgesundheitsblatt – Gesundheitsforschung – Gesundheitsschutz **51** 1358–1369
- [31] Fjeld R A and Owens T M 1988 IEEE Transactions on Industry Applications **24** 725–731
- [32] Sanchez A L, Hubbard J A, Dellinger J G and Servantes B L 2013 Aerosol Science and Technology **47** 606–615
- [33] Zangmeister C D, Radney J G, Vicenzi E P and Weaver J L 2020 ACS Nano **14** 9188–9200
- [34] Verreault D, Moineau S and Duchaine C 2008 Microbiology and Molecular Biology Reviews **72** 413–444
- [35] Duchaine C 2016 American Journal of Infection Control **44** S121–S126
- [36] Liljestrand G and Sahlstedt A V 1925 Skandinavisches Archiv für Physiologie **46** 94–120 (in German)
- [37] Winfried Mueller 2021 FFP-Masken im Test – Testübersicht Kaffeefilter-Design reintechnisch.de <http://www.wikidorf.de/reintechnisch/Inhalt/MaskenFFP2Test> (accessed 02-16-2024)

- [38] Vitalis 2022 Medizinische Einweg-Mund-Nasen-Schutzmaske discounto.de <https://www.discounto.de/Angebot/VITALIS-Mund-Nasen-Masken-4062642/> (accessed 02-16-2024)
- [39] Sky Rabbiter 2022 Einweg Mund-Nasen-Schutz 3-lagig bedruckt amazon.de <https://www.amazon.de/Rabbiter-Mund-Nasen-Schutz-Einfarbig-Atmungsaktive-Multifunktionstuch/dp/B08WLSJBRP/> (accessed 02-16-2024)
- [40] Rösch 2022 Mund- und Nasenmaske, 3-lagig roesch-fashion.com <https://www.carlmarie.de/roesch-mund--und-atemmasken-mund--und-nasenmaske-3-lagig-roesch-1779750.html> (accessed 02-16-2024)
- [41] Adidas 2022 Face cover M/L adidas.de <https://www.amazon.de/adidas-Face-Cover-Medical-Gesichtsbedeckung/dp/B08FC4QRSY?th=1> (accessed 02-16-2024)
- [42] Crom Cr2 2022 Medizinische Einweg-Schutzmaske, Minigröße für kleines Gesicht amazon.de <https://www.amazon.de/Crom-Cr2-Masken-Mundschutz-Einwegmasken/dp/B08GPJ9T84> (accessed 02-16-2024)
- [43] Zangmeister C D, Radney J G, Staymates M E, Vicenzi E P and Weaver J L 2021 ACS Applied Nano Materials **4** 2694–2701
- [44] Rawal A 2020 Indian Journal of Medical Research **152**(1-2) 9–11
- [45] Pöhlker M L, Pöhlker C, Krüger O O, Förster J D, Berkemeier T, Elbert W, Fröhlich-Nowoisky J, Pöschl U, Bagheri G, Bodenschatz E, Huffman J A, Scheithauer S and Mikhailov E 2023 Reviews of Modern Physics **95**(4) 045001
- [46] Stiti M, Castanet G, Corber A, Alden M and Berrocal E 2022 Environmental Research **204** 112072
- [47] Bagheri G, Thiede B, Hejazi B, Schlenczek O and Bodenschatz E 2021 Proceedings of the National Academy of Sciences of the USA **118** e2110117118
- [48] Morawska L J, Agranovski V, Ristovski Z and Jamriska M 2002 Indoor Air **12** 129–137
- [49] Morozov V N and Mikheev A Y 2017 Journal of Breath Research **11** 016006
- [50] Morawska L J, Buonanno G, Mikszewski A and Stabile L 2022 Nature Reviews Physics **4** 723–734
- [51] Cherrie J W, Wang S, Mueller W, Wendelboe-Nelson C and Loh M 2019 Journal of Exposure Science & Environmental Epidemiology **29** 578–583
- [52] Tang J W, Nicolle A D, Klettner C A, Pantelic J, Wang L, Suhaimi A B, Tan A Y, Ong G W, Su R, Sekhar C, Cheong D D and Tham K W 2013 PLoS One **8** e59970
- [53] Jayaweera M, Perera H, Gunawardana B and Manatunge J 2020 Environmental Research **188** 109819
- [54] Varanges V, Caglar B, Lebaupin Y, Batt T, He W, Wang J, Rossi R M, Richner G, Delaloye J and Michaud V 2022 Scientific Reports **12** 4938
- [55] Charvet A, Bardin-Monnier N, Thomas D, Dufaud O, Pfrimmer M, Barrault M, Bourrous S, Mocho V, Ouf F X, Poirier S, Jeanmichel L, Segovia C, Ferry D and Grauby O 2022 Journal of Aerosol Science **160** 105914

- [56] Schumann C and Kekulé A S 2022 MDR Aktuell – Kekulé's Corona-Kompass #307, 14 May 2022 Mitteldeutscher Rundfunk <https://www.mdr.de/nachrichten/podcast/kekule-corona/audio-corona-netzhaut-impfung-masken-antikoerper-infektion-100.html>, in German, (accessed 02-16-2024)
- [57] Hinds W C and Zhu Y 2022 Aerosol Technology : Properties, Behavior, and Measurement of Airborne Particles 3rd ed (New York, NY: Wiley)
- [58] Chughtai A A, Stelzer-Braid S, Rawlinson W, Pontivivo G, Wang Q, Pan Y, Zhang D, Zhang Y, Li L and MacIntyre C R 2019 BMC Infectious Diseases **19** 491 (8pp)
- [59] Kim M, Bae S, Kim J Y, Park S Y, Lim J S, Sung M and Kim S 2020 Infectious Diseases **52** 1–5
- [60] Leung N H L, Chu D K W, Shiu E Y C, Chan K H, McDevitt J J, Hau B J P, Yen H L, Li Y, Ip D K M, Peiris J S M, Seto W H, Leung G M, Milton D K and Cowling B J 2020 Nature Medicine **26** 676–680
- [61] Bai H, Qian X, Fan J, Shi Y, Duo Y, Guo C and Wang X 2021 ACS Industrial & Engineering Chemistry Research **60** 3–36
- [62] Drewnick F, Pikmann J, Fachinger F, Moormann L, Sprang F and Borrmann S 2021 Aerosol Science and Technology **55** 63–79
- [63] Papineni R S and Rosenthal F S 1997 Journal of Aerosol Medicine **10** 105–116
- [64] Morawska L J and Buonanno G 2021 Nature Reviews Physics **3** 300–301
- [65] Dellweg D, Lepper P M, Nowak D, Köhnlein T, Olgemöller U and Pfeiffer M 2020 Pneumologie **74** 331–336
- [66] Elgersma I H, Fretheim A, Elstrøm P and Aavitsland P 2023 Epidemiology and Infection **151** e194, 1–5
- [67] Sandlund J, Duriseti R, Ladhani S N, Stuart K, Noble J and Høeg T B 2024 Archives of Disease in Childhood **109** e1–e7
- [68] Butz U 2005 Rückatmung von Kohlendioxid bei Verwendung von Operationsmasken als hygienischer Mundschutz an medizinischem Fachpersonal Ph.D. thesis Technische Universität München Institut für Anaesthesiologie, Klinikum rechts der Isar, Germany <https://mediatum.ub.tum.de/602557>, in German, (accessed 02-16-2024)
- [69] Rhee M S M, Lindquist C D, Silvestrini M T, Chan A C, Ong J J Y and Sharma V K 2021 BMC Infectious Diseases **21** 354 (7pp)
- [70] Walach H, Traindl H, Prentice J, Weigl R, Diemer A, Kappes A and Hockertz S 2022 Environmental Research **212** 113564
- [71] Acuti Martellucci C, Flacco M E, Martellucci M, Violante F S and Manzoli L 2022 Environmental Health Insights **16** 11786302221123573 (8pp)
- [72] Park A, Khadka S, Sato F, Omura S, Fujita M, Hashiwaki K and Tsunoda I 2022 Scientific Reports **12** 11361

- [73] Kisielinski K, Giboni P, Prescher A, Klosterhalfen B, Graessel D, Funken S, Kempfski O and Hirsch O 2021 International Journal of Environmental Research and Public Health **18** 4344
- [74] Kisielinski K, Wagner S, Hirsch O, Klosterhalfen B and Prescher A 2023 Heliyon **9(4)** e14117, 1–18
- [75] Kisielinski K, Hockertz S, Hirsch O, Korupp S, Klosterhalfen B, Schnepf A and Dyker G 2024 Ecotoxicology and Environmental Safety **275** 115858
- [76] Sinkule E J, Powell J B and Goss F L 2013 The Annals of Occupational Hygiene **57** 384–398
- [77] Engeroff T, Heinsel K, Niederer D, Nienhaus A, Groneberg D A and Vogt L 2024 Scientific Reports **14** 6278
- [78] Langbehn A T, Yermol D A, Zhao F, Thorstenson C A and Niedenthal P M 2022 Affective Science **3** 105–117

Appendix A. Experimental data

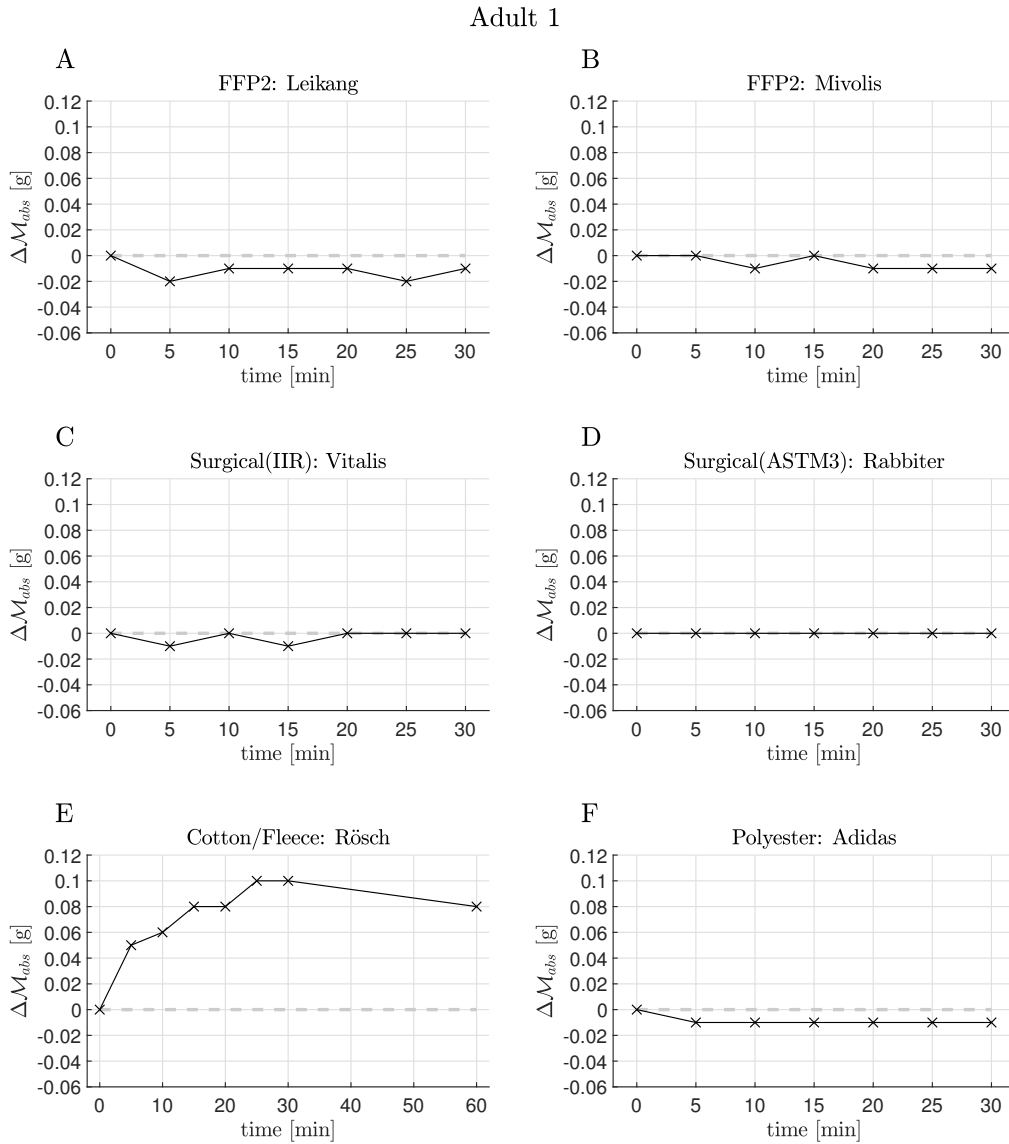


Figure Appendix A.1. Courses over time of water mass absorbed ΔM_{abs} during breathing when wearing different types and models of face masks, one panel for each tested face mask. Mask type and name are given in the panel titles. Only one of the tested face masks, of type cotton/fleece (Rösch), absorbs a measurable amount of water (see panel E), albeit minuscule as compared to the available pore volume \mathcal{V}_{pore} .

Adult 2

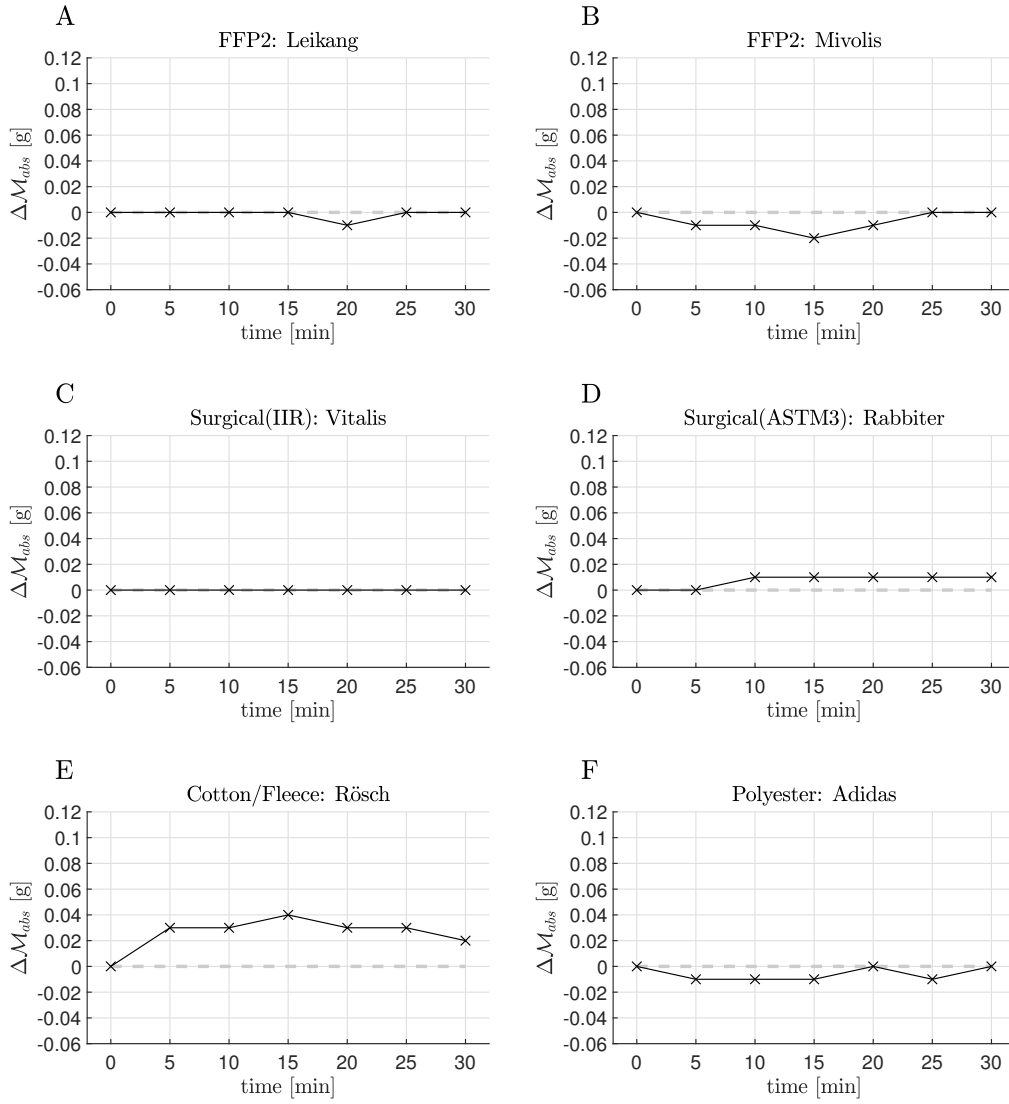


Figure Appendix A.2. Courses over time of water mass absorbed ΔM_{abs} during breathing when wearing different types and models of face masks, one panel for each tested face mask. Mask type and name are given in the panel titles. Only one of the tested face masks, of type cotton/fleece (Rösch), absorbs a measurable amount of water (see panel E), albeit minuscule as compared to the available pore volume \mathcal{V}_{pore} .

Adult 3

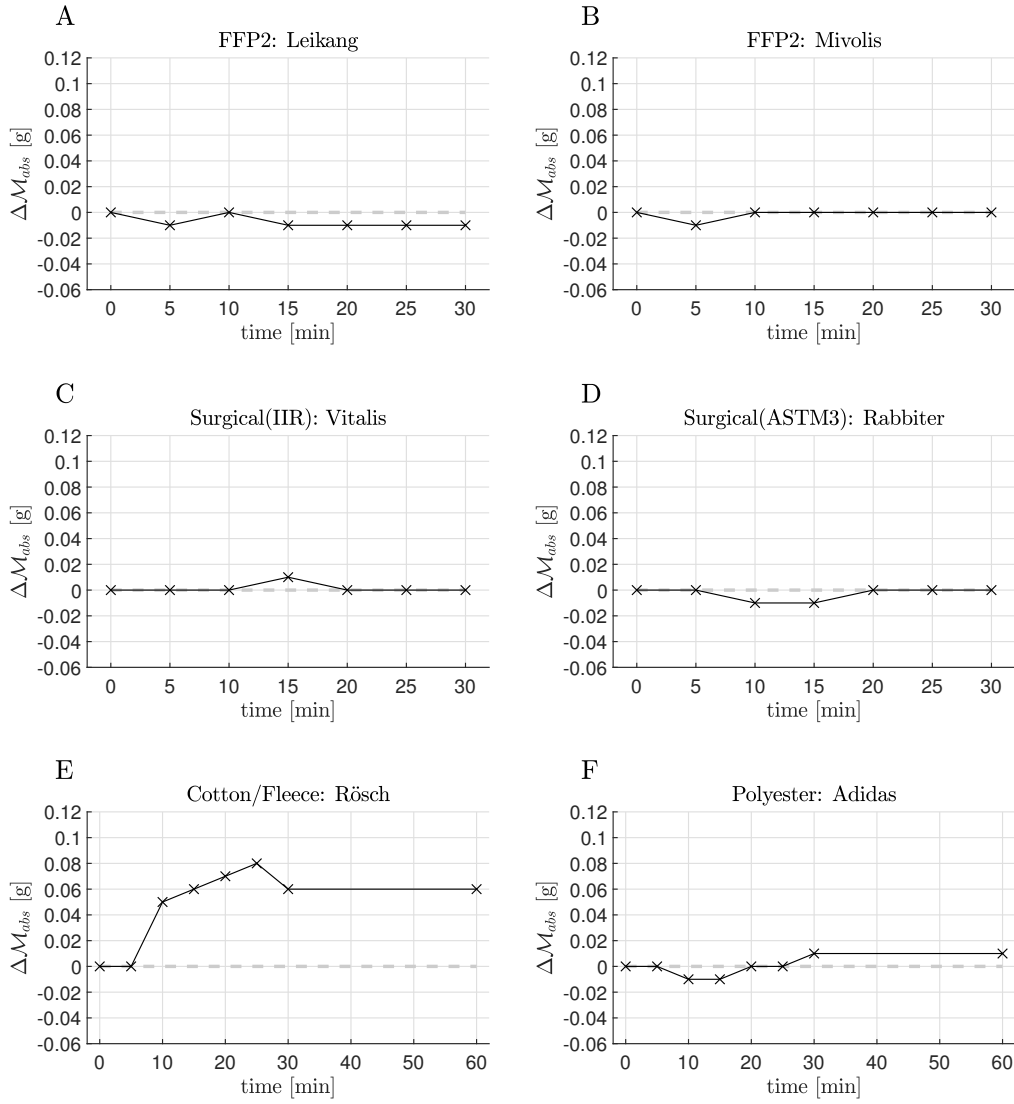


Figure Appendix A.3. Courses over time of water mass absorbed ΔM_{abs} during breathing when wearing different types and models of face masks, one panel for each tested face mask. Mask type and name are given in the panel titles. Only one of the tested face masks, of type cotton/fleece (Rösch), absorbs a measurable amount of water (see panel E), albeit minuscule as compared to the available pore volume \mathcal{V}_{pore} .

Child 1

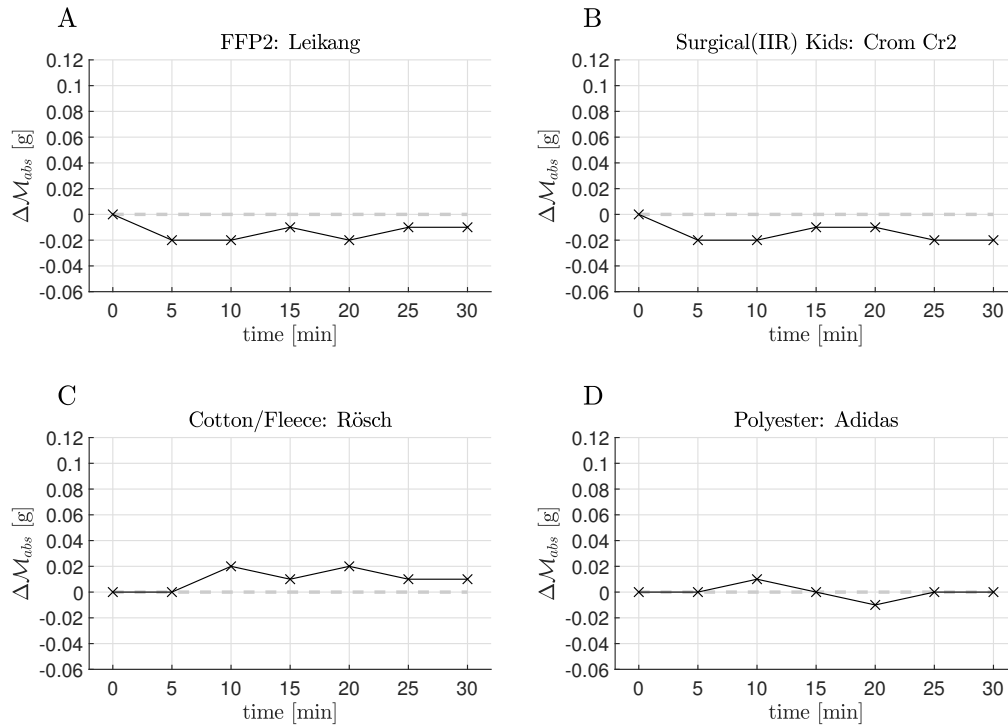


Figure Appendix A.4. Courses over time of water mass absorbed ΔM_{abs} during breathing when wearing different types and models of face masks, one panel for each tested face mask. Mask type and name are given in the panel titles. Only one of the tested face masks, of type cotton/fleece (Rösch), absorbs an only just measurable amount of water (see panel C), minuscule as compared to the available pore volume \mathcal{V}_{pore} .

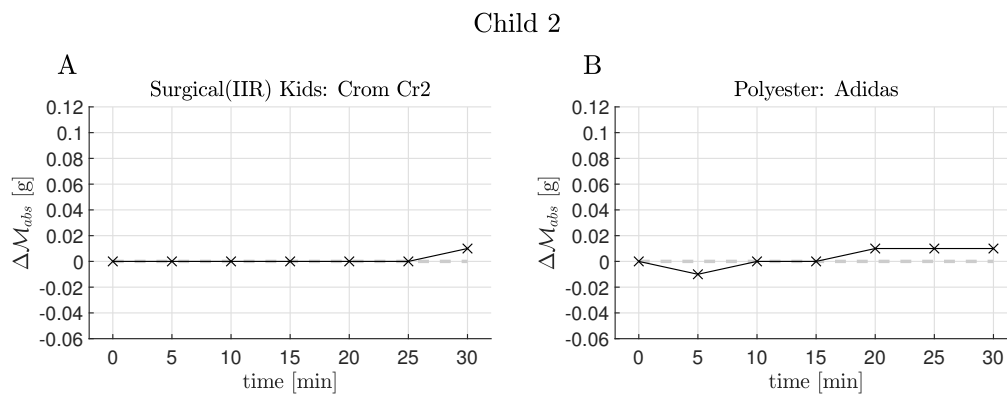


Figure Appendix A.5. Courses over time of water mass absorbed ΔM_{abs} during breathing when wearing different types and models of face masks, one panel for each tested face mask. Mask type and name are given in the panel titles. Both tested face masks, surgical (panel A) and polyester (panel B), do not absorb water at all.