Accumulation of water in face masks during respiration

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Abstract

When humans exhale, they discharge liquid particles containing solid components (e.g. bacteria and virions). These droplets and aerosols are primarily composed of water. In this study, water absorbed from exhaled human breath was measured (precision scale) in vivo (3 adults, 2 children) for 3 different types of face masks (2 FFP2/N95, 3 surgical, 2 cloth) intended for protection from the SARS-CoV-2 virus (diameter 0.1 - 0.15 μm). Accumulation of water in the tested face masks was also assessed when exposed to steam as well as when submerged in a basin of water. Measured water absorption for each mask was compared to the mask's estimated pore volume, i.e. the amount of water possible to be absorbed in-between the mask's fibers. Additionally, a simple physics-based model was used to predict how much water can be absorbed by a face mask and how much time this absorption process will take. The key observation of this study indicates that absorption of water by face masks during human breathing is minuscule to none. A shrinkage mechanism is discussed to explain the discrepancy between these findings and the widely accepted belief that virions (usually bound to water) can be filtered by face masks. Basic energetic considerations on electrostatic attraction between mask material and charged particles are regarded and put into context with the current state of knowledge on physical properties of particles in exhaled human breath. It is inferred that one-fold positively charged particles of diameter 0.7 μm or larger will escape the electrostatic attraction at the mask's surface as their kinetic energy within the typical air stream for quiet breathing ($1\,\frac{\mathrm{m}}{\mathrm{s}}$) exceeds the potential energy ($6.4\cdot 10^{-17}$ J) at the mask's surface. There is a lack of empirical evidence and mechanistic understanding of virion-mask interaction that would support the filtering of particles of smaller sizes. It remains open whether an underlying filtering mechanism to reduce transmission of virions, like SARS-CoV-2, exists at all, and if so, to what extent, and with what harm-to-benefit ratio.

Key words: aerosol; particle; virion; shrinkage; filter efficiency; electrostatic attraction

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Preprint (doi:10.5281/zenodo.8251843) *August 16, 2023*

1. Introduction

Face masks, after an initial period of being recommended *not* to wear [1, 2, 3], have been a staple of public health interventions against the spread of CoViD-19 in the years 2020 through 2023. After recommending cloth and surgical masks for the public [4], face coverings adhering to standards like EN 149 (Europe [5]), or NIOSH-42 CFR 84 (US [6]), commonly referred to as FFP2 masks or N95 respirators, have been widely mandated. 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 [7]. Surgical masks were deemed sufficient in less critical situations, such as during phases of low SARS-CoV-2-positive rates. 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 efficiency.

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 [8, 9]. Among individuals in non-healthcare settings, surgical mask wearing has not been found to significantly reduce association with the incidence of acute respiratory illnesses [10]. The bacterial filter efficiency (BFE) of Tpye II (EN 14683 [11]) or Level 2 (ASTM 2100-23 [12]) 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 $3.0 \pm 0.3\,\mu$m, with the smallest size at $0.65\,\mu$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.

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 [13, 14]. 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 filter efficiency and by 2) their total inward leakage. Particle filter efficiency 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 $0.1\,\mu$m [15] (in N95 respirators $0.075 \pm 0.02\,\mu$m [6]). This size range corresponds exactly to the size of a SARS-CoV-2 virion [16, 17]. 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 efficiency, this time using a test aerosol of particles with a count median diameter of $0{,}6\,\mu$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 vol%, [18]), and 5 times the CO_2 concentration declared as barely acceptable in closed rooms (0.2 vol%, [18]).

The mechanism of filtering exhaled infectious particles remains unclear, as given standards do only test for mechanical filtering properties of inhaled air enriched with particles (technical: polystyrene, mineral dust, castor oil) of a certain size distribution. Also, any electrostatic particle capture is not part of the standard testing. Basic and thorough experimental work on how efficient polystyrene filter materials can absorb either electrically neutralized or charged *technical* aerosols has been performed by Fjeld & Owens already in 1988 [19]. For neutral particles of size 0.5 μm, they found a substantial decrease in filter efficiency as the airflow speed increased (investigated up to 0.2 $\frac{m}{s}$, [19, fig.4]. The same decline in filter efficiency was noted for electrically charged particles, when present at all. A highly significant decrease in electrostatic effect (filter efficiency) with increasing airflow speed was also reported by Sanchez et al. [20], for speed values examined in the range 0.5-2.7 $\frac{m}{s}$, in particular for (technical) particle sizes around 0.1 μm. Recently, these experimental findings have been thoroughly enhanced by Zangmeister et al. [22]. They measured the efficiency 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 μm to 0.825 μm, however, exclusively at an airflow speed as low as 0.06 $\frac{m}{s}$. 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 [23, 24], either bound in 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 m^2 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*

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

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

with a fiber volume of

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

where the mask's mass (without straps) $\mathcal{M}_{mask} = 4.9\,\mathrm{g}$ and the fiber density (whether polyamide, fleece, polyester, or cotton) $\rho_{fib} \approx 1\,\frac{\mathrm{g}}{\mathrm{cm}^3}$ [19, 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 $\mathcal{L}_{mask} = 15.6\,\mathrm{cm}$, width $\mathcal{W}_{mask} = 10.6\,\mathrm{cm}$, and thickness $\mathcal{D}_{mask} = 0.2\,\mathrm{cm}$ as

$$\mathcal{V}_{mask} = \mathcal{L}_{mask} \cdot \mathcal{W}_{mask} \cdot \mathcal{D}_{mask} = 33.1\,\mathrm{cm}^3 \quad . \tag{3}$$

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 respires at low activity, is about half a liter of air ($\mathcal{V}_T = 500\,\mathrm{cm}^3$). 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% [25, p. 118, tab. 8]. Thus, the corresponding water volume in one exhaled breath during low activity comes to $500\,\mathrm{cm}^3 \cdot 4 \cdot 10^{-5} = 0.02\,\mathrm{cm}^3$, i.e. a mass of 0.02 g of water. If this amount of water were *entirely* absorbed during each respiratory cycle, then the above-calculated pore volume ($\mathcal{V}_{pore} = 28.2\,\mathrm{cm}^3$) 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. A.1E and Experiment 3: Fig. A.3E, F).

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 $\rho_{water} \approx 1\,\frac{\text{g}}{\text{cm}^3}$. 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* [g] $\mathcal{M}_{mask}$	length [cm] $\mathcal{L}_{mask}$	width [cm] $\mathcal{W}_{mask}$	thickn. [cm] $\mathcal{D}_{mask}$	p. vol. [cm^3] $\mathcal{V}_{pore}$	p. ratio $\frac{\mathcal{V}_{pore}}{\mathcal{V}_{mask}}$ χ_{pore}
Leikang LK-008	[26]	FFP2/ N95 †	5	adult	yes	5.7	15.6	10.6	0.2	28.2	0.85
Mivolis Osvirol 8000	[26]	FFP2/ N95 †	4	adult	yes	4.1	16.0	10.6	0.13	18.5	0.84
Vitalis Easy Fit	[27]	Surgical (IIR) ‡	3	adult	yes	$3.1^{\#}$	17.3	16.4	$0.07^{\#}$	17.1	0.86
Sky Rabbit Rabbiter	[28]	Surgical (ASTM3) ‡	3	adult	yes	$3.6^{\#}$	$17.5^{\#}$	$15.0^{\#}$	$0.06^{\#}$	12.5	0.79
Rösch Cotton	[29]	Cloth (Cott./Flc.)	3	adult	no	$11.4^{\#}$	$18.2^{\#}$	$14.5^{\#}$	$0.12^{\#}$	21.8	0.69
Adidas Face Cover	[30]	Cloth (Polyester)	2	adult	no	$10.0^{\#}$	17.0	15.3	$0.19^{\#}$	40.9	0.83
Crom Cr2 Kids	[31]	Surgical (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)

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 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 Math-Works, 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

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

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 $[2 \ldots 100]$ g for $\Delta\mathcal{M}_{abs,end}$, and within $[0 \ldots 0.1]\,\mathrm{min}^{-1}$ 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. A.1-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, 0.1 g of water is absorbed, which is equivalent to about the humidity contained in 5 breaths. All other masks 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).

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 $\Delta\mathcal{M}_{abs,end}$ 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 $\Delta\mathcal{M}_{abs,end} < \mathcal{M}_{pore}$. 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

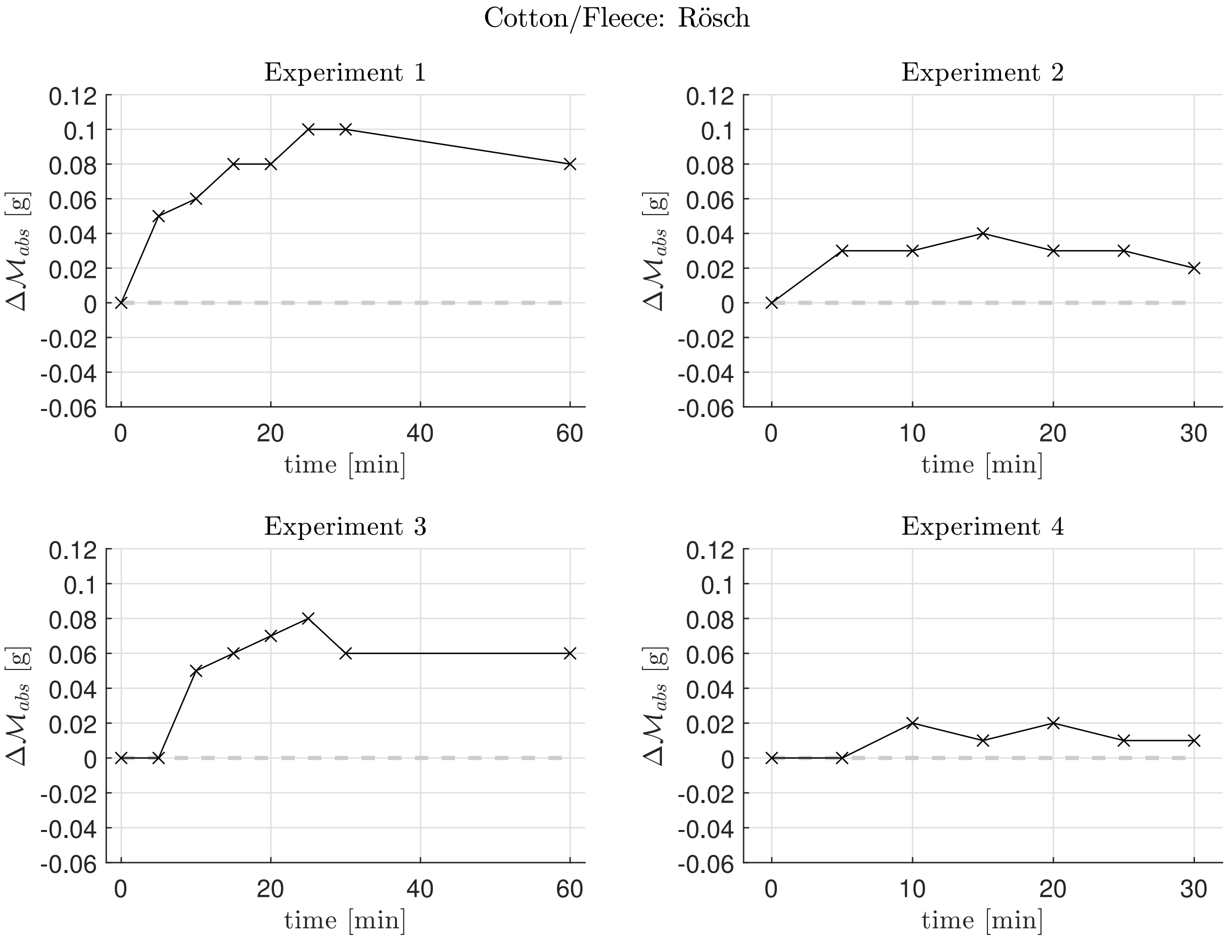

Figure 1: Courses over time of water mass absorbed $\Delta\mathcal{M}_{abs}$ during breathing when wearing the Rösch cloth mask, one panel for each experiment. At maximum, 0.1 g of water is absorbed, which is equivalent to about the humidity contained in 5 breaths.

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.

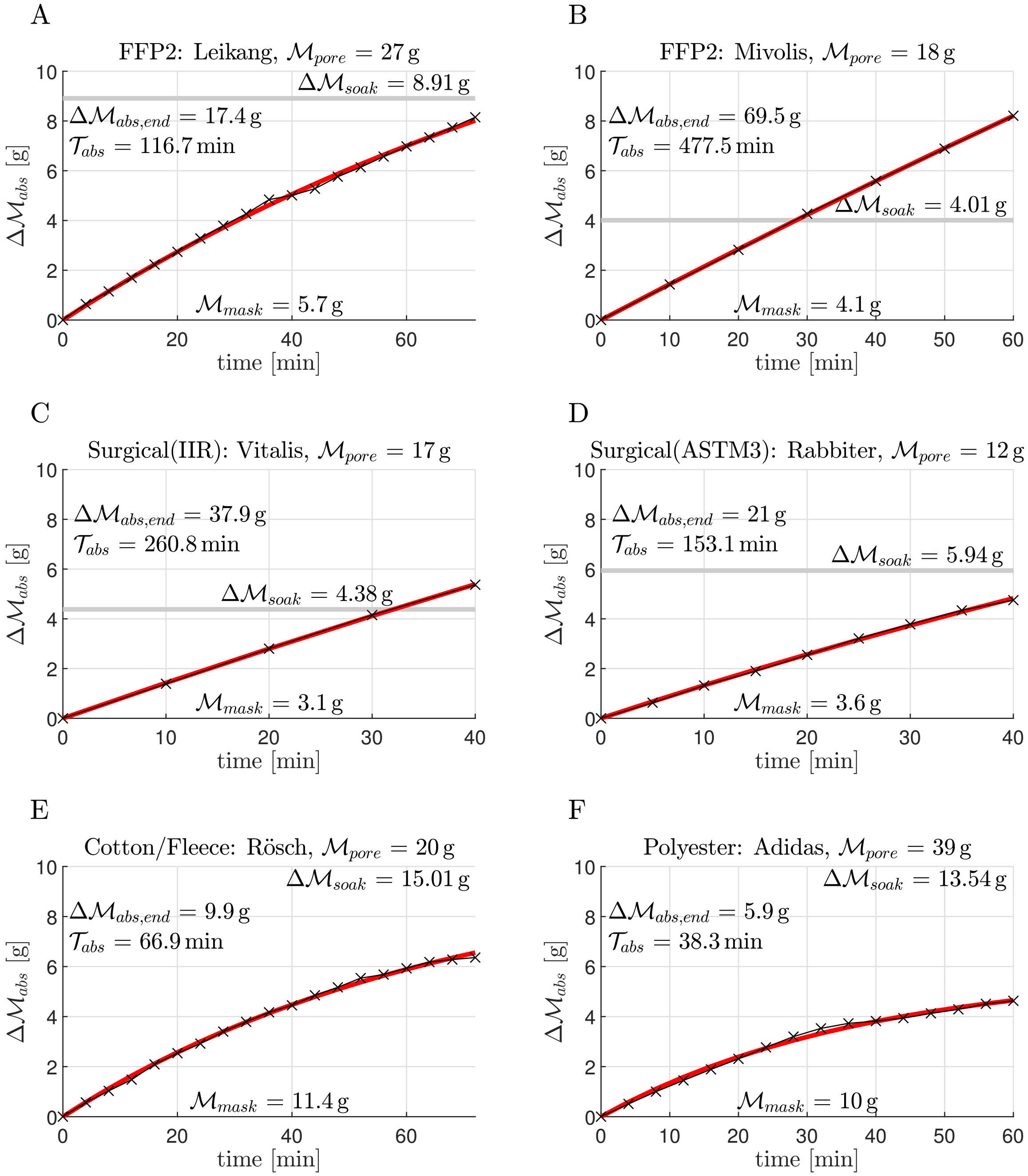

Figure 2: Measured and fitted courses over time of water mass absorbed, $\Delta\mathcal{M}_{abs}$, from steam (see Sec. 2.3), one panel for each tested mask. Mask type, mask name, and pore mass $\mathcal{M}_{pore}$ ($= \mathcal{V}_{pore} \cdot 1\,\frac{\mathrm{g}}{\mathrm{cm}^3}$: water mass equivalent 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 [23, 24]. 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 [23, 24]. Although at least two thirds of a face mask's volume consist of air (Table 1), all our investigated masks, except for one, do not absorb more than the humidity contained in one breath (0.02 g). The only cotton-based mask examined (Rösch) absorbed the equivalent of five breaths at most (0.1 g; see Figure 1). Similar results have been shown for cloth face coverings by Zangmeister et al [32, fig. S1]. This means, generally, just a tiny portion of the theoretically available volume, $\mathcal{V}_{pore}$ (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 [23, 24]: 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 [33, 34]. That is, a breath particle's water loss after exhalation is proportional to its surface area, yet also depending on surrounding humidity [33]. Exhaled particles seem to exist down to at least 0.5 μm [35] if not anything like 0.2 μm [36] or even just 0.02 μm [37]. Some water may still remain adhering to solid particle parts, i.e. the remaining biological material (such as virions) [24, 38] after having shrunk in diameter by a factor of 2.5 (at about 95% relative humidity, [33]) to 4 (below 40% relative humidity, [34]). For example, a virion of size 0.1 μm could have been bound in a particle of size 0.4 μm at the instant of exhalation (100% humidity). Then, within 0.3 ms [fig. 4 in 33] this particle would have shrunk to the size of 0.13 μm at about 90% humidity behind a mask [tab. 1 in 39].

Thus, a shrinkage mechanism could potentially resolve the conflict between our plain and clear 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. Considering that this outcome would leave very small, rather dry particles for the filter material to capture, it 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 μm (in the *dried* state), which is the most prevalent (dry) size in the sub-micron range [37], 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 [37]. 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 μm. After calculating the volume of this sphere, which amounts to $3.4{\cdot}10^{-20}\,\mathrm{m}^3$, we can determine its mass, assuming a density similar to that of water, which is approximately $1000\,\frac{\mathrm{kg}}{\mathrm{m}^3}$ (holds true for virtually any biological material). Consequently, the particle's mass (m) is calculated to be $3.4{\cdot}10^{-17}$ 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 $\frac{\mathrm{m}}{\mathrm{s}}$ during breathing at low physical activity [40]. At an average velocity of $v = 1\,\frac{\mathrm{m}}{\mathrm{s}}$, the kinetic energy of our spherical example particle of radius 0.2 μm amounts to $1.7{\cdot}10^{-17}$ 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 $U = 400\,\mathrm{V}$ [41]. The corresponding potential energy at the surface of the mask for a particle carrying a single elementary charge ($q = 1.6 \cdot 10^{-19}\,\mathrm{C}$) is then $6.4 \cdot 10^{-17}\,\mathrm{J}$ ($= q \cdot U$). Hence, any one-fold positively charged spherical particle of radius $0.2\,\mu\mathrm{m}$ 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. [37], 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 [41].

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 [42]: 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 $1\,\frac{\mathrm{m}}{\mathrm{s}}$ in quiet breathing (Sanchez et al. [20] 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 $0.35\,\mu\mathrm{m}$ (particle size above $0.7\,\mu\mathrm{m}$) 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?

Many people have asked themselves how exactly masks, specified to filter particles down to sizes of about $0.6\,\mu\mathrm{m}$, are actually supposed to block virions of size $0.1\,\mu\mathrm{m}$. To answer this question, a popular expert virologist drew the analogy of a mosquito trying to fly through a charged wire-mesh fence [43]. The reassuring answer focused on electrostatically charged mask's 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 [44], 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 [45, 46, 47] studies experimentally proving presence of virus material on the surfaces of face masks. Chughtai et al. [45] designed a study for health workers to test for virus material present on the outer surfaces of face masks during inhalation. Kim et al. [46] 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. [48] for a recent review, (ii) PCR tests for virus material present on mask surfaces after their use by symptomatic persons in a hospital setting [45, 46, 47], or (iii) surrogate airflow experiments, in which breathing is substituted by (technical) aerosol generation and convection of non-human 'charged dust' (breath particle proxies) [41, 49]. A causal mechanism (instead of mere correlation [41]) between electrostatic charges on masks and its filtration efficiency 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 [41, 42].

An eminently meticulous article from 1988 by Fjeld & Owens [19] 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 ($0.5\,\mu$m). 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" [24] is still missing, fairly detailed data on particle size distribution in various exhalation conditions [35] as well as on airflow (convection) velocities [40] are now available.

Since 1988, considerable advances have been made in understanding the process of exhaled particle shrinkage by evaporation [34, 50]. The degree of shrinkage seems to strongly and primarily depend on the level of air humidity [33], which has been measured behind masks ($>85\%$ as a rule) [39, tab. 1]. Experimental findings on human saliva droplets of sizes ranging within 120-300 μm suggest a shrinkage limit of about one fourth in diameter when the humidity is below 40% [34]. Calculations performed by Pöhlker et al. [33] employed a theoretical model that assumed the shrinkage to be independent of initial size, even down to droplets measuring $0.8\,\mu$m. This finding aligns reasonably well with the observations of Papineni et al. [50], who reported a shrinkage factor of approximately 3.5 for $1\,\mu$m particles, as well as with the shrinkage factor of about 4 observed by Stiti et al. [34] in particles two orders of magnitude larger.

Morozov et al. [37] seem to have encountered another interesting property of the smallest exhaled particles. In their experimental study, they observed that *dried* particles at sizes below $0.5\,\mu$m (with an average size of $0.37\,\mu$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. [32]. The authors argue that hygroscopic particles (e.g. salts like NaCl, which is contained by saliva, mucus, and breath) uptake 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 $0.3\,\mu$m particle grows to $1.3\,\mu$m and the largest dry NaCl particle studied ($0.825\,\mu$m) grows to over $3.6\,\mu$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. [51] 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 [38], 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) [52]: "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 that a specific minimum voltage threshold of the wire is met. 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 (2023), 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 showed, that at least the virions' constant companion, water, is definitely *not* accumulated in 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 0.7μm 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.

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") [53, p. 22] in reducing respiratory viral infections. 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 efficiency 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 [54, 55, 56, 57, 58]. 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 [59].

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, we are consequently prompted to raise the following questions: (1) What is the underlying filtering mechanism, as consistently claimed by authorities (e.g. [13, 14]), that leads to the reduction in the transmission of SARS-CoV-2, influenza etc.? (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 [56] and the elderly, to significantly elevated concentrations of CO_2, increased breathing resistance, higher concentrations of (re-)inhaled pathogens, and impaired recognition of facial expression?

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.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interests

The authors declare no competing interest.

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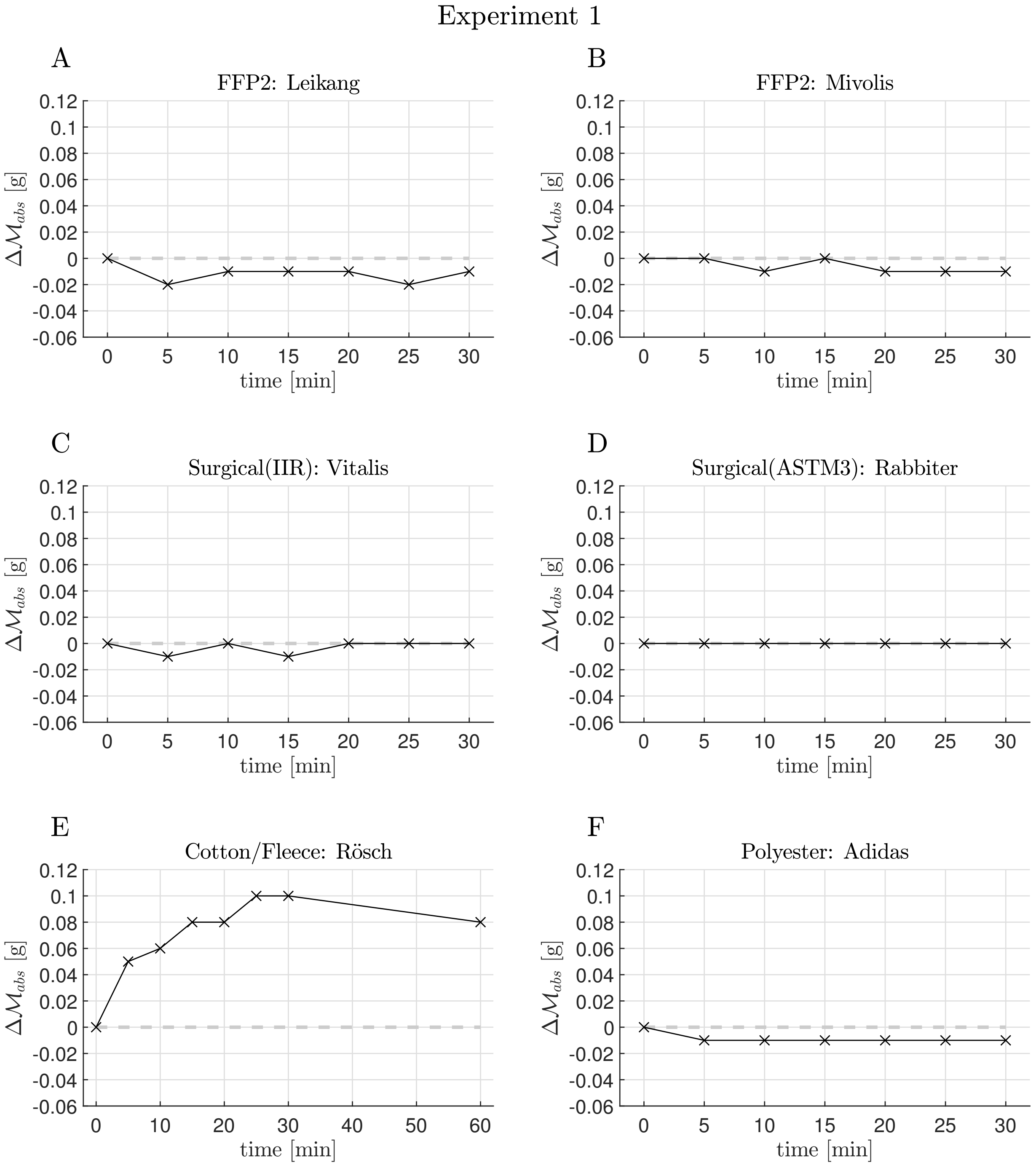
APPENDIX

A. Experimental data


Experiment 1

FFP2: Leikang

FFP2: Mivolis

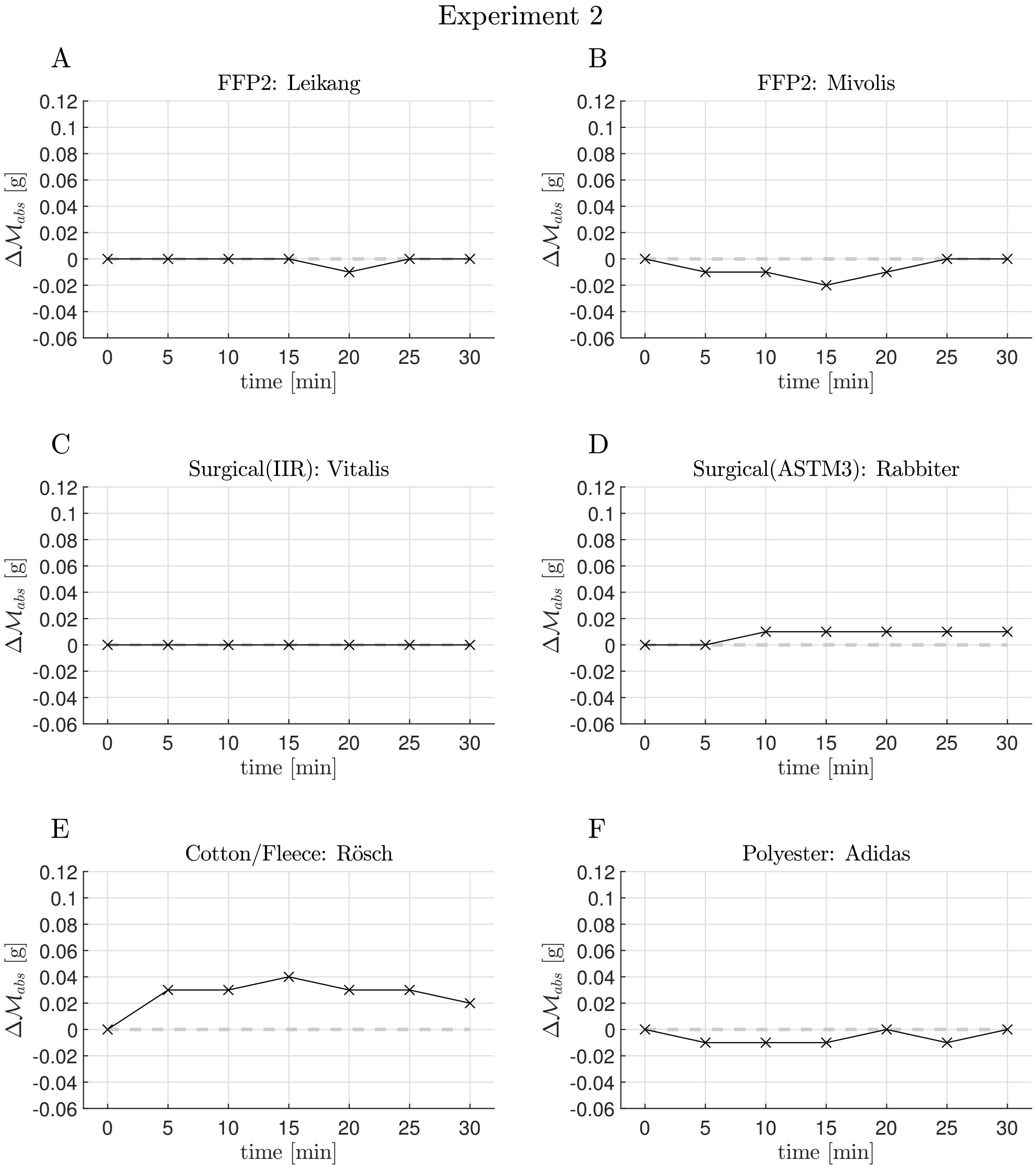
Surgical(IIR): Vitalis

Surgical(ASTM3): Rabbiter

Cotton/Fleece: Rösch

Polyester: Adidas

Figure A.1: Courses over time of water mass absorbed $\Delta\mathcal{M}_{abs}$ 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 $\mathcal{V}_{pore}$.



Experiment 2

A FFP2: Leikang

B FFP2: Mivolis

C Surgical(IIR): Vitalis

D Surgical(ASTM3): Rabbiter

E Cotton/Fleece: Rösch

F Polyester: Adidas

Figure A.2: Courses over time of water mass absorbed $\Delta\mathcal{M}_{abs}$ 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 $\mathcal{V}_{pore}$.

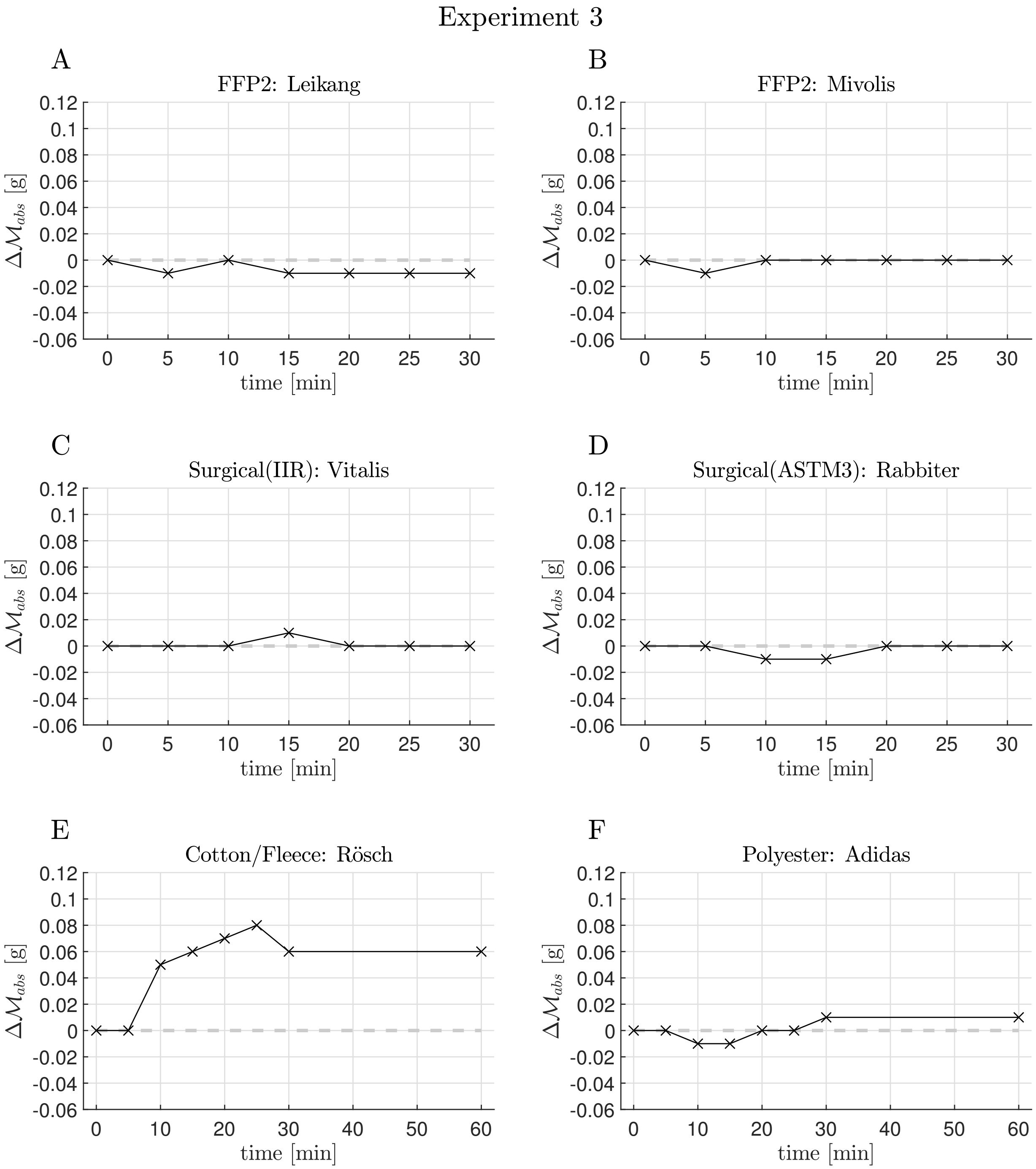


Figure A.3: Courses over time of water mass absorbed $\Delta\mathcal{M}_{abs}$ during breathing when wearing different types and models of face masks, one panel for each tested face mask. Mask type and name are given in the panel titles. Only one of the tested face masks, of type cotton/fleece (Rösch),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

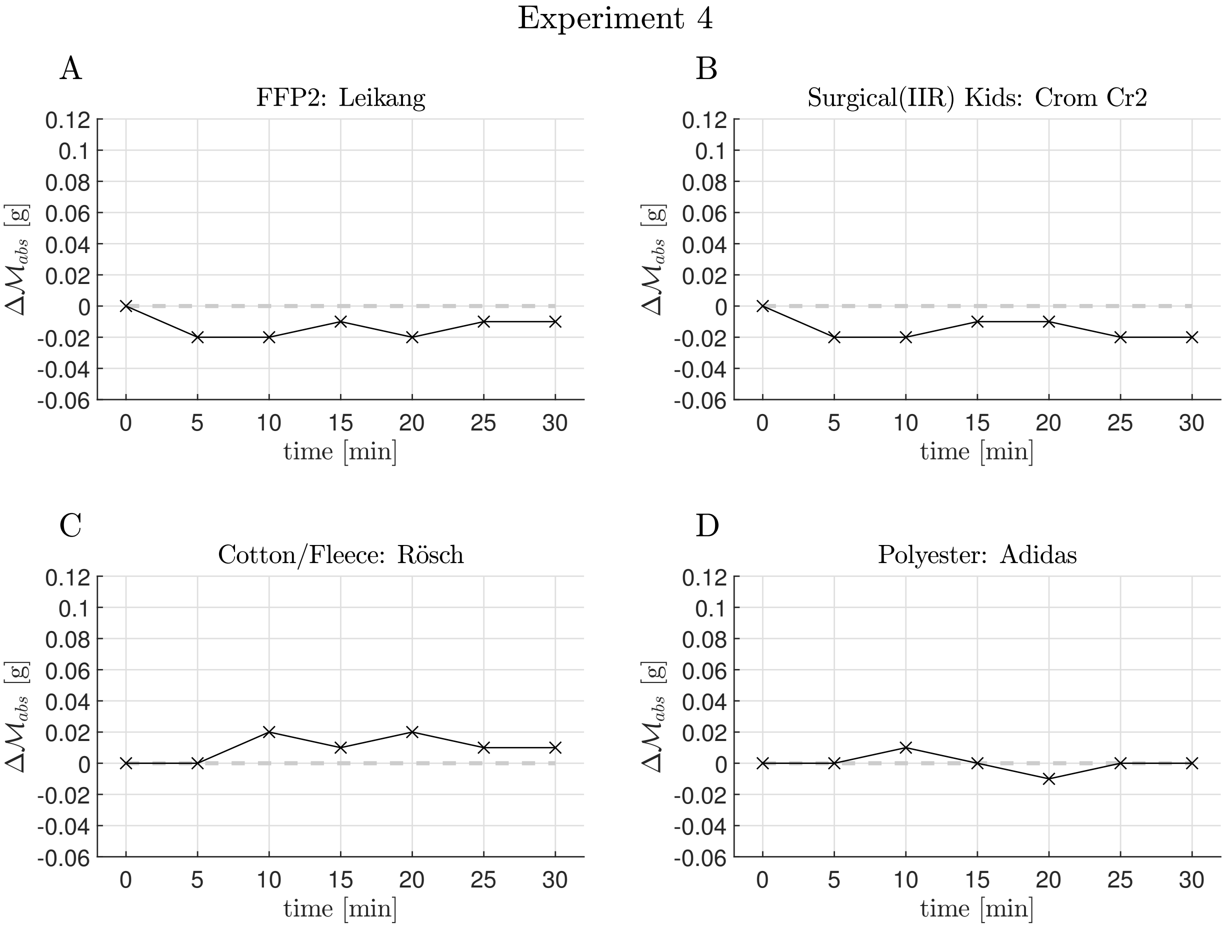


Figure A.4: Courses over time of water mass absorbed $\Delta\mathcal{M}_{abs}$ during breathing when wearing different types and models of face masks, one panel for each tested face mask. Mask type and name are given in the panel titles. Only one of the tested face masks, of type cotton/fleece (Rösch),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

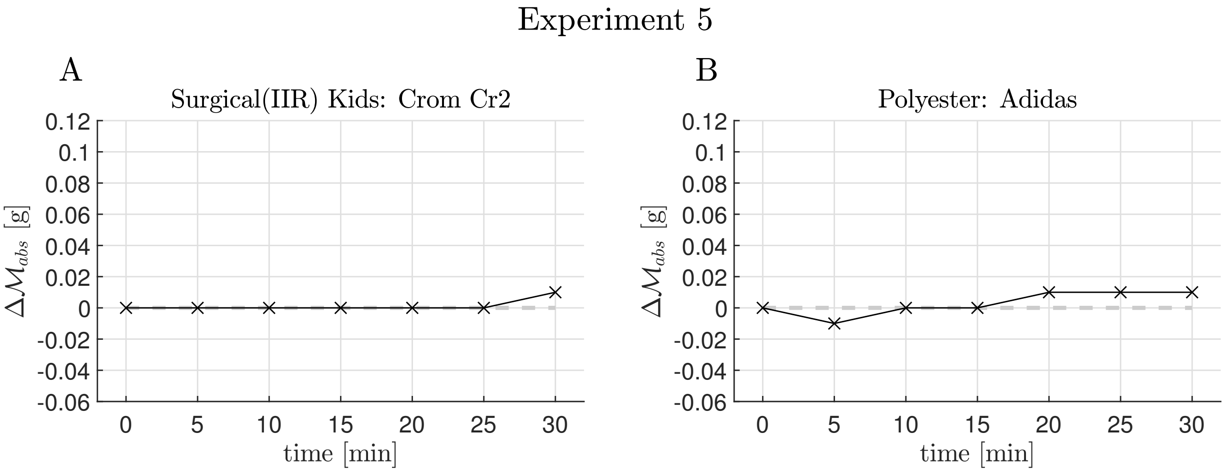


Figure A.5: Courses over time of water mass absorbed $\Delta\mathcal{M}_{abs}$ during breathing when wearing different types and models of face masks, one panel for each tested face mask. Mask type and name are given in the panel titles. Both tested face masks, surgical (panel A) and polyester (panel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