Testing of outward leakage of different types of masks with a breathing manikin head, ultraviolet light and coloured water mist

Ortiz, Marco A.; Ghasemieshkaftaki, Marzieh; Bluyssen, Philomena M.

DOI
10.1080/17508975.2021.1951153

Publication date
2021

Document Version
Final published version

Published in
Intelligent Buildings International

Citation (APA)
Ortiz, M. A., Ghasemieshkaftaki, M., & Bluyssen, P. M. (2021). Testing of outward leakage of different types of masks with a breathing manikin head, ultraviolet light and coloured water mist. *Intelligent Buildings International*, *14*(5), 623-641. https://doi.org/10.1080/17508975.2021.1951153

Intelligent Buildings International

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tibi20

Testing of outward leakage of different types of masks with a breathing manikin head, ultraviolet light and coloured water mist

Marco A. Ortiz, Marzieh Ghasemieshkaftaki & Philomena M. Bluyssen

To cite this article: Marco A. Ortiz, Marzieh Ghasemieshkaftaki & Philomena M. Bluyssen (2022) Testing of outward leakage of different types of masks with a breathing manikin head, ultraviolet light and coloured water mist, Intelligent Buildings International, 14:5, 623-641, DOI: 10.1080/17508975.2021.1951153

To link to this article: https://doi.org/10.1080/17508975.2021.1951153

INTELLIGENT BUILDINGS INTERNATIONAL
2022, VOL. 14, NO. 5, 623–641
https://doi.org/10.1080/17508975.2021.1951153

Testing of outward leakage of different types of masks with a breathing manikin head, ultraviolet light and coloured water mist

Marco A. Ortiz, Marzieh Ghasemieshkaftaki and Philomena M. Bluyssen

Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, The Netherlands

ABSTRACT

Since the outbreak of COVID-19, wearing a mask, voluntary or obligatory, has led to diverse and numerous designs. Guidelines for minimum requirements include tests for visual inspection, strength, filtration, and breathing resistance, but not for the fit of a mask. The fit of a mask was assessed by testing the outward leakage of exhaled breath based on the visualization of coloured mist exhaled by a manikin head. Fourteen masks were selected based on differences in design, such as type of material, shape (cheek wings vs. none), filter type, and the number of layers. Leakage expressed in mean mist percentages (visualized with a camera), patterns of coloured mist left inside the masks, as well as visual fit of the masks on the manikin head, showed that a loose fit mask results in more leakage. Also, combining quantitative with qualitative assessment proved to be complementary. Future tests should be conducted on a range of users, covering the best fit over time as well breathability, use, and comfort. The use of face masks, whatever their characteristics, seem an adequate strategy to reduce the dispersion of potential 'infected' aerosols into the space from people, as opposed to not wearing one.

ARTICLE HISTORY
Received 15 February 2021
Accepted 30 June 2021

KEYWORDS
Masks; COVID-19; aerosols; SARS-CoV-2; outward leakage

Introduction

What is needed to minimize the transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has been questioned since the first outbreaks of COVID-19. SARS-CoV-2 can be transmitted in three ways: (1) directly (through virus-carrying droplets) when in close vicinity by coughing, sneezing, or talking (Chen et al. 2020); (2) indirectly via deposited or transmitted infectious droplets via surfaces; and (3) can be transmitted through virus-carrying small airborne droplets (also named 'aerosols') emitted by infected individuals, a transmission route for which evidence is increasing (Prather et al. 2020; Allen and Marr 2020; Asadi et al. 2020; Morawska et al. 2020). To reduce direct transmission from mainly large infectious droplets, the physical distancing of individuals has been adopted. For indirect transmission cleaning surfaces, washing hands, and sneezing/coughing in the elbow are advised. For airborne transmission, it has been recommended (e.g. (Morawska et al. 2020), (REHVA 2020), (ASHRAE 2020)): (a) to provide sufficient and effective ventilation (that supplies clean outdoor air and minimizes recirculating air); and (b) to supplement general ventilation with airborne infection controls such as local exhaust, high-efficiency air filtration (Bluyssen, Ortiz, and Zhang 2021), and/or germicidal ultraviolet lights in ventilation systems (Martin et al. 2008). The early adoption of universal face masks by all the public, even when asymptomatic, in certain Southeast Asian countries may have played a role in the effectiveness of such countries to diminish the spread of the virus and the death count (Su et al. 2020; Lim et al. 2020). This is supported by the fact that

CONTACT Marco A. Ortiz m.a.ortizsanchez@tudelft.nl Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, Delft 2628 BL, Netherlands

Supplemental data for this article can be accessed https://doi.org/10.1080/17508975.2021.1951153.

universal mask wearing can also be effective for lowering the spread of the virus, also amongst asymptomatic wearers (Leung et al. 2020). For people who need to or tend to come close to (possible) infected persons, personal protective equipment is used (e.g. facial masks, protective gloves, respirators). Additionally, face mask or other types of face coverings are used by the public, whether mandatory or not, to prevent spreading (direct and/or airborne transmission) of the virus to others (MacIntyre and Chughtai 2020; Tcharkhtchi et al. 2021).

The use of face masks by the public since the outbreak of COVID-19 has led to diverse and numerous designs, but also critical questions about whether mask use reduces the compliance with other recommended strategies, such as physical distancing; or about whether wearing a mask protects the wearer from becoming infected themselves; and most importantly which criteria should a public mask fulfil to indeed the prevent spread of the virus to others (Howard et al. 2021). Chu et al. (2020) reviewed interventions against SARS-CoV-2 as well as against SARS and MERS (Middle East Respiratory Syndrome) and found that the use of masks could result in a reduction of the risk of infection (Chu et al. 2020). Widespread mask-wearing seems to lower the incidence of COVID-19 (Chu et al. 2020; Van Dyke et al. 2020; Mitze et al. 2020) although a causal relationship has not been confirmed. The incidence of COVID-19 in Kansas counties where the wearing of masks in public spaces was mandated, decreased after this mandate, while in Kansas counties without mask mandates the incidence continued to increase (Van Dyke et al. 2020). Also, in Germany after wearing face masks became mandatory in public transport and shops, the number of newly registered COVID-19 infections seems to have reduced (Mitze et al. 2020).

The virus SARS-CoV-2 has a size of around 100 nm (0.1 μm) in diameter and is surrounded by or embedded in a fluid comprising mainly of water. When a person exhales, talks, or sneezes, a range of droplets, from very small and airborne (aerosols) to larger and heavier ones, are brought into the air (Morawska et al. 2009). These expiratory droplets have the physical properties of viscoelastic fluids, and hence do not behave as a Newtonian fluid, however, their airborne behaviour is similar to that of a gas (Bhat et al. 2010; Ai and Melikov 2018; Chao, Wan, and Sze To 2008). The viral load contained in a droplet, and the amount needed to be infected and develop COVID-19 is still being studied (Buonanno, Morawska, and Stabile 2020). Studies on the effects of masks on the flow of coughs have shown that surgical masks redirect the cough backward, while N95 reduced the speed of the jets (Tang et al. 2009), however, the degree to which a mask traps the aerosols is not known yet

Guidelines for minimum requirements, methods of testing, and use of public masks have been introduced all over the world and are updated regularly (e.g. (WHO 2020; AFNOR 2020; NEN 2020; CDC 2020; CEN 2020; NSAI 2020)). It is emphasized that these masks for public use are to protect others, not the wearer. With proper use of the mask, the risk of spreading droplets from the mouth and nose to the environment should be decreased. These guidelines comprise of recommendations for material use (should not contain chemicals that can harm health), the comfort of wearing, fit to face (contact surface as large as possible; minimum outward leakage), etc. Tests are described for visual inspection, strength, filtration, and breathing resistance. However, for outward leakage, no test has been defined (yet).

Mask filtration studies have focused on filtration tests of different types of masks, using a standard mix of particles or based on particle emission by mask-wearers, usually without considering the fit (the potential outward leakage caused by ‘bad’ fit) (Asadi et al. 2020; Fischer et al. 2020; Akhtar et al. 2020). The filtration efficiency of a mask is represented by the capacity of holding particles and viruses in the air, specified with an efficiency ratio including particle size, filtrated air quantity, and wearing time (Tcharkhtchi et al. 2021). In a recent study performed by Pan et al. (2021), three tests to assess the effectiveness of several face coverings were performed by monitoring the concentration of particles: the material filtration efficiency, the inward protection efficiency, and the outward protection efficiency on a manikin. The tests indicated that the fit of the mask was important. Similarly, Konda et al. (2020) found that leakages can decrease the performance of a mask: improper fit of the mask (gaps) resulted in over a 60% decrease in the overall mask’s efficiency.

More recently, the CDC has proposed that double masking, is a viable alternative to improve the fit and reduce the number of exhaled particles. A study suggested that combining a cloth mask with a medical procedure mask can decrease the number of particles expelled from simulated coughs (Brooks et al. 2021). Other studies have assessed the performance of different materials for effective homemade masks: it was suggested that several materials and combinations thereof can be used to make a homemade mask that can meet several standards, including those for pressure differences, particle filtration efficiency, and resistance to wetting (Wang et al. 2020). Another study suggested that most fitted face mask alternatives, other than N95, will provide less filtration of the required >95%, except for expired N95 respirators or used and sterilized ones (Sickbert-Bennett et al. 2020). A study performed to assess the efficacy of surgical masks to contain aerosols containing the coronavirus and the influenza virus, suggested that, when categorizing aerosols as particles of less than 5 microns, surgical masks can diminish the dispersal of respiratory droplets into the environment but not of aerosols (Leung et al. 2020).

Next to monitoring the number of particles that are filtrated, visualization of air leakage can be used. A study visualizing the leakage by using schlieren imaging concluded that jets from coughs when wearing a surgical mask are leaked through the sides, but with lower momentum. While wearing an N95 respirator will reduce the leak through the perimeter seal, however, the jet will penetrate through the mask material, at a lower velocity (Tang et al. 2009). For the visualization of aerosols and/or droplets, recently most studies have used airflow measurements or local measurements such as laser visualization of sprays and coughing, of which some in combination with a smoke or soap bubble generator and a manikin head (e.g. (Bluyssen, Ortiz, and Zhang 2021); (Morawska et al. 2009); (Verma, Dhanak, and Frankenfield 2020b); (Wölfel et al. 2020); (Stadnytskyi et al. 2020); (Verma, Dhanak, and Frankenfield 2020a)).

This study aimed at assessing the fit of a range of face masks by testing the outward leakage of exhaled breath based on the visualization of coloured mist exhaled by a manikin head. Therefore, it is worth highlighting the fact that this study does not focus on filtration efficiency. Several commercially available and masks and respirators were selected based on differences in design, such as type of material, shape (cheek wings vs. none), filter type, and the number of layers, while a respirator and a surgical mask were also selected.

Methods

Study design

Water mist coloured with a fluorescent tracking fluid (Liqui Moly)was generated with the use of ultrasonic vibrations and introduced with a simulated human breathing system through a manikin head in the Experience room of the SenseLab in Delft (Bluyssen et al. 2018) (see Figures 1–4). The manikin head was covered with different nose-mouth masks. The apparatus simulated the exhaling of an infected person, while the outward leakage of the coloured water mist was monitored by a camera at two different positions for different masks. The ventilation rate and the air temperature in the Experience room were kept constant at 1200 m^3/h (mixing ventilation) and 22°C, respectively.

Experimental set-up

An extruded polystyrene foam manikin adult (Figure 5) head was placed at position A on one of the tables in the Experience room (Figures 1 and 3a). The head was carved to create a comparative volume of an adult's

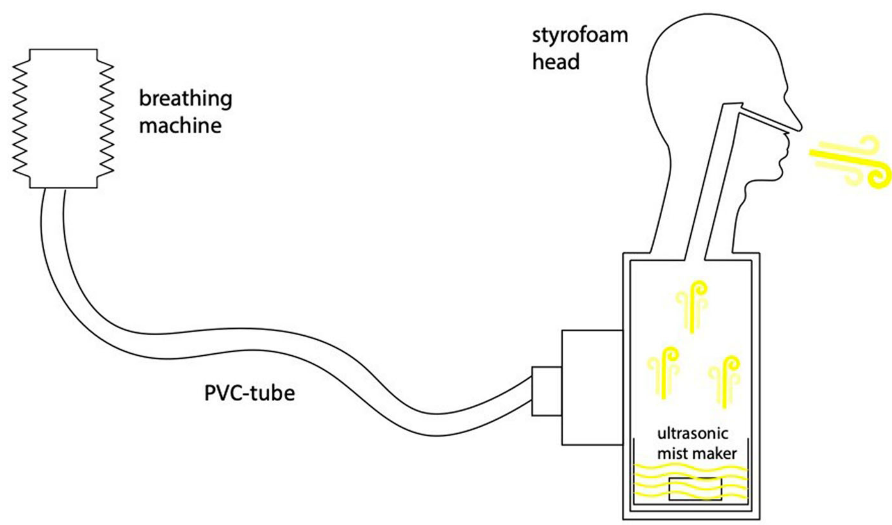


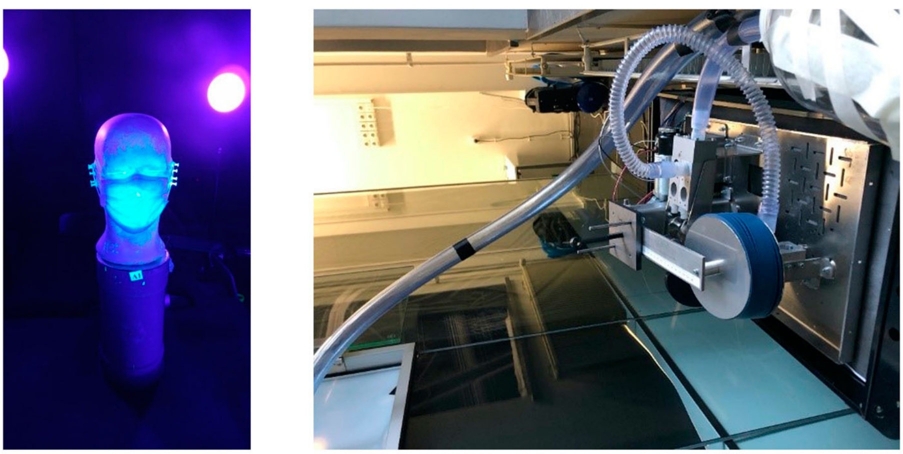
Figure 1. Section from the set-up to produce coloured mist through a manikin head.

Figure 2. Set-up of the manikin head with mask in the experience room.

head and to create a connection between the neck of the head and the nostrils. The nostrils were made by drilling two 10 mm orifices connecting the larger tube. Based on earlier studies regarding nostril opening, a size of 10 mm diameter was chosen (Yi and Yoon 2016).

A mechanical breathing system (ventilator designed by the project Inspiration of the TU Delft: https://www.projectinspiration.nl/specification/), placed outside of the Experience room, provided air via a 5-metre long PVC-tube with an external diameter of 48 mm (Figure 3b) – the tube went through a 50 mm hole into the Experience room – and to the other side to a PVC-cylinder with the manikin head on top. In this box, water mist was generated and built up with an ultrasonic mist maker (Ueetek ultrasonic fogger mist maker) via ultrasonic vibrations. The water was mixed with fluorescent tracking liquid with a ratio of one part of the tracking liquid to 9 parts of distilled water. This ratio was chosen because if the ratio is higher, the mist maker won't produce enough mist, and if it is lower the mist is not completely fluorescent. The non-dyed mist produced with this method has a particle size in the range of 3–7 μm; however, it is not known whether the addition of dye changes this parameter.

The breathing machine provided circa 0.5 L (not inhaling, only exhaling) in 1.25 s, resulting in a breathing cycle of 2.5 s (24 exhalations per minute, similar to moderate physical activity). Normal breathing lies around 15 times per minute (4 s per breathing cycle) and one breath of air amounts to approximately 0.5 L (Barrett et al. 2019).



(a) (b)

Figure 3. (a) Manikin head on a box with an ultrasonic mist maker. (b) Breathing machine outside the Experience room.

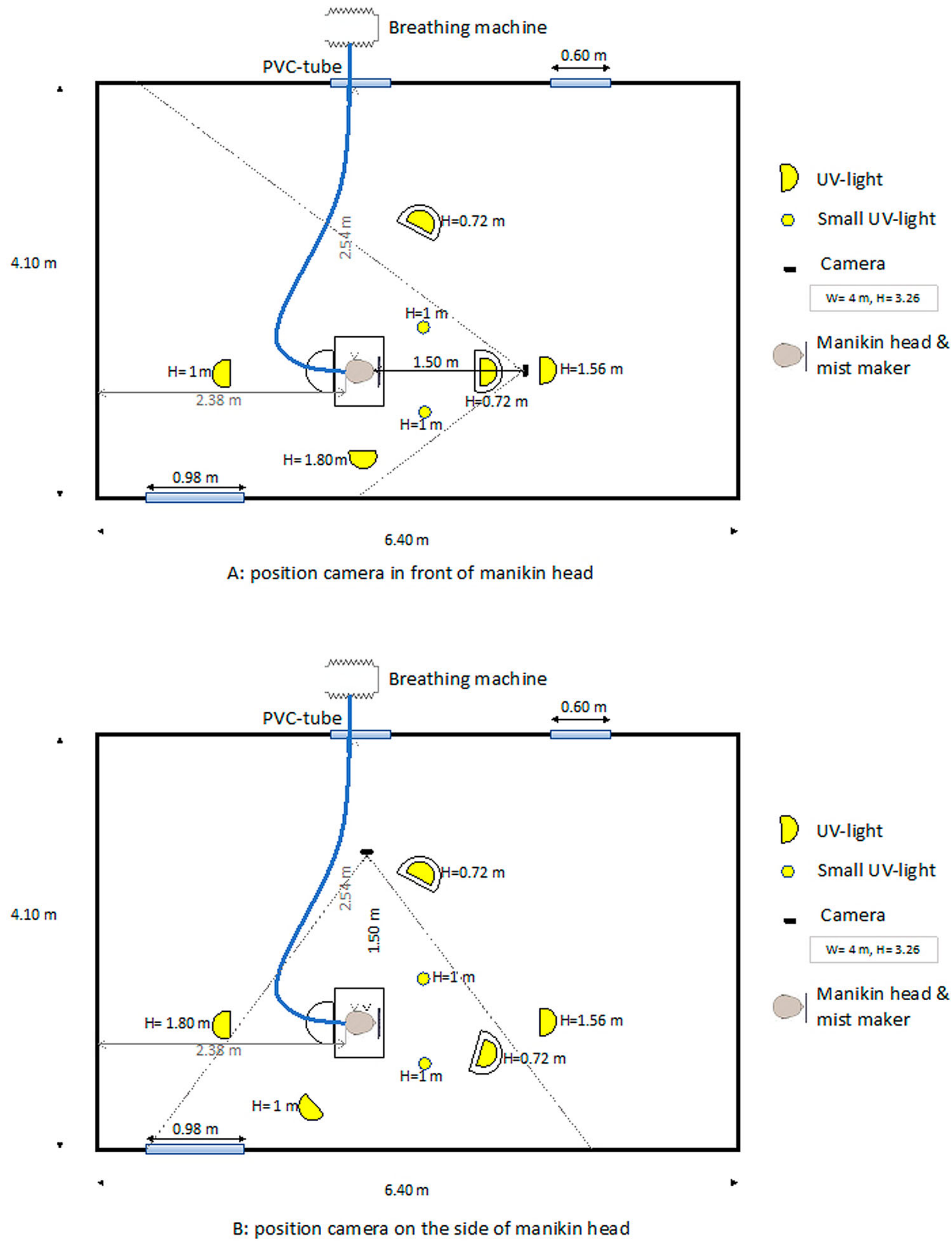


Figure 4. Experimental set-up for the two positions of the camera: (A) in front of the manikin head; (B) on the side of the manikin head.

Surrounding the set-up, six UV-lights were positioned to highlight the exhaled mist (Figures 1 and 4). To minimize the reflection of light by background objects (mostly walls and desks), surfaces were covered with black paper or foil. Additionally, all lights inside the SenseLab were turned off, and windows were covered, to have the least possible false light coming into the Experience room.

A camera (GoPro HERO 8 Black) was installed at a tri-pod and used to acquire images (one picture every two seconds with a wide-angle – 130 degrees), either in front of the manikin head or on the side (see Figure 4). The camera was placed 1.5 metres away from the head, both for the front and side recordings, covering an area of 4 × 3.26 m^2.

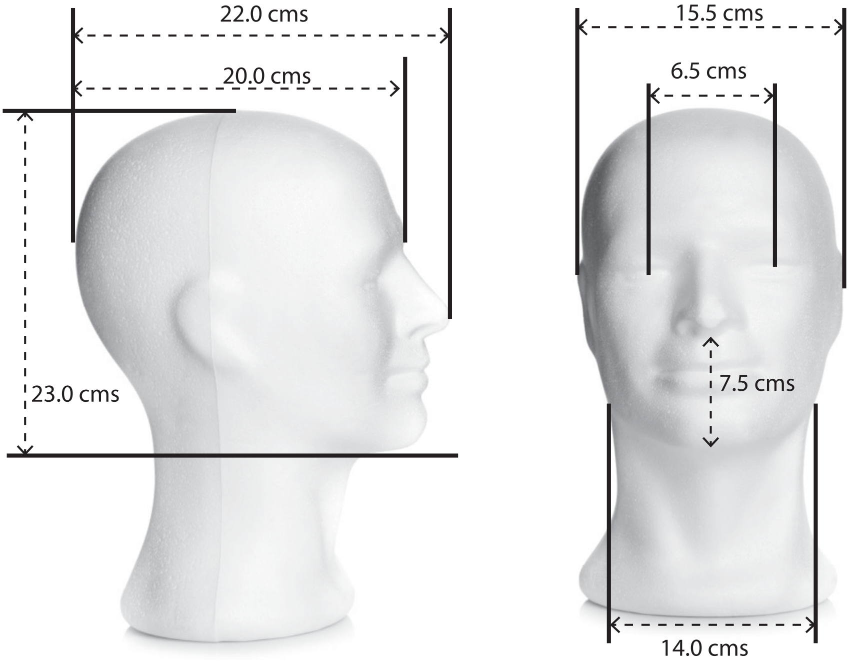


Figure 5. Extruded polystyrene foam adult head.

Test scheme and procedure

Fourteen different masks were selected based on differences in characteristics, namely: number of layers, filter type, presence of fenders, and nose piece type. These characteristics were chosen as these are the ones that vary most amongst masks offered in the market from which consumers can choose. Additionally, for woven masks, the number of threads per square centimetres was also used. this was done by drawing a square of one centimetre by one centimetre on the fabric of the mask, taking a high-quality zoom picture, and counting the number of threads vertically and horizontally.

In Table 1, the characteristics of the selected masks are presented. Codes were given to the masks to maintain their anonymity. Letters A through N were used to give individuality of the mask, and numbers indicated their precedence, mainly 1: medical masks; 2: commercial masks from a pharmacy; 3: homemade masks according to governmental guidelines; 4-7: specific brand.

Each mask was tested twice for both positions of the camera, for two minutes (visual steady state leakage was reached after 90 s). Additionally, a test was performed without any mask (also twice). The protocol was as follows:

- Experience room and general space lights off. UV-lights on.
- Put mask on the manikin head.
- Plug in the mist maker.
- Let mist build up for 1 min
- Turn on the camera (GoPro) and the lung.
- Count 2 min of lung running and the camera taking pictures after the lung and the camera are turned on. Researchers stay outside the room
- After 2 min, one researcher goes in, to record exhalations with a cell phone and yellow filter.
- After recording, turn off the lung and the camera, unplug the mist maker and remove the mask.
- Repeat step one with the next mask.

The production of mist remained constant during the two minutes, as did the breathing rate. After the first run of experiments and the last, a picture of the interior of the masks was taken to record the

Table 1. Selected masks to be tested on the outward leakage.

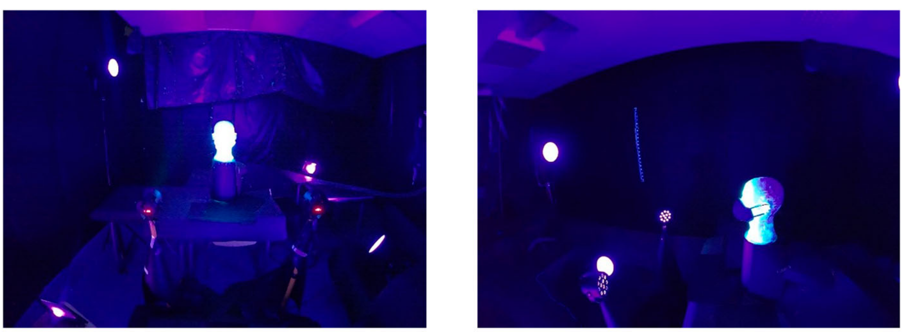
Code	Material	Layers	Inner Layer	Thread / cm^2	Filter type	Fenders	Size particle	Nose Piece type
A1	outer: acrylic bond inner: extra fine glass fibre	3	-	non-woven		no	$PM_{0.3}$ - 55-90%	inside wire
B1	electrostatic polypropylene	4	-	non-woven	KN95	no	$PM_{0.3}$ -95%	inside wire
C2	polyester 100%	2	-	woven: 14x14	-	no	-	none
D2	cotton 100%	3		woven: 42x42 outer; 34x34 inner	-	yes	-	inside wire
E3	cotton 100%	12	-	woven: 11x20	-	no	-	none
F4	out: polyester spun bond; in: electrostatic synthetic fibres	3	1	non-woven	KN95	yes	$PM_{0.3}$ -95%	silicone
G5	electrostatic polypropylene	6	4	outer: Inner: non-woven		yes		silicone perimeter
H6	electrostatic polypropylene	6	4	outer: Inner: non-woven		yes		silicone perimeter
I7	electrostatic polypropylene	4	-	non-woven	KN95	no	$PM_{0.3}$ -95%	foam
J3	100% cotton old bedsheets	2	-	woven: 21*21	-	no	-	none
K3	100% cotton in and out	2	-	woven: 58x58 outer; 67x67 inner	-	no	-	inside wire
L2	100% polyester + filter	3	1	woven: 32x32 inner and outer	$PM_{2.5}$	no	$PM_{2.5}$<95%	none
M2	100% polyester	1	-	woven: 29x29		no	-	none
N2	50% bamboo, 50% polyamide	2	-	woven: 17x17 inner and outer	-	no	-	inside wire

pattern the mist takes to exit the perimeter seal of the masks. Additionally, the dimensions of each mask were measured.

Data management and analysis

A four-step process was performed to manage and analyse the resulting images. First, the images were processed with FFmpeg, an image processing open-source software. Specifically, background subtraction was performed with the full sequence of images (see Figures 6a and b). The method is a technique that detects moving elements between each consecutive image in the sequence in a static frame. As a result, the final footage only highlights the moving elements, which represent the mist escaped from the masks.

Secondly, the resulted sequence of images, without background were processed with Image Colour Summarizer v.0.77. The software creates descriptive statistics related to the colours of the image. Specifically, it clusters the colours of the image and provides a percentage of each colour. In this case, clustering was performed for two colours, that of the subtracted background and that of the mist. Mist percentages were calculated for each image taken every 10 s of the two minutes breathing experiment. Additionally, mist percentages were drawn for images between the 40th and 90th seconds.



(a) (b)

Figure 6. (a) Frame from the front view. (b) Frame from the side view.

Finally, the mean mist percentage and the sum of mist percentages for each mask were calculated for each run, based on the images between 40th and 90th second. To compare mist percentages for the different masks, the two runs per position, and for the different positions of the camera, independent t-testing and one-way ANOVA were used with SPSS version 26. The one-way ANOVA tests were performed on the means from the front leakage and the side leakage, to determine whether statistically significant differences existed between the percentage of mist leakage from masks between the 40th second and the 90th second of the experiments. The t-tests were performed to determine whether the means of the two tests in both test series for each mask could be considered to be the same. Logistic regression was also performed to examine possible associations between the mask variables with the masks' performance ranking. Additionally, qualitative descriptions of the mist distribution as well as the pattern of mist left behind inside the masks were made.

Results

Outward leakage

Figure 7 presents the percentage of mist over the full experiment for every 10 s. A graph was produced for each mask with the camera on the side of the manikin head (two times) and for each mask with the camera on the front of the manikin head (two times). Appendix A presents the pictures and the percentage of mist for images taken at second 40; 50; 60; 70; 80 and 90 for each mask tested on the side (twice) and in front (twice).

Pattern of mist in mask interior

The images taken from the patterns of mist deposited/filtered by the masks are presented in Figure 8. A picture of each mask while on the manikin's head together with the dimensions of the masks and a description of their fit can be found in Figure 9.

Statistical analysis

The means of the two tests performed for each mask in the period from the 40thto the 90th second were calculated for both the front and side test series. Figure 10 shows the mean percentage of mist for pictures taken between the 40th and the 90th second, for each mask tested on the side and in front (twice). Additionally, a qualitative description of the mist distribution is presented for the side and front tests, per mask. The results presented in Table 2, for both the front and side test series, show that except for 4 cases in the front series (D2, E3, F4, and N2) and 3 cases in the side series (B1, D2, and K3), the means of the two runs can be considered the same.

The results of the one-way ANOVA tests indicate statistical differences for all four series of tests and also for the means of both the front and the side tests. Then, the performance ranking of the masks was performed based on the mean values of the two series of tests (see Table 2).

T-testing was performed to determine whether the differences between the mean percentages of the mist of the masks were statistically different from each other for the front and the side series (Table 3). Based on the outcome, a new leakage performance ranking of masks was performed (Table 4). Logistic regression was performed to examine possible associations between the mask variables with the masks' performance ranking (Table 5).

Discussion

Quantitative comparison

Outward leakage of different masks

The mean outward leakage expressed in a percentage of mist varied from 3.9% (SD=0.4) to 20.0% (SD=4.5) in the front series, while in the side series from 3.8% (SD=0.5) to 25.4% (SD=1.2). The tests without masks resulted in respectively 36.7% (SD=1.3) and 6.4% (SD=1.0) for front and side tests.

The ranking of the mean outward leakage expressed in a percentage of mist was performed for both series of tests, which is shown in the last column of Table 2 for both the front series and the side series.

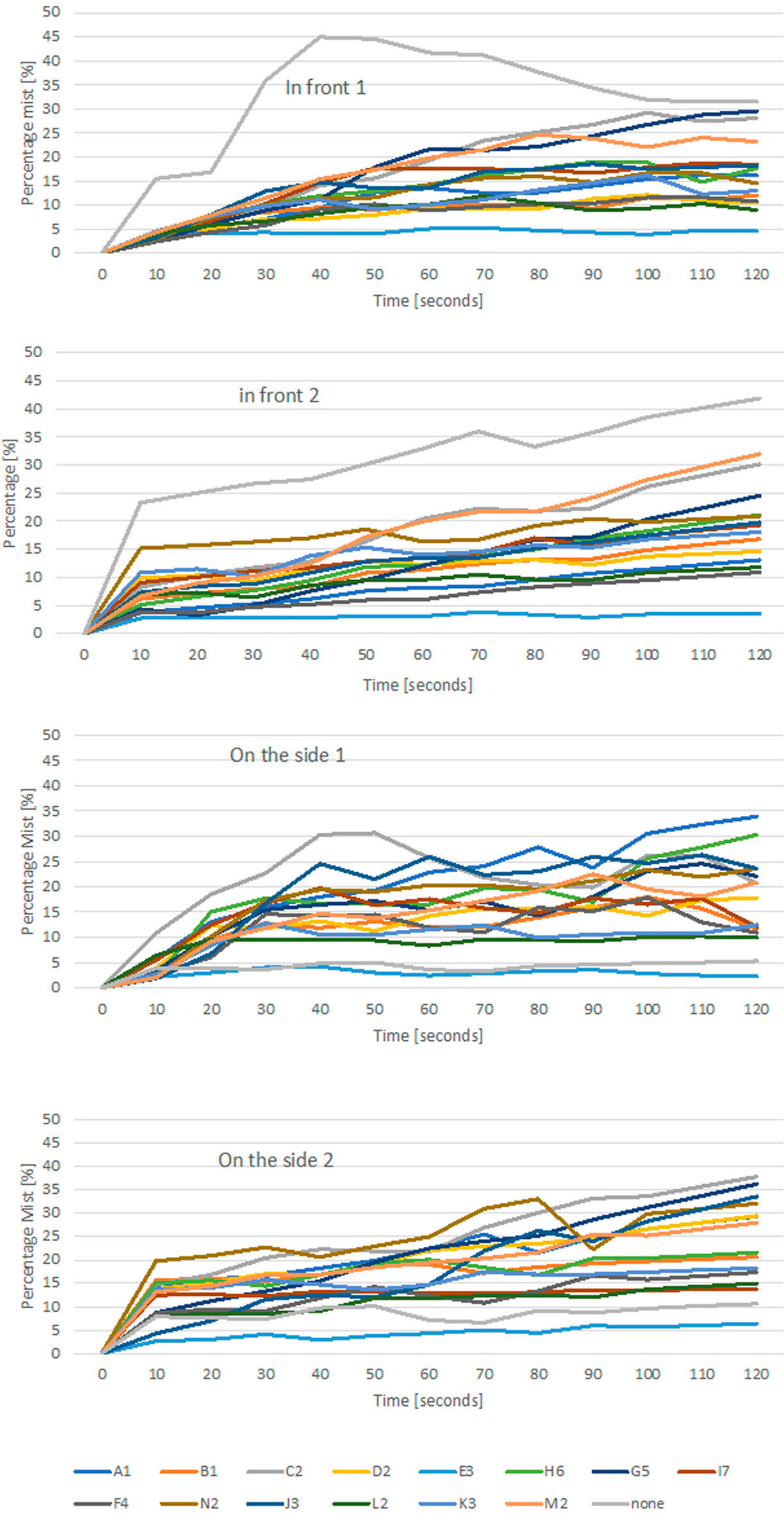


Figure 7. The percentage of mist over the full experiment for every 10 s an image per mask with the camera on the side of the manikin head (two times) and with the camera in front of the manikin head (two times).

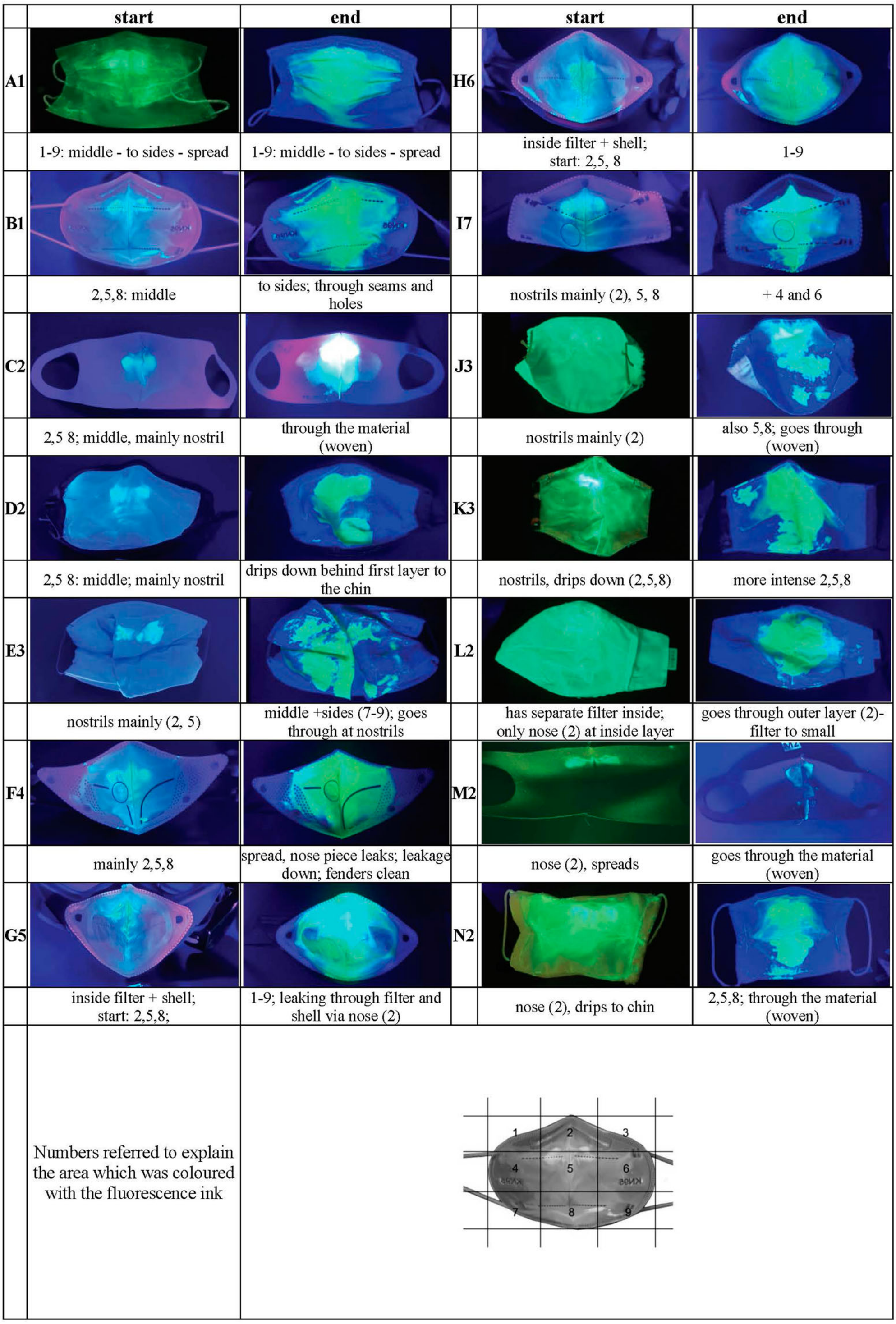


Figure 8. Fluorescence colouring inside the masks after the first and last series of tests, including a qualitative assessment of the colouring pattern.

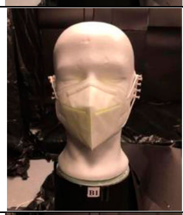
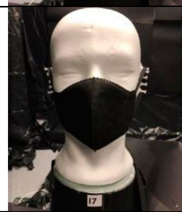
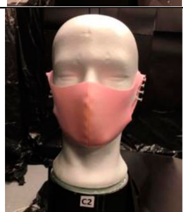
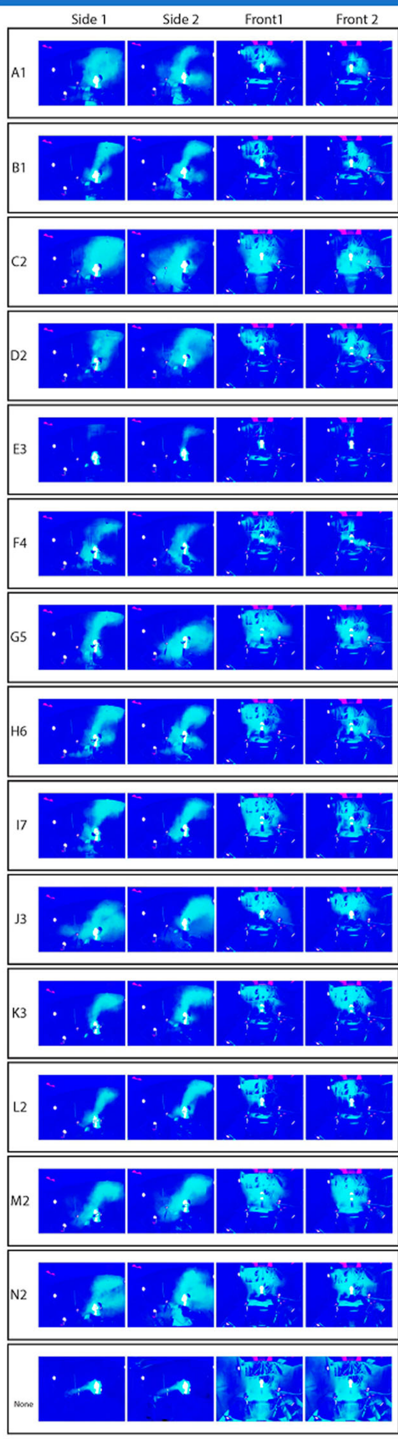
A1		Size: H=9.2cm; W=17.5cm H (opened) = 14cm Fit: loose- open on the sides Product: factory	H6		Size: H=15cm; W=26cm Fit: loose- open on the down side Product: factory
B1		Size: H=15.5cm; W=20cm Fit: tight Product: factory	I7		Size: H=14cm; W=20cm Fit: open on the top and down Product: factory
C2		Size: H=12.4cm; W=18cm Fit: loose - open on the top and sides Product: factory	J3		Size: H=18.5cm; W=23cm Fit: loose - open on the top and sides Product: handmade old RIVM guidelines
D2		Size: H=12cm; W=22cm H(opened)=17cm Fit: open on the sides Product: factory	K3		Size: H=14cm; W=23cm Fit: open on the sides Product: handmade
E3		Size: H=14cm; W=21cm Fit: tight Product: handmade CDC guidelines	L2		Size: H=14cm; W=24cm Fit: tight - open on the top Product: factory
F4		Size: H=14cm; W=24cm Fit: tight Product: factory	M2		Size: H=12cm; W=18cm Fit: loose - open on the top and sides Product: factory
G5		Size: H=14cm; W=26cm Fit: loose - open on the down side Product: factory	N2		Size: H=9cm; W=17cm H(opened)=14.5cm Fit: loose - open on the sides Product: factory

Figure 9. Tested masks on manikin head, dimensions and fit.

To determine whether this ranking was statistically relevant, t-testing was performed in which the mean outward leakage expressed in a percentage of mist between masks, was compared for the in front and the side series (Table 3).



Side series	Mask	Front series
mainly above and behind, front, down	A1	mainly above and right side
mainly above and behind, front, down	B1	mainly above and right side
above, front, behind, down (everywhere)	C2	above, left and right sides, down (everywhere)
above, front, behind	D2	above, sides
slightly above	E3	slightly above
above, front, down	F4	mainly above; right and left side
above, front, behind, down-difference in side 1 and 2	G5	above, left and right side, down (everywhere)
above, front, behind, down - difference in side 1 and 2	H6	above, left and right side, down (everywhere)
above, front, down	I7	above, left and right side, down (everywhere)
above, front, behind	J3	above, left and right side
above, little in front	K3	above, left and right side
above, little in front	L2	above
above, front, behind, down	M2	above, left and right side, down (everywhere)
above and back mainly, slightly front, down	N2	above, left and right side, down
Only in front	None	everywhere

Figure 10. Qualitative description of the visualization of the mean percentage of mist for pictures taken between the 40th and the 90th second, for each mask tested on the side (twice) and in front (twice).

Table 2. Means of percentages, sums (40-90 s) and t-tests.

mask	mean 1 (SD)	mean 2 (SD)	t-test$_{mean1-2}$ (p)[a]	mean$_{1-2}$ (SD)	mean$_{sum}$ (SD)	Leakage ranking
in front series						
A1	12.4 (1.6)	8.4 (1.6)	4.5 (0.0012)	10.5 (1.5)	62.8 (17.1)	4
B1	9.7 (0.4)	11.6 (1.8)	−2.4 (0.0503)	10.6 (1.0)	63.7 (8.0)	5
C2	20.8 (5.2)	19.3 (3.9)	0.5 (0.6071)	20.0 (4.5)	120.3 (6.0)	14
D2	9.0 (1.4)	12.5 (0.6)	−5.6 (**0.0008**)	10.8 (0.8)	64.6 (14.6)	6
E3	4.6 (0.5)	3.2 (0.4)	5.7 (**0.0003**)	3.9 (0.4)	23.4 (6.0)	1
F4	9.8 (0.6)	7.0 (1.5)	4.3 (**00035**)	8.4 (1.0)	50.1 (11.9)	2
G5	19.8 (4.7)	12.9 (3.9)	2.8 (0.0197)	16.4 (4.2)	98.1 (29.2)	12
H6	15.3 (2.8)	13.2 (2.6)	1.4 (0.2047)	14.3 (2.7)	85.5 (8.9)	8
I7	16.9 (1.1)	14.2 (1.9)	2.9 (0.0191)	15.6 (1.3)	93.3 (11.4)	10
J3	15.9 (2.1)	13.7 (1.9)	1.9 (0.0938)	14.8 (1.9)	88.6 (9.2)	9
K3	11.6 (2.0)	14.8 (0.8)	−3.7 (0.0102)	13.2 (1.2)	79.1 (13.8)	7
L2	9.8 (1.3)	9.6 (0.6)	0.5 (0.6234)	9.7 (1.0)	58.3 (1.3)	3
M2	20.4 (3.7)	19.5 (4.1)	0.4 (0.6953)	20.0 (3.8)	119.8 (3.9)	13
N2	13.9 (2.0)	18.1 (1.6)	−4.0 (**0.0030**)	16.0 (1.4)	95.6 (17.7)	11
F[b]	21.8 (**0.000**)	24.6 (**0.000**)		26.5 (**0.000**)	22.9 (**0.000**)	
none	40.8 (4.1)	32.6 (3.3)	−14.4 (0.005)	36.7 (1.3)	119.8 (3.9)	
on side series						
A1	22.7 (3.6)	22.0 (2.8)	0.3 (0.7454)	22.4 (2.9)	134.1 (2.6)	12
B1	13.2 (1.5)	18.3 (1.1)	−6.7 (**0.0001**)	15.7 (1.2)	94.4 (21.9)	6
C2	24.8 (4.9)	26.0 (4.8)	−0.4 (0.6772)	25.4 (1.2)	152.4 (5.1)	14
D2	14.4 (1.9)	21.5 (2.9)	−5.0 (**0.0008**)	18.0 (2.3)	107.8 (30.1)	7
E3	3.2 (0.6)	4.4 (1.0)	−2.4 (0.0463)	3.8 (0.5)	22.8 (4.8)	1
F4	13.8 (1.9)	13.2 (2.1)	0.5 (0.6032)	13.5 (1.8)	81.0 (2.6)	4
G5	16.4 (1.4)	22.5 (4.6)	−3.1 (0.0207)	19.5 (2.5)	116.8 (26.0)	10
H6	17.7 (1.5)	18.6 (1.6)	−1.1 (0.3189)	18.2 (0.8)	108.9 (3.9)	8
I7	17.0 (1.7)	13.2 (2.1)	5.4 (0.0029)	15.1 (0.9)	90.6 (16.2)	5
J3	23.9 (1.9)	18.6 (6.2)	2.0 (0.0910)	21.2 (3.3)	127.4 (22.7)	11
K3	10.9 (0.9)	15.7 (1.5)	−6.6 (**0.0002**)	13.3 (1.0)	79.9 (20.4)	3
L2	9.3 (0.5)	11.6 (1.3)	−4.1 (0.0062)	10.4 (0.6)	62.6 (9.7)	2
M2	17.1 (3.3)	20.4 (3.0)	−1.8 (0.1072)	18.8 (3.1)	112.5 (13.6)	9
N2	20.0 (0.8)	25.8 (5.1)	−2.8 (0.0387)	22.9 (2.5)	137.2 (24.6)	13
F[b]	53.8 (**0.000**)	20.0 (**0.000**)		47.7 (**0.000**)	47.7 (**0.000**)	
none	4.3 (0.7)	8.6 (1.4)	2.9 (0.017)	6.4 (1.0)	38.6 (18.2)	

[a]a negative value for the t-test means that the percentage of mist for the second series was less than for the first series. p is bold means statistically relevant difference for the two means with $p < 0.001$. [b]F-value from one-way ANOVA test.

For both the front and the side series, mask E3 performed the best, with the lowest outward leakage (respectively 3.9% (SD=0.4) and 3.8% (SD=0.5)). The worst performing mask in both series, mask C2 (respectively 20.0% (SD=4.5) and 25.4% (SD=1.2)), did not differ statistically with mask M2 (20.0% (SD=3.8)) in the front series, and with mask N2 of the side series (22.9% (SD=2.5)).

Additionally, in the front series, masks F4 and L2; as well as masks A1, B1 and D2; masks H6, J3 and I7; and masks N2 and G5, showed no statistical difference in mean values. In the side series, masks K3 and F4; masks I7 and B1; masks D2, H6, M2 and G5; and masks J3 and A showed no statistical difference in mean values.

Compared to ‘no mask’, only mask E3 is better performing in the side evaluation, while for the in-front evaluation, all masks are better than no mask. This outcome indicates that wearing a mask prevents exhaled breath to move in front, but can move the ‘aerosols’ to the side, back, down, and up, depending on the design of the mask.

Outward leakage and design variables

From the logistic regression, only the variable of fit (loose vs tight) showed to have a statistically significant association between masks ranked in the top half and the number of layers. Specifically, it shows what can be confirmed qualitatively, that a tight fit plays an important role in the good performance of the mask. In this study, only one of the top six ranked masks presented a loose fit (in the side test series).

In terms of fit test, according to AFNOR (AFNOR 2020), NEN (NEN 2020), and CEN (CEN 2020), consumers need to pay attention to the fit of the mask in their own face, by making sure that all the perimeter of the mask is in contact with the skin, leaving no gaps between.

Table 3. Comparison of percentage mist between different masks with t-test for in front and on side series.

	in front series												
mask	E3	F4	L2	A1	B1	D2	K3	H6	J3	I7	N2	G5	M2
F4	−10.3*	-											
L2	−15.9*	−1.8 (0.11)	-										
A1	−9.7*	−2.8*	−1.7 (0.13)	-									
B1	−16.1*	−3.3*	−1.9 (0.08)	0.5 (0.63)	-								
D2	−24.7*	−4.0*	−2.6*	0.5 (0.65)	−0.1 (0.92)	-							
K3	−18.8 (0.1)	−7.0*	−6.2*	−2.5*	−4.2*	−4.8*	-						
H6	−9.7*	−5.2*	−4.6*	−3.0*	−3.7 (0.01)	−3.8*	−1.5 (0.18)	-					
J3	−13.0*	−6.9*	−6.2*	−3.8*	−4.0*	−5.2*	−2.2 (0.06)	−0.3 (0.80)	-				
I7	−22.8*	−10.8 (0.11)	−10.4*	−5.5*	−8.3 (0.1)	−9.5*	−4.0*	−0.7 (0.48)	−0.5 (0.61)	-			
N2	−17.2*	−8.8 (0.82)	−8.2*	−4.8*	−6.6*	−7.2*	−3.1*	−0.6 (0.59)	−0.3 (0.75)	0.2 (0.84)	-		
G5	−7.1*	−4.5*	−4.1*	−3.2*	−3.6*	−3.6*	−2.3 (0.06)	−1.2 (0.26)	−1.1 (0.31)	−0.9 (0.40)	−1.0 (0.37)	-	
M2	−13.3*	−9.1 (0.62)	−8,59*	−6.8*	−7.8*	−7.9*	−5.7*	−3.5*	−3.6*	−3.7*	−3.6*	−1.4 (0.20)	-
C2	−10.2*	−7.2*	−6.7*	−5.5*	−6.1*	−6.2*	−4.6*	−3.0*	−3.1*	−3.0*	−3.0*	−1.3 (0.21)	−0.1 (0.89)
	on side series												
	E3	L2	K3	F4	I7	B1	D2	H6	M2	G5	J3	A1	N2
L2	−19.7*	-											
K3	−21.5*	−6.1*	-										
F4	−12.5 (0.09)	−3.9*	−0.2 (0.83)	-									
I7	−26.3 (0.19)	−10.2*	−3.3*	−1.9*	-								
B1	−22.8 (0.16)	−9.7 (0.82)	−3.9*	−2.5	−1.0 (0.33)	-							
D2	−14.6*	−7,.*	−4.6*	−3.7*	−2.8*	−2.1 (0.07)	-						
H6	−38.2 (0.40)	−18.9*	−9,67*	−5.7*	−6.3 (0.23)	−4.2*	−0.2 (0.85)	-					
M2	−11.6*	−6.4*	−4.1*	−3.6*	−2.8*	−2.2 (0.07)	−0.5 (0.63)	−0.5 (0.66)	-				
G5	−15.3*	−8.7*	−5.7*	−4.8	−4.1*	−3.4*	−1.1 (0.30)	−12 (0.26)	−0.4 (0.67)	-			
J3	−12.7*	−7.9*	−5.6*	−5.0*	−4.4*	−3.8*	−2.0 (0.08)	−2.2 (0.07)	−1.3 (0.21)	−1.1 (0.32)	-		
A1	−15.5*	−9.9*	−7.3*	−6.4*	−5.9*	−5.2*	−2.9*	−3.5*	−2.1 (0.06)	−1.9 (0.09)	−0.6 (0.55)	-	
N2	−18.0 (0.28)	−11.6*	−8.6*	−7.3*	−7.0*	−6,2*	−3.5*	−4.4*	−2.5*	−2.4 (0.04)	−1.0 (0.36)	−0.3 (0.75)	-
C2	−41.9 (0.29)	−27.7*	−19.8*	−13.5*	−17.1 (0.08)	−14.4*	−7.1*	−12.8*	−4.9*	−5.4*	−2.9*	−2.4*	−2.2 (0.06)

Note: The numbers are t-values from t-tests; a positive number means that the percentages mentioned in the first column is larger than in the first row, and vice versa. *statistically relevant for $p < 0.05$; p is noted between brackets when not statistically relevant.

Table 4. Performance ranking of masks based on comparison of mean mist percentage for in front and on side series.

	In front		On side	
rank	masks	% mist	masks	% mist
			none	6.4
1	E3	3.9	E3	3.8
2	F4 and L2	8.4-9.7	L2	10.4
3	A1, B1 and D2	10.5-10.8	K3 and F4	13.3-13.5
4	K3	13.2	I7 and B1	15.1-15.7
5	H6, J3 and I7	14.3-15.6	D2, H6, M2 and G5	18.0-19.5
6	N2 and G5	16.0-16.4	J3 and A1	21.2 - 22.4
7	C2 and M2	20.0	C2 and N2	22.9-25.4
	none	36.7		

Note: none, test without mask, was not included in the ranking.

Table 5. Univariate analysis of top half ranking and mask characteristics (on the side).

Mask characteristic	Top half n/N	Bottom half n/N	Exp(B) (95% CI)	*p*-value
Fenders vs no	1/6	3/8	0.33 (0.02-4.40)	0.404
Nose piece vs none	4/6	5/8	1.20 (0.13-11.05)	0.872
Layers two or less vs more than two	1/6	4/8	0.20 (0.02-2.57)	0.217
Filter vs no filter	2/6	5/8	3.33 (0.36-30.70)	0.288
Woven vs non-woven	3/6	5/8	0.60 (0.07-5.13)	0.641
Height above 14 cm vs smaller	6/6	4/8	-	0.999
Width above 20 cm vs smaller	6/6	4/8	-	0.999
Loose fit vs tight fit	1/6	6/8	0.06 (0.005-0.97)	**0.047**

p is bold means statistically relevant difference for $p < 0.05$.

SWiFt guidelines from Ireland (SWiFT 2020), claim that to ensure an optimal fit, visual fit tests should be conducted on a range of users (head size or age). Additionally, they encourage user tests to be conducted, in which the following attributes should be covered to have the best fit over time: elastic and head harness adequate length and materials, strong attachment of head harness parts, comfortable seams, and stitching across nose and sides, comfortable nose piece, breathing comfort and moisture issues.

In terms of visual inspections, standardization guidelines across different countries (AFNOR 2020; NEN 2020; CEN 2020) suggest that manufacturers carry out a visual inspection of masks to ensure their compliance. These inspections need to ensure that the materials present no defects, such as tears, detachments, looser fit, deformation, or wear of materials. It is also recommended that, in the case of reusable masks, consumers conduct the same inspection after each wash.

More recently, the ASTM has published a face mask covering standard, which specifies a standardized method and performance criteria in terms of the breathability, leakage around the edges, and reusability of face masks (ASTM-2021).

Qualitative comparison

Patterns and mist distribution

From the coloured patterns and the mean images presented in Figures 8 and 9, respectively, a qualitative assessment was performed.

Figure 8 shows that the test with mask E3 did not produce a lot of mist in both the front and the side test. The second best was mask L2, showing mainly mist above the mannikin head. Colouring inside these two masks at the start (see Figure 8) was mostly focused on the nostrils area and not in the entire mask, but at the end of the tests, the colouring patterns increased inside the mask and the coloured mist went through the outer layers in both of them.

Compared to masks E3 and L2, masks D2, F4, K3, B1, and A1 produced more mist in the environment from two sides (see Figure 10) and their amount of mist production is like each other. Colouring inside these masks F4, K3, B1, and A1at the start was not only focused on the nostrils part (part 2 based on Figure 8) but also spread inside them. In the end, the colouring patterns were completely scattered. Colouring inside mask D2 differed most, it started in section 2 and at the end, the colouring didn't spread but dripped down.

For Figure 10, masks C2, G5, H6, N2, M2, I7, and J3 produced high amounts of mist on the sides and showed the most leakage. Additionally, based on Figure 8, the distribution of the coloured mist inside these masks was different. At the start, colouring inside masks G5 and H6 was scattered, as opposed to the colouring in masks C2, M2, I7, N2 and J3, which was focused on the nostrils area. At the end, colouring patterns were scattered in masks G5, H6 (from part 1-9) and I7 but in masks C2, N2, M2 and J3 colouring was mostly seen in the middle. Moreover, the coloured mist went through the outer layers of masks C2, G5, N2, M2 and J3.

Outward leakage and design of masks

In terms of qualitative observations, outward leakage through the face seal perimeter seems to be highly dependent on the fit of the mask around the nose of the manikin (achieved by a nose piece), and by the fit against the cheeks of the manikin, achieved by several characteristics, including, the size of the mask and its shape (flat, sewn) (Figure 8). A poor nose fit will eject mist upwards while a poor cheek fit will do so from the side. However, such characteristics are not essential in masks, for example, L2 and E3 are two of the best performers, yet do not present any nose pieces. The number of layers seems to play a greater role in the leakage, masks with fewer than two layers perform worse, as can be seen with the results of C2; M2; N2; and J3. Finally, masks with a central seam, as opposed to a single flat sheet, seem to provide a better fit around the face of a wearer.

Furthermore, outward leakage also depended on the material of the mask. Generally, woven materials allowed the mist to go through the material, while non-woven ones did not. This was seen in the masks C2 and M2, two of the worst performers, since they present an elastic material whose threads stretch when worn. Additionally, filters used in the masks of this study were always made of non-woven materials (KN95 or $PM_{2.5}$); therefore, filters should be a good addition to any mask, as seen with L2, a regular mask which performance seems to improve considerably due to the presence of the filter.

Currently, most standardization guidelines do not present outward leakage or fitting testing of masks. Most guidelines focus the performance suggestions on tests related to head harness stress tests (up to five times donning and doffing), filtering efficacy tests (following in their turn specific guidelines), and breathing resistance and air permeability test (to determine differential pressure and constant flow) (CEN 2020).

Therefore, the inclusion of perimeter seal fit testing could be advantageous to further ensure the optimal performance of face masks for the public. Such testing could be limited to the observation of leakage through the nose bridge, cheeks, and chin with different head shapes, and sizes, to offer the better suiting mask to consumers.

Strength and limitations

Although the fit of a mask is considered to be an important feature of the mask to prevent outward leakage, no test yet has been recommended for this. The study presented in this article is a first attempt to provide a way of assessing masks on their outward leakage with the presented methodology, which could be considered a strength.

In this particular test, qualitative and quantitative assessments were used. This mixed-method analysis proves to be particularly useful in this study because they complement each other: the quantitative test was limited to two-dimensional footage of the front and side of a breathing manikin. Therefore, combining it with the qualitative observations of the patterns of mist along with the patterns on the inside of the mask, provide a more complete evaluation as from which routes (chin, nose, cheeks, or through material) the water mist escapes through the gaps of the face seal perimeter.

Tests were performed for two minutes to stabilize the production of mist while avoiding the condensation of mist inside the mask or the air tubes, which could be the case if the mist runs for longer periods.

One limitation mist leaking through the material of the mask itself, rather than around the face seal perimeter, was also visible with the technique used, both in the front and the side footage. However, it is not easy to distinguish how much of the mist was leaking through the material or around the face seal perimeter.

Another limitation of the present experiment is that the tests recorded from the front were performed on the same day, while those from the side were performed a week apart. The mist production rate of the fogging machine was not known. However, it is possible that discrepancies in the production changed from one use to the other.

Additionally, the fluorescent liquid used in this experiment does not have the same viscoelastic properties that expelled aerosol droplets have, which may change the amount of escaped mist. The amount of leaked mist may also be influenced by the laboratory settings of temperature of humidity, which were kept constant in the experiments of this study, however, further studies may be conducted with variations of humidity and temperature.

Furthermore, the data gathered is a two-dimensional representation of the mist in space. As a result, a missing element of the data is the concentration of that mist: some areas of mist may be of higher concentration than others.

Additionally, a further element that should be evaluated is the performance of masks over time. Although in the present study masks were used for four tests of two minutes each, and also for some extra tests in case of repetitions, they were not used for long enough, considering what several manufacturers claim their masks to be useful for. Homemade masks or non-filtered, layered, woven masks that tend to only absorb the mist (i.e. E3) may soak after a few hours of use.

Moreover, only one head type of Styrofoam material was used to test the masks. However, the market for face masks is universal and should thus be tested with different sizes and shapes of heads, representing different genders, ethnicities, and ages.

Finally, tests of actual comfort and ergonomics with real people should be performed, in order to compare results of the present tests with the preferences of different types of wearers, with glasses, smaller heads, etc. to assess not only the fit but comfort, breathability, and usability.

Conclusions

From the study presented here can be concluded that the use of mixed methods to assess the fit of the mask by visualizing the breath of a human with coloured water mist could be an adequate solution to incorporate as part of the testing and assessment of masks in guidelines for standardization.

Qualitative and quantitative methods complement each other: on the one hand, quantitative visualization of mist allows to measure the leaked amount of mist in a two-dimensional manner, both in terms of patterns created within the space around the wearer but also in terms of routes of escape. While the quantitative analysis complements the routes of escape of mist by inspecting the actual possible gaps in the face seal perimeter between the mask and the skin.

The results of the fourteen masks tested showed that tighter-fitting masks seem to perform better than loose ones. Tight-fitting masks can be achieved with the right size, shape, or nose clip. In the present study, only one head size was used, however, further studies are needed to generate a better fitting assessment. Nevertheless, the use of face masks, whatever their characteristics, seem an adequate strategy to reduce the amount dispersion of potential 'infected' aerosols into the space from people, as opposed to not wearing one. However, this dispersion while wearing a mask, is partly redistributing these exhaled aerosols into the space, mainly sideways, upwards, and downwards. These should be dealt with through appropriate ventilation strategies.

Acknowledgments

We thank the TU Delft University funding and Telecom Lifestyle Fashion BV for their financial contribution and Gerrit Feenstra from DNW for his support in creating the test set-up.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Dr. Marco A. Ortiz is a postdoctoral researcher in the Chair of Indoor Environment at the TU Delft. His main research focus is on the comfort behaviours of occupants and their effects on energy consumption. He earned his Ph.D. in the Faculty of Architecture and the Built Environment (2019) and holds an MSc in Industrial Design Engineering (2014) both from the TU Delft.

Marzieh Ghasemieshkaftaki is a Ph.D. student in the Faculty of Architecture and Built Environment at the TU Delft. She holds an MSc in Architecture from the Islamic Azad University, West Tehran Branch (2014). Her Master's and Ph.D. research focuses on the health and comfort of occupants in educational buildings.

Prof. dr. Philomena M. Bluyssen, initiator and creator of the SenseLab, was appointed full Professor Indoor Environment in 2012 at the Faculty of Architecture and the Built Environment of the Delft Technical

University of Technology, after working for more than 21 years for TNO, a research institute in the Netherlands. She holds a master's degree (building engineer) from the Technical University of Eindhoven (1987) and a Ph.D. from the Technical University of Denmark (1990). She has written more than 260 publications in (inter)national journals and conference proceedings. For the Indoor Environment Handbook: How to make buildings healthy and comfortable, she was awarded the Choice Outstanding Academic Titles of 2010 Award. Her book titled 'The Healthy Indoor Environment – How to assess occupants' wellbeing in buildings', published by Taylor & Francis in 2014, was awarded the Interior Design Educators Council 2016 book award.

ORCID

Marco A. Ortiz http://orcid.org/0000-0002-9087-9666
Philomena M. Bluyssen http://orcid.org/0000-0002-5732-5362

References

AFNOR. 2020. "SPEC S76-001." *Barrier Masks: Guide To Minimum Requirements, Methods Of Testing, Making, and Use*.

Ai, Z. T., and Arsen Krikor Melikov. 2018. "Airborne Spread of Expiratory Droplet Nuclei Between the Occupants of Indoor Environments: A Review." *Indoor Air* 28 (4): 500–524.

Akhtar, Javed, Abner Luna Garcia, Leonardo Saenz, Sarada Kuravi, Fangjun Shu, and Krishna Kota. 2020. "Can Face Masks Offer Protection from Airborne Sneeze and Cough Droplets in Close-up, Face-to-Face Human Interactions?—A Quantitative Study." *Physics of Fluids* 32 (12): 127112.

Allen, Joseph G., and Linsey C. Marr. 2020. "Recognizing and Controlling Airborne Transmission of SARS-CoV-2 in Indoor Environments." *Indoor Air* 30 (4): 557–558. doi:10.1111/ina.12697.

Asadi, Sima, Nicole Bouvier, Anthony S. Wexler, and William D. Ristenpart. 2020. "The Coronavirus Pandemic and Aerosols: Does COVID-19 Transmit via Expiratory Particles?" *Aerosol Science and Technology* 54 (6): 635–638. doi:10.1080/02786826.2020.1749229.

Asadi, Sima, Christopher D Cappa, Santiago Barreda, Anthony S Wexler, Nicole M Bouvier, and William D Ristenpart. 2020. "Efficacy of Masks and Face Coverings in Controlling Outward Aerosol Particle Emission from Expiratory Activities." *Scientific Reports* 10 (1): 1–13.

ASHRAE. 2020. "Position Document on Infectious Aerosols." ASHRAE Accessed April 14, 2020. https://www.ashrae.org/file%20library/about/position%20documents/pd_infectiousaerosols_2020.pdf.

ASTM. 2021. "F3502-21: Standard Specification for Barrier Face Coverings." In. West Conshohocken, PA: ASTM International.

Barrett, Kim E, Susan Barman, Jason Yuan, and Heddwen Brooks. 2019. *Ganong's Review of Medical Physiology, Twenty Sixth Edition*, edited by Michael Weltz and Peter J. Boyle. Vol. 26: McGraw-Hill Education, New York, USA.

Bhat, Pradeep P, Santosh Appathurai, Michael T Harris, Matteo Pasquali, Gareth H McKinley, and Osman A Basaran. 2010. "Formation of Beads-on-a-String Structures During Break-up of Viscoelastic Filaments." *Nature Physics* 6 (8): 625–631.

Bluyssen, Philomena M, Marco Ortiz, and Dadi Zhang. 2021. "The Effect of a Mobile HEPA Filter System on 'Infectious' Aerosols, Sound and air Velocity in the SenseLab." *Building and Environment* 188: 107475.

Bluyssen, Philomena M, Freek van Zeist, Stanley Kurvers, Martin Tenpierik, Sylvia Pont, Bart Wolters, Luuk van Hulst, and Darell Meertins. 2018. "The Creation of SenseLab: a Laboratory for Testing and Experiencing Single and Combinations of Indoor Environmental Conditions." *Intelligent Buildings International* 10 (1): 5–18.

Brooks, John T, Donald H Beezhold, John D Noti, Jayme P Coyle, Raymond C Derk, Francoise M Blachere, and William G Lindsley. 2021. "Maximizing fit for Cloth and Medical Procedure Masks to Improve Performance and Reduce SARS-CoV-2 Transmission and Exposure, 2021." *Morbidity and Mortality Weekly Report* 70 (7): 254.

Buonanno, Giorgio, Lidia Morawska, and Luca Stabile. 2020. "Quantitative Assessment of the Risk of Airborne Transmission of SARS-CoV-2 Infection: Prospective and Retrospective Applications." *Environment International* 145: 106112.

CDC, Center for Disease Control Prevention. 2020. "Considerations for Wearing Masks.".

CEN. 2020. "Community Face Coverings-Guide to Minimum Requirements, Methods of Testing and Use." In. Management Centre, Brussels, Belgium: CEN-CENELEC.

Chao, Christopher Yu Hang, M. P. Wan, and G. N. Sze To. 2008. "Transport and Removal of Expiratory Droplets in Hospital Ward Environment." *Aerosol Science and Technology* 42 (5): 377–394.

Chen, Wenzhao, Nan Zhang, Jianjian Wei, Hui-Ling Yen, and Yuguo Li. 2020. "Short-range Airborne Route Dominates Exposure of Respiratory Infection During Close Contact." *Building and Environment* 176: 106859.

Chu, Derek K., Elie A. Akl, Stephanie Duda, Karla Solo, Sally Yaacoub, Holger J. Schünemann, Derek K. Chu, et al. 2020. "Physical Distancing, Face Masks, and eye Protection to Prevent Person-to-Person Transmission of SARS-CoV-2 and COVID-19: a Systematic Review and Meta-Analysis." *The Lancet* 395 (10242): 1973–1987. doi:10.1016/s0140-6736(20)31142-9.

Fischer, Emma P, Martin C Fischer, David Grass, Isaac Henrion, Warren S Warren, and Eric Westman. 2020. "Low-cost Measurement of Face Mask Efficacy for Filtering Expelled Droplets During Speech." *Science Advances* 6 (36): eabd3083.

Howard, Jeremy, Austin Huang, Zhiyuan Li, Zeynep Tufekci, Vladimir Zdimal, Helene-Mari van der Westhuizen, Arne von Delft, Amy Price, Lex Fridman, and Lei-Han Tang. 2021. "An Evidence Review of Face Masks Against COVID-19." *Proceedings of the National Academy of Sciences* 118 (4):e2014564118.).

Konda, Abhiteja, Abhinav Prakash, Gregory A Moss, Michael Schmoldt, Gregory D Grant, and Supratik Guha. 2020. "Aerosol Filtration Efficiency of Common Fabrics Used in Respiratory Cloth Masks." *ACS Nano* 14 (5): 6339–6347.

Leung, Nancy HL, Daniel KW Chu, Eunice YC Shiu, Kwok-Hung Chan, James J McDevitt, Benien JP Hau, Hui-Ling Yen, Yuguo Li, Dennis KM Ip, and J. S. Malik Peiris. 2020. "Respiratory Virus Shedding in Exhaled Breath and Efficacy of Face Masks." *Nature Medicine* 26 (5): 676–680.

Lim, S., H. I. Yoon, K. H. Song, E. S. Kim, and H. B. Kim. 2020. "Face Masks and Containment of COVID-19: Experience from South Korea." *The Journal of Hospital Infection* 106 (1): 206.

MacIntyre, C. Raina, and Abrar Ahmad Chughtai. 2020. "A Rapid Systematic Review of the Efficacy of Face Masks and Respirators Against Coronaviruses and Other Respiratory Transmissible Viruses for the Community, Healthcare Workers and Sick Patients." *International Journal of Nursing Studies* 108: 103629. doi:10.1016/j.ijnurstu.2020.103629.

Martin, Stephen B, Chuck Dunn, James D Freihaut, William P Bahnfleth, Josephine Lau, and Ana Nedeljkovic-Davidovic. 2008. "Ultraviolet Germicidal Irradiation: Current Best Practices." *Ashrae Journal* 50 (8): 28.

Mitze, Timo, Reinhold Kosfeld, Johannes Rode, and Klaus Wälde. 2020. "Face Masks Considerably Reduce COVID-19 Cases in Germany." *Proceedings of the National Academy of Sciences* 117 (51): 32293–32301.

Morawska, L. J. G. R., G. R. Johnson, Z. D. Ristovski, Megan Hargreaves, Kerrie Mengersen, Shay Corbett, C Yu Hang Chao, Yuguo Li, and David Katoshevski. 2009. "Size Distribution and Sites of Origin of Droplets Expelled from the Human Respiratory Tract During Expiratory Activities." *Journal of Aerosol Science* 40 (3): 256–269.

Morawska, Lidia, Julian W. Tang, William Bahnfleth, Philomena M. Bluyssen, Atze Boerstra, Giorgio Buonanno, Junji Cao, et al. 2020. "How Can Airborne Transmission of COVID-19 Indoors be Minimised?" *Environment International* 142: 105832. doi:10.1016/j.envint.2020.105832.

NEN. 2020. "SPEC 1-2:2020 versie 1." *Mondkapjes voor publiek gebruik deel 2 – Eisen voor fabrikanten en importeurs in het kader van COVID-19.*

NSAI. 2020. SWiFT 19. 2020. "Barrier Masks for Consumers - Requirements." In. Dublin, Ireland: NSAI Standards.

Pan, Jin, Charbel Harb, Weinan Leng, and Linsey C Marr. 2021. "Inward and Outward Effectiveness of Cloth Masks, a Surgical Mask, and a Face Shield." *Aerosol Science and Technology 55(6)*, 1–17.

Prather, Kimberly A, Linsey C Marr, Robert T Schooley, Melissa A McDiarmid, Mary E Wilson, and Donald K Milton. 2020. "Airborne Transmission of SARS-CoV-2." *Science* 370 (6514): 303–304.

REHVA. 2020, April 3. "REHVA (2020) COVID-19 Guidance Document." REHVA. https://www.rehva.eu/activities/covid-19-guidance.

Sickbert-Bennett, Emily E, James M Samet, Phillip W Clapp, Hao Chen, Jon Berntsen, Kirby L Zeman, Haiyan Tong, David J Weber, and William D Bennett. 2020. "Filtration Efficiency of Hospital Face Mask Alternatives Available for use During the COVID-19 Pandemic." *JAMA Internal Medicine* 180 (12): 1607–1612.

Stadnytskyi, Valentyn, Christina E Bax, Adriaan Bax, and Philip Anfinrud. 2020. "The Airborne Lifetime of Small Speech Droplets and Their Potential Importance in SARS-CoV-2 Transmission." *Proceedings of the National Academy of Sciences* 117 (22): 11875–11877.

Su, Vincent Yi-Fong, Yung-Feng Yen, Kuang-Yao Yang, Wei-Juin Su, Kun-Ta Chou, Yuh-Min Chen, and Diahn-Warng Perng. 2020. "Masks and Medical Care: two Keys to Taiwan's Success in Preventing COVID-19 Spread." *Travel Medicine and Infectious Disease, N*ov-Dec 2020;38:101780.

Tang, Julian W, Thomas J Liebner, Brent A Craven, and Gary S Settles. 2009. "A Schlieren Optical Study of the Human Cough with and Without Wearing Masks for Aerosol Infection Control." *Journal of the Royal Society Interface* 6 (suppl_6): S727–SS36.

Tcharkhtchi, Abbas, Navideh Abbasnezhad, M. Zarbini Seydani, Nader Zirak, Sedigheh Farzaneh, and Mohammadali Shirinbayan. 2021. "An Overview of Filtration Efficiency Through the Masks: Mechanisms of the Aerosols Penetration." *Bioactive Materials* 6 (1): 106–122.

Van Dyke, Miriam E, Tia M Rogers, Eric Pevzner, Catherine L Satterwhite, Hina B Shah, Wyatt J Beckman, Farah Ahmed, D. Charles Hunt, and John Rule. 2020. "Trends in County-Level COVID-19 Incidence in Counties with and Without a Mask Mandate—Kansas, June 1–August 23, 2020." *Morbidity and Mortality Weekly Report* 69 (47): 1777.

Verma, Siddhartha, Manhar Dhanak, and John Frankenfield. 2020a. "Visualizing Droplet Dispersal for Face Shields and Masks with Exhalation Valves." *Physics of Fluids* 32 (9): 091701.

Verma, Siddhartha, Manhar Dhanak, and John Frankenfield. 2020b. "Visualizing the Effectiveness of Face Masks in Obstructing Respiratory Jets." *Physics of Fluids* 32 (6): 061708.

Wang, Dijia, Yanjun You, Xiaoli Zhou, Zhiyong Zong, Hao Huang, Hui Zhang, Xin Yong, Yifan Cheng, Liu Yang, and Qiong Guo. 2020. "Selection of Homemade Mask Materials for Preventing Transmission of COVID-19: a Laboratory Study." *PloS one* 15 (10): e0240285.

WHO. 2020. "Advice on the Use of Masks in the Context of COVID-19: Interim Guidance, 6 April 2020." In.: World Health Organization.

Wölfel, Roman, Victor M Corman, Wolfgang Guggemos, Michael Seilmaier, Sabine Zange, Marcel A Müller, Daniela Niemeyer, Terry C Jones, Patrick Vollmar, and Camilla Rothe. 2020. "Virological Assessment of Hospitalized Patients with COVID-2019." *Nature* 581 (7809): 465–469.

Yi, Byung-Ju, and Hyun-Soo Yoon. 2016. "Review of Computer-Aided Sinus Surgery." *Hanyang Medical Reviews* 36 (4): 248–253.