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Impact of medical face mask wear on bacterial filtration efficiency and breathability

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ABSTRACT

Wearing a medical mask for longer than the manufacturer's recommended 4 h would reduce the number of masks used and limit their environmental impact. The objective of this study was to determine if a medical mask could be worn for an extended period of time by simulating different wearing conditions. A simulator was developed to reproducibly study various experimental conditions (wearing time, breathing pattern, mask fit, inhaled air humidity) by placing the masks on a 3D replica of the upper airways connected to a respiratory pump. Medical mask performance was determined by assessing normative requirements: bacterial filtration and breathability. No impact on performance was observed for wearing times from 2 h to 8 h. Similarly, when simulating moderate respiratory effort or at rest, various humidity levels in the inhaled air or different fitting conditions, no influence on performance was found. These results imply that none of these experimental conditions appear to have a significant impact on mask performance. In conclusion some medical masks can be used for up to 8 h under different wearing conditions without significant decrease in their bacterial filtration and breathability performance. This recommendation of a possible rise of usage duration would limit mask waste, and thus environmental consequence.

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1. Introduction

Face masks should be used as part of a comprehensive prevention strategy to limit airborne virus transmission. In the context of the Coronavirus disease 2019 (COVID-19) pandemic, wearing a face mask was one of the most widespread barrier measures. Depending on the epidemic level of contaminations, it has been most of the time mandatory in indoors and outdoors public places in many countries around the world (Ministère des Solidarités et de la Santé, 2020; Centers

Abbreviations: BFE, Bacterial Filtration Efficiency; CFU, Colony Forming Units; DP, Differential Pressure; MPPS, Most Penetrating Particle Size; PP, Polypropylene; SD, Standard Deviation; SMS, Spunbound, Meltblown, Spunbound

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for Disease Control and Prevention, 2020; Anon, 2020; Commonwealth of Massachusetts, 2020). Indeed, even if wearing a face mask alone is not sufficient to provide an absolute level of protection against COVID-19, it is now considered as a highly effective measure in addition to vaccination, physical distancing, keeping rooms well ventilated and disinfecting hands and surfaces (European Center for Disease prevention and Control (ECDC), 2020). Wearing a face mask becomes a normal part of being around other people in case of respiratory disease pandemic. Thus, the appropriate use, storage and cleaning or disposal of masks are essential to make them as effective as possible.

Medical face masks are medical devices that are subject to specific requirements set by standards. In Europe, the performance requirements are described in the AFNOR NF EN 14683:2019 (BSI Standards Publication, 2019) norm. In addition to a maximum bioburden to be respected, medical masks must reach limit values corresponding to a minimum bacterial filtration efficiency (BFE) of 95 or 98%, and a maximum differential pressure (DP, defining the breathability) of 40 or 60 Pa cm⁻² (BSI Standards Publication, 2019). Indeed, based on their BFE and DP values, medical face masks can be classified into 3 categories:

- Type I masks (BFE \geq 95% and a DP \leq 40 Pa cm⁻²),
- Type II masks (BFE \geq 98% and a DP \leq 40 Pa cm⁻²),
- Type IIR masks, (BFE \geq 98% and a DP \leq 60 Pa cm⁻²) including specific requirements for splash resistance.

Type IIR and Type II masks, being the most effective in term of bacterial filtration, are used by health care workers (compared to type I masks). They were also widely used during the covid-19 epidemic. For these reasons, this study focuses on type IIR mask.

The SARS-CoV-2 virus, whose diameter has been reported within 60–150 nm (Park et al., 2019; Kim et al., 2020; Ren et al., 2020; Zhu et al., 2020), is emitted in respiratory droplets during expiration while breathing, talking, sneezing and coughing. As the airborne particles persist in the air, their size varies strongly, depending on environmental conditions. However, the aerosol size distributions can be assumed as mainly smaller than 5 μ m (Johnson et al., 2011; Asadi et al., 2019; Morawska et al., 2019).

In order to limit the airborne virus transmission, medical face masks were recommended to the whole population which rapidly led to a global shortage of medical face masks during the earlier months of the COVID-19 pandemic. In addition to the tension on supply, these single-use disposable masks induce a serious consequence on the environment adding to the already existing issue of micro plastic pollution in marine and land environments (Asim et al., 2021; Du et al., 2022; Ray et al., 2022). Indeed, it is estimated that the waste generated from medical face masks in Asia is more than 16 000 tons per day (Sangkham, 2020). Alternative solutions that could help to minimize supply tension and environmental implications of the increased use of medical face masks include: (i) substituting the medical face mask (which contains polypropylene) by reusable cloth masks which are more eco-friendly but tend to have lower performances notably in term of filtration efficiency and/or breathability (Wilson et al., 2021; Morais et al., 2021), (ii) reusing medical face masks after a decontamination step (Alcaraz et al., 2022; Charvet et al., 2022) and (iii) increasing the duration of wearing of medical masks while respecting a single use.

In the early months of the COVID-19 pandemic, the World Health Organization (WHO) recommended mask to be worn for a maximum of 4 h (World Health Organisation, 2020). This was based in particular on a study performed by Radonovich et al. (2009) showing that after 4 h, the acceptability and tolerance of the mask by healthcare personnel begins to decrease. In some countries, the recommendation to wear a mask for an extended period of time could have been a solution to limit medical mask shortages. However, there is a lack of scientific evidence on the effect of increased wearing time on mask standard performances such as BFE and breathability.

Li et al. (2022), using polydispersed salt composition, found that at two breathing volumes of 15 L min⁻¹ and 30 L min⁻¹, a medical face mask was able to maintain its filtration efficiency up to 8 h for particles sizes ranging from 0.3 to 10 μ m. Varanges et al. (2022) also studied the effect of contact with body fluids (sweat and saliva) during the extended use of medical face masks. They concluded that after 8 h, saliva and sweat had minor implications on the particle filtration efficiency of medical face masks. These authors however did not study the influence of other parameters such as mask fit, gas humidification and breathing patterns on the BFE and breathability of the medical face masks.

Therefore, this study focuses on the extended duration of wearing medical face masks with the aim of evaluating the effect of the other parameters mentioned above on the bacterial filtration efficiency and breathability of a type IIR mask. This work focuses only on two main standard requirements according to NF EN 14683:2019: BFE (indicating the filtering capacity of the mask material) and DP (indicating the breathability of the masks material).

2. Materials and methods

2.1. Material

The masks used in this study were Type IIR medical face masks produced by the BioSerenity company (France) (SKU: 1016-07007-EU). The masks were comprised of non-woven polypropylene SMS (Spunbound, Meltblown, Spunbound) fibers.

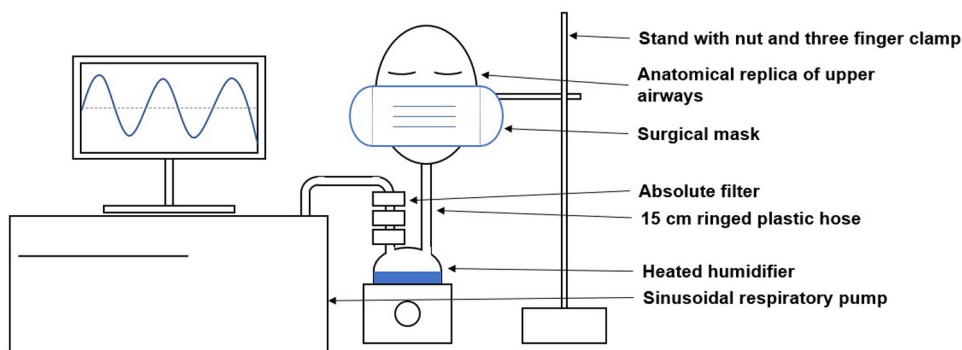


Fig. 1. Scheme of the mask-wearing simulator.

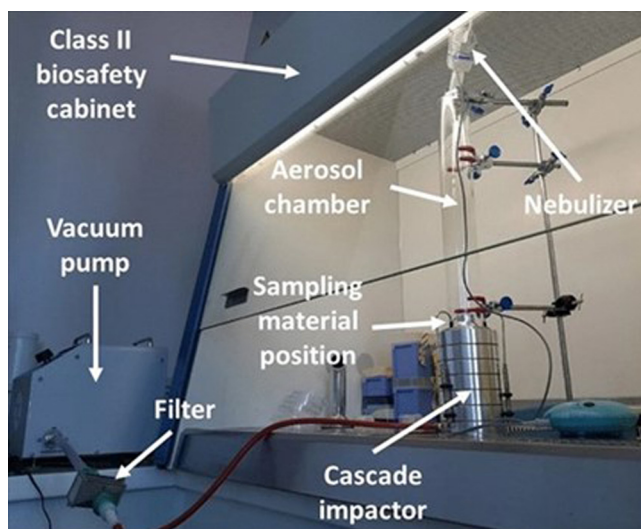


Fig. 2. Experimental set-up for the evaluation of the BFE compliant with the EN14683:2019 standard test method (30) (Whyte et al., 2022a).

2.2. Mask-wearing simulator

To simulate wearing of the mask, a previously validated anatomical replica of adult upper airways was used (Durand et al., 2011; Montigaud et al., 2019). The mask was applied directly to this mannequin head so as to cover the nose and the mouth, and the elastic band was fixed by a knot at the back of the mannequin head. The mannequin head was connected to a 15 cm ringed pipe representing the trachea and then to a medical heated humidifier. The humidifier (Fisher&Paykel MR410) was connected to a sinusoidal respiratory pump (Pari Compas II, Pari GmbH, Starnberg, Germany). The action of the sinusoidal respiratory pump varied according to several parameters such as the mobilized tidal volume, the duration of exhalation and inhalation and the number of respiratory cycles. The schematic representation is displayed in Fig. 1. A pictorial representation is also presented in Supplementary Fig. S1.

2.3. Bacterial Filtration Efficiency (BFE)

The evaluation of BFE was performed according to the NF EN 14683:2019 standard (6) using an experimental procedure previously validated (Pourchez et al., 2021; Alcaraz et al., 2022; Whyte et al., 2022a). The experimental set-up is presented in Fig. 1. An aerosol stream containing a known concentration of *Staphylococcus aureus* ATCC 29213 was generated using a vibrating mesh nebulizer (E-flow, Pari GmbH, Starnberg, Germany) (Fig. 2).

The generated aerosol was drawn through a glass aerosol chamber by a vacuum pump. The mask samples were clamped between the aerosol chamber and a six stage Andersen viable Cascade Impactor.

The tests were performed by putting the interior of the mask in contact with the aerosolized bacteria. Each sample was conditioned at 21 ± 5 °C and $85 \pm 5\%$ relative humidity for at least 4 h to reach atmospheric equilibrium prior to testing in compliance with EN14683:2019. To evaluate the BFE of a mask, at least 5 distinct samples were submitted to the test, consisting of a series of eight successive measurements.

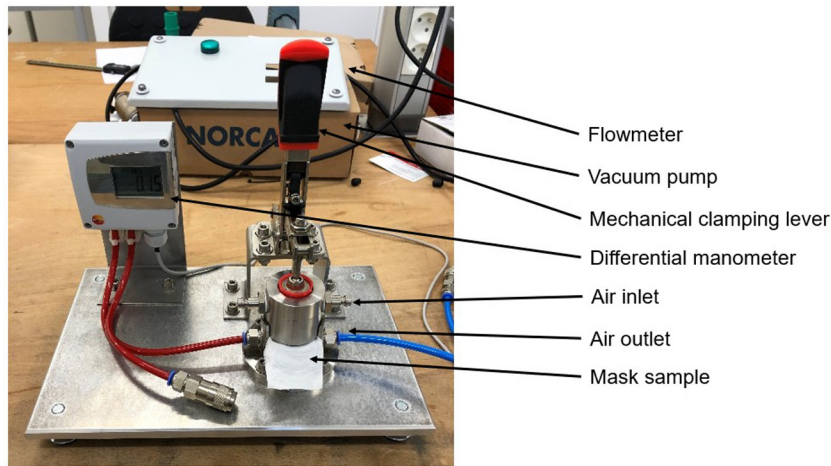


Fig. 3. Experimental set-up for the evaluation of the DP compliant with the EN14683:2019 standard test method.

The Petri dishes obtained were incubated at $37 \pm 2^\circ\text{C}$ for 22 ± 2 h. The Colony Forming Units (CFU) were counted with an automatic colony counter Scan 4000 (Interscience). The results obtained were expressed in both CFU and in BFE. The BFE was calculated as:

$$BFE = \frac{C - T}{C \times 100} \quad (1)$$

where C is the mean of the two positive runs of the total CFU of the six plate counts, and T is the total CFU of the six plate counts for each test sample. For each series of 5 masks analyzed for BFE, the BFE class of a mask was determined by the lowest BFE obtained within the 5 samples tested.

2.4. Differential pressure

The test for the breathing resistance was performed according to the NF EN 14683:2019 standard procedure. The experimental set-up is presented in Fig. 3. The differential pressure was obtained and expressed in Pa cm^{-2} . The differential pressure drop across the mask material was then used as an indicator of breathing resistance. A negative-control run was performed to make sure there was no air leakage in the device and that the air flow was the same at the inlet and outlet, without any mask.

2.5. Experimental design to simulate the impact of wearing parameters on mask performances

In order to evaluate the influence of wearing time, the masks were set on the replica and breathing was simulated for 2, 4 and 8 h. The influence of the mask fit was simulated by taping the sides of the mask on the anatomical replica of upper airways to prevent air leakage. The masks were also tested without air humidification in order to evaluate the influence of humidification on mask performances. Finally, the tidal volume was increased while the respiratory (exhalation and inhalation) times were decreased to determine the influence of breathing pattern. The two different breathing pattern simulated light activities (tidal volume of 500 mL, 2 s of inhalation, 3 s of exhalation) and moderate activities (tidal volume of 900 mL, 1.2 s of inhalation, 1.8 s of exhalation). These parameters (tidal volume, duration of the respiratory cycle, etc.) were modeled on physiological respiratory parameters (Cordier and Brune, 1988; Guyton et al., 2015). A brand-new unworn mask was used as a reference. The experimental design is summarized in Table 1.

2.6. Statistical analysis

Statistical analyses were performed with GraphPad Prism 9 (Dotmatics, USA). The parameters were compared to the reference values using a Kruskal–Wallis test with confidence interval at 95%. For a difference to be significant, the p value of the test should be inferior to 0.05. Results are expressed as mean with standard deviations (SD) for differential pressure. For the BFE, results are expressed in: total number of CFU obtained for each series of 5 masks, the lowest BFE obtained for each series, and the mean with SD of the five BFE value obtained for each mask in a series. Statistical analysis is performed using all BFE values and the SD.

Table 1

Experimental design to simulate the impact of wearing parameters on mask performances (impact of wearing time: condition 1 vs. condition 2 vs. condition 3; impact of breathing pattern: condition 2 vs. condition 4; impact of air humidification: condition 2 vs. condition 5; impact of mask fit: condition 2 vs. condition 6). The reference masks did not undergo the wearing simulation, hence the “N/A”. Each condition was compared to reference masks.

Experimental simulation of wearing	Wearing time	Air humidification	Mask fit	Breathing pattern		
				Tidal volume	Inhalation time	Exhalation time
Reference: new unworn mask	0h	N/A	N/A	N/A	N/A	N/A
Condition 1 (2 h-wear)	2 h	Yes	Loose	500 mL	2 s	3 s
Condition 2 (4 h-wear)	4 h	Yes	Loose	500 mL	2 s	3 s
Condition 3 (8 h-wear)	8 h	Yes	Loose	500 mL	2 s	3 s
Condition 4 (4 h-wear + effort)	4 h	Yes	Loose	900 mL	1.2 s	1.8 s
Condition 5 (4 h-wear W/O humidification)	4 h	No	Loose	500 mL	2 s	3 s
Condition 6 (4 h-wear with sealed fit)	4 h	Yes	Tight	500 mL	2 s	3 s

Table 2

Bacterial filtration efficiency according to the different experimental conditions. No statistical difference was observed between all these experimental conditions. The minimum BFE is the value that is considered from a quality assurance point of view in relation to the regulatory test.

Experimental simulation of wearing	5 tested Masks per series					Average \pm SD	Minimal BFE
	A	B	C	D	E		
Reference: new unworn mask	99.95%	100.0%	100.0%	100.0%	100.0%	99.99 \pm 0.02%	99.95%
Condition 1 (2 h-wear)	100.0%	100.0%	100.0%	100.0%	100.0%	100.0 \pm 0.0%	100.0%
Condition 2 (4 h-wear)	100.0%	99.97%	100.0%	100.0%	100.0%	99.99 \pm 0.02%	99.97%
Condition 3 (8 h-wear)	100.0%	100.0%	99.92%	99.96%	100.0%	99.98 \pm 0.04%	99.92%
Condition 4 (4 h-wear + effort)	100.0%	100.0%	100.0%	100.0%	100.0%	100.0 \pm 0.0%	100.0%
Condition 5 (4 h-wear W/O humidification)	100.0%	100.0%	100.0%	100.0%	100.0%	100.0 \pm 0.0%	100.0%
Condition 6 (4 h-wear with sealed fit)	100.0%	100.0%	100.0%	100.0%	100.0%	100.0 \pm 0.0%	100.0%

3. Results

3.1. Breathability

Impact of the wearing parameters on the breathability are presented in Fig. 4. All the masks were compliant to the breathability requirement ($DP \leq 60 \text{ Pa cm}^{-2}$) of a type IIR mask according to NF EN 14683:2019. A DP of 0 Pa cm^{-2} was obtained for the negative control run. The reference unworn mask recorded an average DP of 32.1 Pa cm^{-2} .

DP results for 3 different wearing times (2 h, 4 h and 8 h) varied in the $30.3\text{--}32.8 \text{ Pa cm}^{-2}$ range. Besides in conclusion there is no influence of the wearing time on DP, since the results showed no significant differences between the reference unworn mask ($32.1 \pm 1.8 \text{ Pa cm}^{-2}$) and the masks worn for 2, 4 and 8 h ($p > 0.47$).

DP for masks worn in a situation of light respiratory effort ($32.8 \pm 2.1 \text{ Pa cm}^{-2}$) was similar to that of the reference unworn mask at $32.1 \pm 1.8 \text{ Pa cm}^{-2}$ ($p > 0.99$). DP for masks worn during moderate respiratory effort was at $31.4 \pm 0.4 \text{ Pa cm}^{-2}$ but no statistical difference was found either between them and the reference unworn masks ($p > 0.99$).

DP for masks worn without air humidification was at $31.6 \pm 0.5 \text{ Pa cm}^{-2}$. No significant variation was found between them and masks worn with air humidification ($32.8 \pm 2.1 \text{ Pa cm}^{-2}$) ($p > 0.99$). There was no statistical variation between the conditions without inhaled gas humidification and the reference unworn mask ($p > 0.99$).

Finally, although the tightly fitted mask had a lower differential pressure ($30.7 \pm 1.0 \text{ Pa cm}^{-2}$) compared to the loose fitted mask and the reference unworn mask, no statistical variations were observed among the values ($p > 0.47$).

3.2. Bacterial Filtration Efficiency

Results of BFE tests are presented in Table 2, as well as minimal values and standard deviations for each experimental conditions. Fig. 5 shows the results of the BFE test in terms of number of colony-forming units, meaning the total number of bacteria, for each conditions, that passed through the fibers of the medical mask out of the 1700 to 3000 bacteria initially sent to the mask.

As can be seen in Table 2, the minimal BFE for each series that is used to determine the class of a mask was above the threshold of 98% (as required by the EN 14683:2019 for type IIR masks).

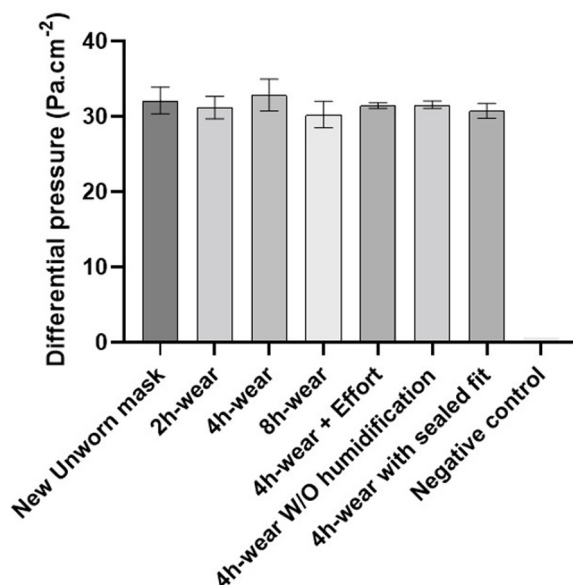


Fig. 4. Comparison of differential pressure (Pa cm⁻²) measured for reference (new unworn mask) and masks worn under different conditions. Standard deviations of mask samples are represented in the graph. For negative control, the differential pressure is equal to 0 Pa cm⁻². No statistical difference was observed between all these experimental conditions.

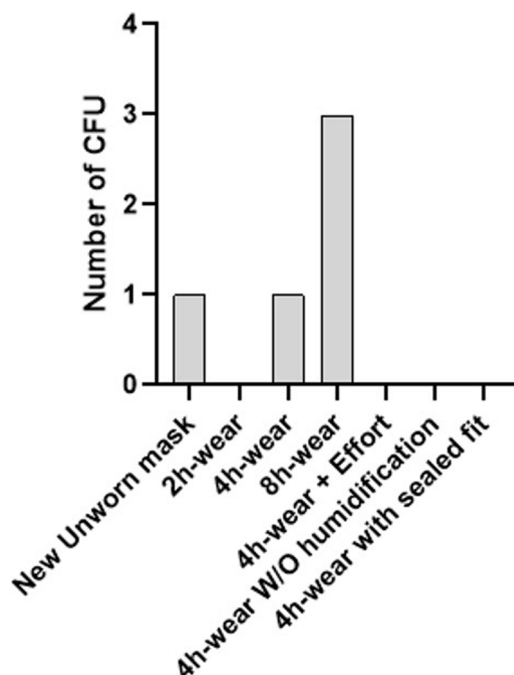


Fig. 5. Total number of colony forming units (CFU) detected for a series of 5 samples for each experimental conditions.

Total number of CFUs obtained for new unworn masks was 1 CFU, 0 CFU for conditions 1, 1 CFU for conditions 2 and 3 CFUs for conditions 3. Average BFE obtained for new unworn masks was 99.99%, 100% for conditions 1, 99.99% for conditions 2 and 99.98% for condition 3. No significant difference was found between these conditions, for which only time varied ($p > 0.93$). No CFU was found for both conditions 4, 5 and 6, corresponding to an average BFE of 100%. No significant difference was found between new unworn masks and any of these conditions ($p > 0.99$). Besides, in absence of mask (the positive control of the BFE test), the number of CFU was in the 1700–3000 range and in the absence of the bacterial aerosol stream, no CFU was found.

4. Discussion

To the best of our knowledge, this is the first study that has characterized the standard performance according to EN14683:2019 of face masks in terms of BFE and DP up to an 8-hour wear simulation. It was demonstrated that BFE and DP are maintained after 8 h of wearing whatever the conditions used (*i.e.* humidification of gases, mask fitting ...).

A good performance of face mask is the result of a compromise between two competing requirements: the bacterial filtration efficiency and the breathability. Indeed, the filtration layers must have an average pore diameter small enough to trap airborne particles, but at the same time if the pore diameter is too small, the filtration layer prevents the user from breathing comfortably. For this reason, face mask filtration layers cannot be fabricated below a minimal pore diameter. Medical face masks are composed of three layers, each of different composition. Usually polypropylene (PP) and polyacrylonitrile are used for the fabric. The outer layer is made of spunbonded, non-woven PP and its pore size is up to 100 μm . The middle layer is usually made of meltblown non-woven fabric. Its pore size is around 20 μm (Ju et al., 2021). Particle capture by medical face masks results from several capture mechanisms (Chen and Huang, 1998; Sanchez et al., 2013; Ju et al., 2021): Brownian diffusion for small particles agitated by Brownian motion, direct interception for bigger particles driven close to the fibers, and impaction for the biggest particles with high inertia and leaving airflow lines. Brownian diffusion is the most effective mechanism for capturing particles with sizes $< 0.1 \mu\text{m}$ while impaction/interception is dominant for particles sizes $> 0.5 \mu\text{m}$. When the mask material is charged, electrostatic forces contribute to particle capture especially for particles in the range size of $0.1\text{--}0.5 \mu\text{m}$ (*i.e.* the Most Penetrating Particle Size (MPPS) zone where no mechanism is dominant). For the average particle size of $3 \mu\text{m}$ required for BFE analysis, impaction and interception are the most dominant mechanisms. If any of the above properties of the mask are degraded when the mask is worn (pore size, specific orientation or displacement of the filter layer fibers, change of electrostatic charge), a loss of filtration quality of the mask for certain airborne particle size ranges may be observed.

Generally, medical masks are loose fitted and do not fit perfectly to the face. This means that, some of the inhaled and exhaled aerosol does not pass through the filtration layer. One can thus wonder if this air leakage on the mask sides can lead in our simulation test to an underestimation compared to the real life in the case of better mask fitting. In our study, mask performances (*i.e.* BFE and DP) remained unchanged after a 8-hour wear simulation with sealed fit, suggesting that the way the mask is worn is not a significant factor in affecting mask performances.

The parameters of the experimental conditions 1, 2 and 3 differ only in the wearing time. Therefore, they allow to determine the possible mechanical impact of breathing cycles on the mask properties. The porous matrix created by the spatial organization of mask fibers contributes to aerosol filtration. As a result, change in the spatial organization of these fibers could alter the filtration efficiency. When an airflow is generated through the mask, a mechanical stress on fibers is generated. A possible risk is that the spatial organization of fibers can be changed by this repeated stress induced by breathing cycles. However in this work, DP and BFE results did not detect any significant change in mask performance. Thus, it can be concluded that the repetition of airflow through the mask over time does not appear to be an obstacle to maintain mask performances up to 8 h of wear.

Other parameters having an effect on the porous matrix of the mask filtration layer are the respiratory frequency and the tidal volume. By increasing the tidal volume, and simultaneously reducing the duration of inhalation and exhalation, a stronger and more frequent airflow is created for a same wearing time. Consequently, a greater effort is then exerted for a single breath on the mask fibers, even more so if the volume of air mobilized is increased. Thus, for the same wear duration, a more important respiratory effort (increase of respiratory frequency and tidal volume simulating moderate physical activities) could create a rise of pore diameter compared to respiratory effort condition simulating an individual at rest. DP and BFE values however showed no significant variations between these two conditions.

The humidity of the inhaled gas is also a possible critical parameter on mask performances (Zangmeister et al., 2021; Li et al., 2022). Since medical masks have hygroscopic properties, this humidity is stored directly by the fibers of the inner layer of the mask. Then, the humidity could favor a displacement of the fibers and increase the porosity or on the contrary could, by being absorbed by these fibers, make them swell and decrease the porosity. Humidity could also affect another property of the mask. Fibers having absorbed too much humidity could lose their electrostatic properties and no longer filter small particles (Whyte et al., 2022b). All things considered, our DP and BFE results demonstrated no significant impact of the humidification of the inhaled gas. During a situation of moderate respiratory effort, breathing generates more humidity. Our results however show that the mask can be kept and stay effective even if humidity accumulates on the inside of the mask. This conclusion also supports the idea that the mask does not lose its effectiveness when worn during a situation of moderate respiratory effort.

Even if the duration of mask wear can be extended, the following conditions must be respected:

- Good tolerance and acceptability by the users.
- No excessive humidity on the filtering part of the mask.
- Maintaining the physical integrity of the mask (*e.g.*, elastic and filtering part).
- No proven risk of projection of infectious droplets.
- Maintenance of performances in terms of standard requirements (*i.e.* bacterial filtration efficiency and breathability).

A strength of this study is that the influence of various respiratory parameters is measured, while coming as close as possible to physiological conditions. This work also uses breathability as a comparison criteria, which is rarely done in similar studies. However, one must keep in mind that a medical mask must not be soiled to preserve protecting the wearer and outsiders. Thus, the fabric should not be handled when worn. This aspect is not taken into account in this study but should be under real conditions of use. Additionally, the probability of manipulating the mask increases with time, as the discomfort generated by the mask increases. A clinical study could help to provide more information on this point.

Another point to keep in mind is that medical face masks used in this study are considered as a reference for excellent quality medical masks. Our objective is not to carry out a screening study on a large number of masks, in order to determine if there are surgical masks of poor quality whose filtration efficiency could be altered according to different wearing parameters (duration, humidity, breathing cycle, mask-fit). Our objective in this article is to determine, in the case of a surgical mask of excellent quality (we took as reference a surgical mask of a company which was selected by the French governmental authorities in order to contribute to the constitution of a French strategic stock of masks in the event of sanitary crisis) if a mask of the excellent quality could be worn for a longer period of time (especially for health care personnel in case of shortage as we experienced in Europe in spring 2020), or if this type of mask could be of interest in order to limit the number of masks used in the general population and thus reduce the environmental impact induced by surgical masks. We consider that this objective, to determine if the “good quality” masks manufactured by European manufacturers, in particular to supply hospitals and to constitute national strategic stocks, can be used for longer periods than the current 4-hour recommendations, is of major interest. All things considered, we would like to emphasize that the main message of this study is not to say that all surgical masks can be used for up to 8 h of wear. Indeed, our sampling of a single mask of excellent quality produced by a European producer does not allow us to generalize our findings to all types of medical face masks (regardless of their producer and country of manufacture) even respecting the EN14683 standard. We must therefore remain more careful and thus our main message is to affirm that medical face masks could be used for up to 8 h of wearing. We have indeed demonstrated that it is possible to extend the duration of wearing the mask for at least 8 h, but only for a brand of surgical masks that is considered to be of excellent quality.

Finally, in this study we did not include the presence of bacteria in the exhaled air. This point is very important to answer the objective of the potentially negative impact on health of the presence of commensal flora on the internal part of the mask. From a hygienic point of view, even if the performance and in particular the filtration efficiency of the mask is not altered after 8 h of wear, this wearing duration could be inadvisable if at the same time the bacterial load on the inner face of the mask becomes problematic in terms of pathogenicity. This point will be the subject of further studies. Nevertheless, in order to evaluate the performance of the mask on a wearing simulator, which is the objective of our study, it seems preferable to carry out the experiments in the absence of bacteria in the exhaled air. Indeed, the potential effect of the bacteria emitted by the exhaled air could be to “clog” the pores of the masks, and thus to improve the filtration efficiency. In other words, the presence of bacteria in the exhaled air could hide a possible degradation of filtration performance induced by the wearing conditions. However, as no impact on filtration is measured with the non-biological parameters of mask wearing that are taken into account in our simulator (humidity, wearing time, mask fitting, breathing cycle), the bacterial flora of exhaled air can in no way reduce the filtration quality of the mask (but on the contrary clog the pores of the masks and improve filtration efficiency). It is therefore important to examine the impact of non-biological parameters of mask wearing, independently of biological parameters (such as the presence of bacteria in exhaled air during mask simulation) which may be a source of bias.

5. Conclusions

The brand of medical mask investigated appears to remain effective under all simulated wearing conditions. This work supports the findings that a medical face mask could be worn for an extended period of time up to 8 h without significant loss of performances. Of course, the generalization of these findings to all types of medical face masks will have to be studied in a next future. Besides, the humidity of the inhaled air, the design of the breathing pattern (simulating moderate physical activity or at rest) and the fit of the mask to the face do not affect the standard requirements of bacterial filtration efficiency and breathability initially determined for a manufacturers' recommended wearing duration of 4 h. By increasing the wearing time of medical face masks used in the general population for the prevention of airborne viral or bacterial contamination, the environmental impact could be decreased. The logistical strain could also be considerably reduced in case of a new worldwide mask shortage.

CRedit authorship contribution statement

Quentin Armand: Conducted the experiments, Wrote the manuscript, Contributed the review of the manuscript. **Henrietta Essie Whyte:** Conducted the experiments, Contributed the review of the manuscript. **Paul Verhoeven:** Designed bacterial filtration experiments, Contributed the review of the manuscript. **Florence Grattard:** Contributed the review of the manuscript. **Lara Leclerc:** Contributed the review of the manuscript. **Nicolas Curt:** Contributed the review of the manuscript. **Sophie Perinel Raguey:** Contributed the review of the manuscript. **Jérémy Pourchez:** Designed bacterial filtration experiments, Wrote the manuscript, Contributed the review of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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