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Original Research

Influence of microstructure and physical characteristics in the performance of non-professional masks sold in São Paulo

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ABSTRACT

Objectives: This study evaluates the performance of eight non-professional face masks sold in São Paulo, Brazil, to prevent aerial transmission of the SARS-CoV-2.

Study design: This was a case report with comparative testing.

Methods: The masks manufactured with different materials and designs were quantified according to their performance to prevent COVID-19 using two indicators: filtration efficiency (FE) and differential pressure. The fabric grammage and microscopy of the layers were analyzed to understand their influence on the performance indicators.

Results: The results show no correlation between grammage in the FE and increasing grammage can compromise breathability indicator. Masks manufactured with cotton widely commercialized during the pandemic have non-uniformized results in FE indicators.

Conclusions: There was no evidence between grammage and the number of layers in the FE indicator. The results pointed out that the layer's composition and the microstructure are the best way to evaluate the performance of non-professional masks used to prevent the aerial transmission of the SARS-CoV-2.

Introduction

The COVID-19 was declared a pandemic by the World Health Organization (WHO) in May of 2020 and has infected more than 270 million people worldwide, with about five and a half million deaths.[1]

The transmission mechanism between humans occurs by direct interaction, contact with contaminated objects, and mainly by aerosol particles.[2–4] Therefore, the most effective way to reduce transmission is through social distancing, vaccination, hygiene, and massive use of facial masks, not only in hospitals but by the entire population.[4–9] Furthermore, face masks have shown effective in reducing the spread of the virus by blocking droplets and aerosols expelled by coughing or talking.[10,11]

In Brazil, the production capacity of professional masks is not sufficient to fulfill the population demand. Because of these shortages, the use of non-professional masks by the Brazilian population becomes a reality because they are cheaper to produce and can improve the local economy.[12] Furthermore, a differential of the non-professional mask compared with a disposal professional mask is that it can be reused after washing without reducing the demand for new masks.[13]

The professional masks, such as N95 and surgical, have better performances for their standardized design and certification systems than non-professional ones concerning filtration efficiencies.[14–17] However, there are only recommendations from the Brazilian Health Regulatory Agency[18,19] that masks should preferably be manufactured with cotton and three layers. These institutions also

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recommend that the masks should present grammage (mass of fabric per area) varying between 20 and 40 g/m^2. However, there is no evidence that these recommendations improve mask performance.

Furthermore, the WHO suggested that non-professional masks should have a filtration efficiency (FE) above 70% and breathability below 6 mmH$_2$O/cm^2 (60 Pa/cm^2). However, the correlation between the physical characteristics and the non-professional masks' performance has not been conducted yet. This study aims to evaluate the influence of physical characteristics and microstructure in the FE and breathability of eight non-professional masks.

Methods

This research is an extension of the first study published by the authors,[17] where the FE of Brazilian face masks was evaluated. Eight non-professional face masks with different numbers of layers sold in different regions of São Paulo city were evaluated. The samples were selected by a journalist from the Globo television network (the biggest in the country) to be tested for an interview. The interview aimed to evaluate the performance of several non-professional masks helping the Brazilian population choose best ones and provide recommendations for manufacturers.[f] The samples were selected at different sales points across the city, with the selection criteria being the diversity of materials and designs between masks. The eight types of masks are easily found for sale and effectively used by the population.

Analysis of face masks

Aerosol size distribution measurements

The aerosol size distribution was measured using the FE parameter, which correlates the filtration capacity and the retain aerosol particles capacity. Considering a fixed filtration area, the higher the efficiency, the higher the particle retention.

Considering there is no standardized test to calculate this parameter, we used a non-standard technique for measuring FE according to the procedures described by Morais et al., 2021.[17] According to the authors,[17] the instrumentation to measure the aerosol size distribution involved an ATM 226 aerosol generator (TOPAS, Saxe, Germany) that produced NaCl aerosol particles with a mean size distribution peak at 100–120 nm and a Scanning Mobility Particle Scan (SMPS), model 3080 (TSI, Minnesota, USA), measured the particle size distribution in the size range 20–800 nm. The SMPS is coupled to a 3771 condensation particle counter (TSI, Minnesota, USA). The mask FE was calculated according to the study mentioned previously, considering the particle number size distribution of blank samples and filtered aerosols. The variability of the analyzes was estimated based on the standard deviation of the measurements. Three measurements were conducted per mask.

Pressure drop

Pressure drop (ΔP) is related to breathability and represents the effort required to breathe. Therefore, the higher the pressure drop, the lower the breathability and the less comfortable it is for the user wear a mask with the same filtration area.

Similar to FE, there is no standardized test to calculate the breathability. Hence the procedures described by Morais et al.[17] were used. The process involves attaching the mask in two supports with a circular cross-section of 4.92 cm^2 (25 mm in diameter) where the air pressure passes through the mask fabric with a flow of 100 L/min. Differential pressure drop (ΔP) is expressed in mmH$_2$O/cm^2, and values above 8 mmH$_2$O/cm^2 are considered unbreathable. Three measurements of pressure drop were conducted per mask.

Quality factor

The quality factor (QF) is indicative of the quality of the mask. According to Zangmeister et al.,[16] the QF is a relation between the FE and the pressure drop and can be calculated according to Equation (1). Higher values are better and represent the ideal situation—higher FE and lower pressure drop.

$$QF = (-\ln(1 - FEmin / 100))\Delta P \tag{1}$$

Analysis of filter materials

Layer's performance

After analyzing the samples, the masks were cut to evaluate the filtering materials' layers separately. The procedures described in sections 2.1.1 to 2.1.3 were performed for each layer individually, conducting three measurements for FE and three measurements for pressure drop.

Modeling the performance of face masks

Based on the results of FE per layer, we propose a method to estimate the total filtration of a mask as a function of the layers' properties, as shown in Equation (2). Where MF is mask filtration, FL1, FL2, and FL3 are the filtrations of the first, second, and third layers, respectively. Drewnick et al.[20] propose a similar method.

$$MF \approx FL1 + (100 - FL1) \times \left(\frac{FL2}{100}\right) + \left[(100 - FL1) \times \left(\frac{FL2}{100}\right)\right] \times \left(\frac{FL3}{100}\right) \tag{2}$$

For the model of breathability, we assumed that the sum of the pressure drop of all layers can be used to calculate an estimated pressure drop of the mask, as proposed by Drewnick et al.[20]

Grammage

The samples were cut with a scalpel in 4 × 4 cm squares. The layers were weighed separately on a scale (Ohaus, model Adventurer), and the values obtained were converted into grammage (grams per square meter). For masks with more than one layer, the weight was considered as the sum of each layer of fabric.

Digital microscopy

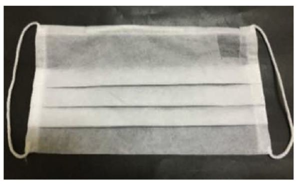
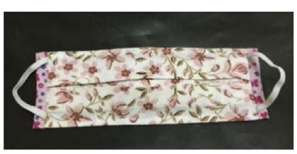
A digital microscope (Hirox model KH770, with mxg-2500REZ lens) was used for microstructure analysis. All layers of the masks were analyzed in the magnifications 50× (H-view = 6344.72 μm) and 100× (H-view = 3098.42 μm). The thickness of the fabrics was estimated by positioning the masks between two glass slides connected with modeling clay on the edges. The slides were pressed together to prevent the fabric to move, without squeezing it. Using the "*2D measurements*" tool (that measures the distance between two reference points on the image generated by the microscopy), 20 measurements of thickness were collected for each sample and used to calculate the average and standard deviation. An example of thickness measurement can be found in Figure S1 of the Supplementary Materials.

Results

Photographs and the structural characteristics of the face masks used in this study are found in Table 1. The set is composed of three

[f] (Interview link: https://globoplay.globo.com/v/8618565/programa/.Starting at 1:51:00. Registration is free, but required.)

Table 1
Description of the masks analyzed in the study, based on the number and composition of layers, dimensions of the mask and the elastic, and the presence or absence of nasal clip.

Number	Photo	Description
1		• Two layers of polyamide and elastane fabric. • 14.5 × 7.2 cm (not stretched) and 19.2 × 9.4 cm (stretched) • 20 cm long elastic • No nasal clip
2		• Two layers of non-woven, probably SMS. • 18.2 × 10.5 cm • 13.5 cm long elastic and 8.2 cm length • With nasal clip.
3		• Two layers of cotton fabric. • 16.8 × 8.5 cm • 17.5 cm long elastic. • No nasal clip.
4		• Single layer of neoprene. • 11.5 × 15.2 cm • No nasal clip and front stitching.
5		• Two layers of cotton fabric and a central layer of paper towel. • 22.8 × 7.4 cm • 9.8 cm long elastic. • No nasal clip.
6		• Two layers of cotton fabric. • 22.8 × 7.4 cm • 9.8 cm long elastic. • No nasal clip.
7		• Three layers: Inner and outer with cotton fabric and central with non-woven (probably SMS) layer • 20.4 × 9.5 cm at the ends and 13.2 cm in the central region • 20.6 cm long elastic. • No nasal clip and with central stitching.
8		• Single layer of polyurethane foam. • 11.9 cm × 8.4 cm • No nasal clip.

masks of fabric, one made of non-woven, two hybrids, and two of foam. The dimension and characteristics of the masks varied between samples, and only mask 2 (non-woven) presented nasal clip. The benchmark presented in a study by Morais et al.[17] evaluated 198 non-professional masks manufactured in Brazil. The cotton ones represented 27% with different layers, the non-woven and SMS non-woven represent 20% and 29%, the hybrid 16% and foam 2%. Although we do not include all the fabrics and masks available in the Brazilian market, our samples seem representative of the most used ones.

Fig. 1 shows the main results obtained by the tests of FE, pressure drop, and grammage. The results show no correlation between FE and pressure drop, or FE and grammage, with mask 2 (nonwoven) presenting the best characteristics.

Fig. 2 presents the microscopy results only for the first layer of each mask. The images of the remaining layers are presented in the Supplementary Materials. The arrange, size, and distribution of pores seems to be the main factor concerning FE and breathability.

Table 2 summarizes the main results found for the study, and Fig. 3 shows the correlation between the experimental results and estimated values calculated for FE and breathability. Based on the correlations obtained in Fig. 3, it can be assumed that both FE and

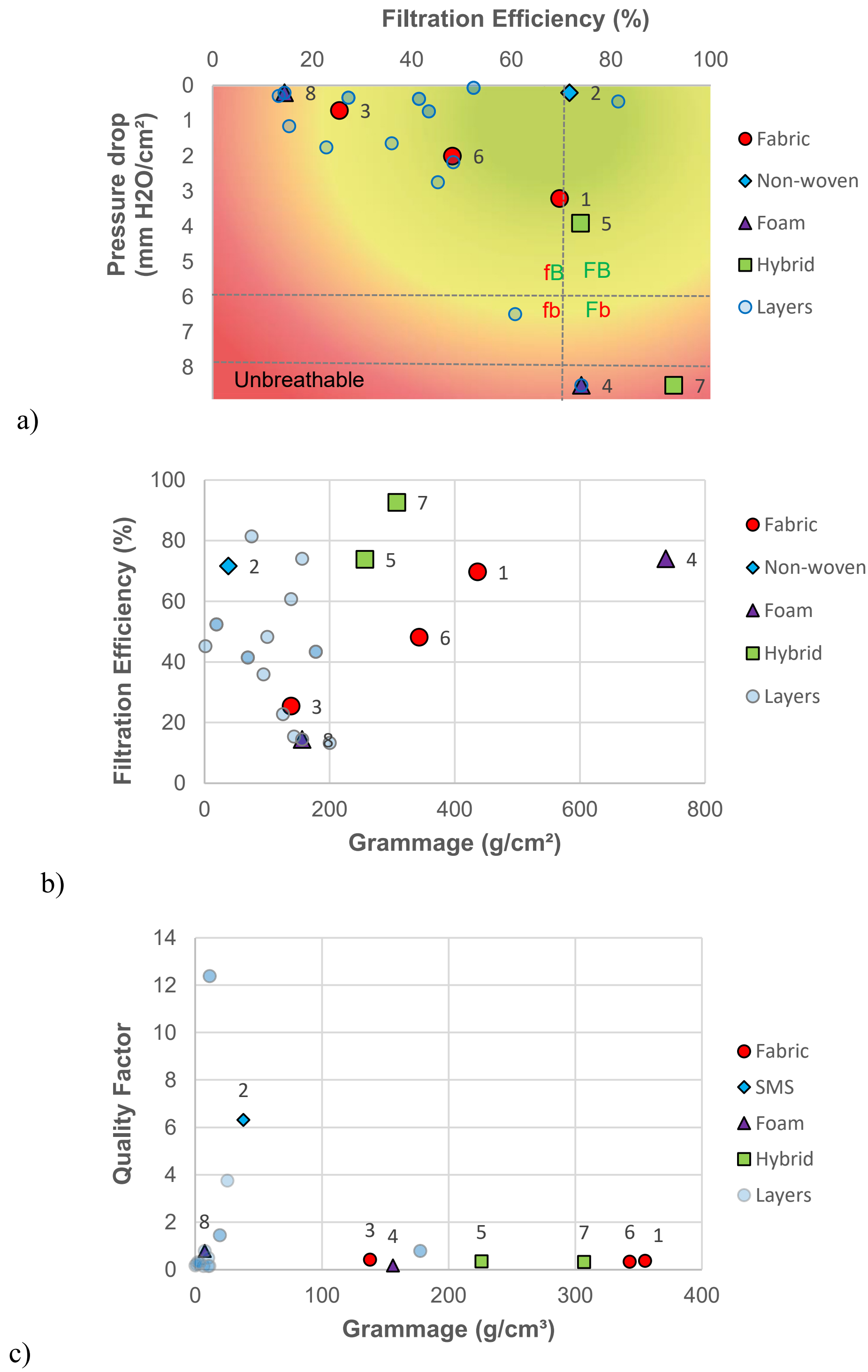


Fig. 1. Main results obtained during the research. (a) Filtration efficiency as a function of pressure drop, (b) grammage as a function of filtration efficiency, and (c) grammage as a function of quality factor.

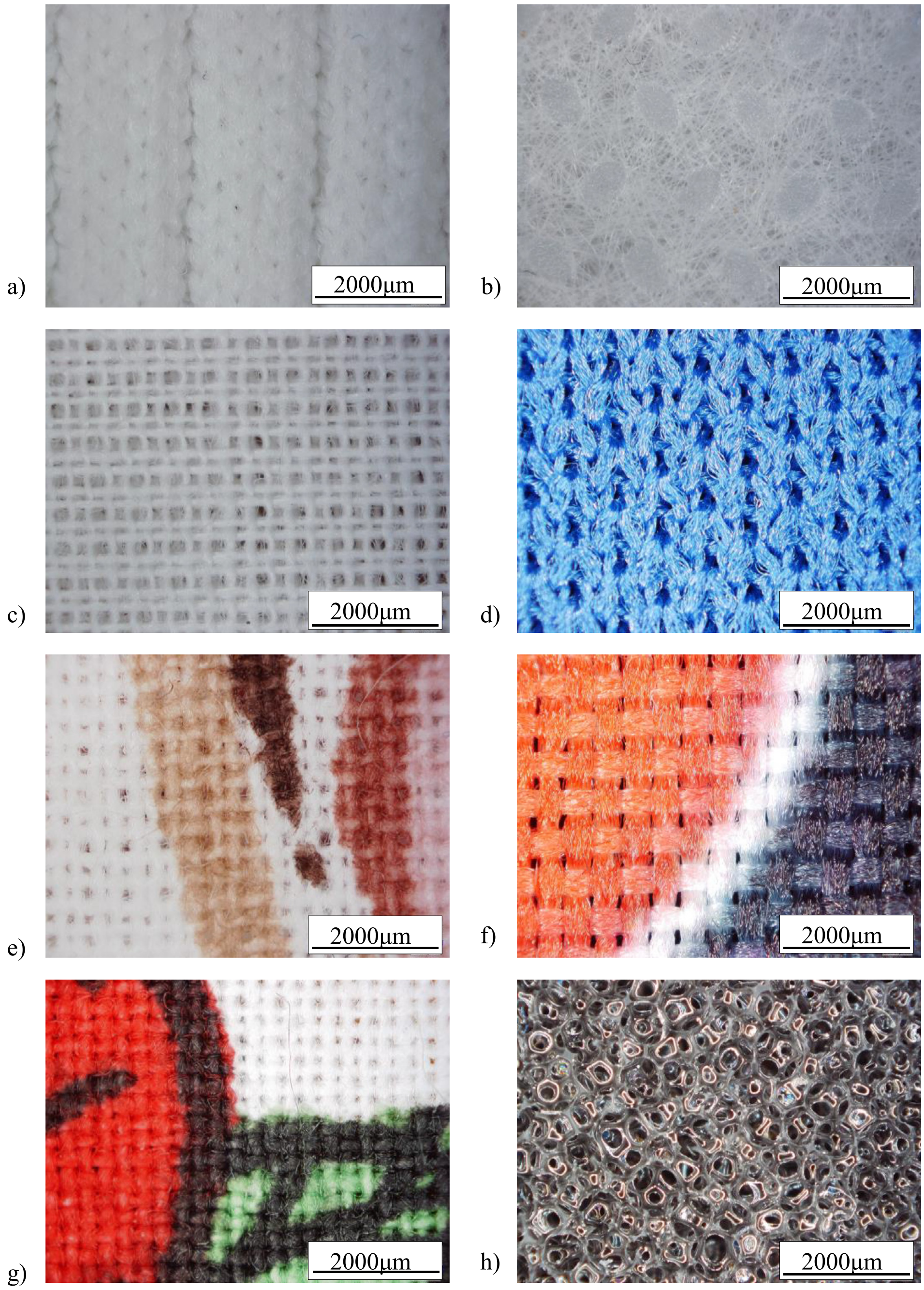


Fig. 2. Microscopic analysis of the first layer of each mask. (a) Mask 1 made with elastane material, (b) Mask 2 made with non-woven SMS, (c) Mask 3 made with cotton, (d) Mask 4 for neoprene, (e) Mask 5, with the first layer composed of cotton, (f) Mask 6 made with cotton, (g) Mask 7, with the first layer made of cotton, and (h) Mask 8, composed of polyurethane foam.

breathability can be calculated based on the characteristics of each layer that composes the mask.

Discussion

Masks and their layers

Cotton fabrics were popular, but the sample includes masks combining various synthetic materials, such as neoprene and polyurethane foams. The nasal clip was present only in a non-woven mask, with a design similar to surgical. Besides FE, we included pressure drop because in a mask with an excellent filtration performance with a very high pressure drop, most of the air will be forced at the interface between the mask and the user's face, defeating the filtration. Because our goal is to understand the performance, we also included layer basic characterization through microscopy analysis.

Digital microscopy was used to investigate the physical characteristics of various layers of the masks, as described in Section 2.2.3.

Mask 1 (thickness = 2387.20 μm ± 31.70 μm) presented two layers of elastane and polyamide with few pores, which allowed a high FE, whereas the effort required to breathe was close to the maximum recommended value from WHO. However, the elastane

Table 2
Summary of physical test results of masks and layers.

Number	Layer	Grammage (g/cm^2)	Filtration efficiency (%)			Differential pressure (mmH$_2$O/cm^2)			Quality factor	
			Layer	Total	Eq 2	Layer	Total	Eq 3	Layer	Total
1	Polyamide + elastane	177.5	43.42 ± 2.67	69.73 ± 1.38	67.99	0.73 ± 0.18	3.20 ± 0.09	1.46	0.78	0.37
		177.5	43.42 ± 2.67			0.73 ± 0.12			0.78	
1s*		–	27.30 ± 10.00	–	47.15	0.34 ± 0.09	–	–	0.94	–
		–	27.30 ± 10.00			0.34 ± 0.11			0.94	
2	Non-woven	19	52.41 ± 1.50	71.71 ± 1.60	77.35	0.06 ± 0.01	0.20 ± 0.00	0.12	12.38	6.31
		19	52.41 ± 1.50			0.06 ± 0.01			12.38	
3	Cotton	69	41.49 ± 2.93	25.47 ± 0.37	66,01	0.37 ± 0.05	0.70 ± 0.09	0.74	1.45	0.42
		69	41.49 ± 2.93			0.37 ± 0.04			1.45	
4	3 soldered layers of neoprene	156	74.05 ± 1.91	74.05 ± 1.91	74,05	>8	>8	>8	0.17	0.17
5	Cotton	125	22.83 ± 2.86	73.88 ± 1.32	78.17	1.75 ± 0.33	3.9 ± 0.28	6.66	0.15	0.34
	Paper towel	1	48.32 ± 1.33			2.74 ± 0.57			0.22	
	Cotton	100	45.26 ± 2.60			2.17 ± 0.35			0.3	
6	Cotton	143	15.40 ± 4.74	48.19 ± 0.94	26.64	1.15 ± 0.17	2.00 ± 0.09	1.44	0.15	0.33
		200	13.29 ± 2.93			0.29 ± 0.07			0.49	
7	Cotton	138	60.75 ± 1.93	92.66 ± 0,46	95.35	6.48 ± 1.43	>8	8.56	0.14	0.32
	Non-woven	75	81.48 ± 0.83			0.45 ± 0.01			3.75	
	Cotton	94	35.99 ± 5.09			1.63 ± 0.17			0.27	
8	Polyurethane foam	156	14.47 ± 3.87	14.47 ± 3.87	14,47	0.20 ± 0,02	0.20 ± 0,00	0.20	0.78	0.78

Filtration efficiency is presented as global measured, global estimated by eq (2) and per layer. *s = stretched mask.

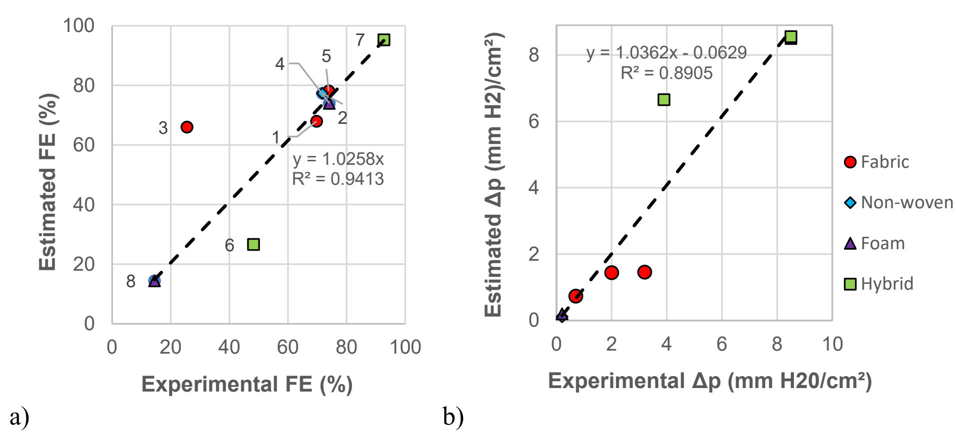


Fig. 3. (a) correlation between experimental filtration efficiency and estimated filtration efficiency and (b) correlation between experimental pressure drop and estimated pressure drop.

fabric tends to stretch during use which increases the size of the pores and reduces FE (Table 2).

Mask 2 was manufactured with two layers of conventional non-woven, probably SMS, that presents some weld points. The microstructure of the filaments is disordered, providing pores with heterogeneous sizes and without constant positioning. By overlaying the two layers of non-woven, the FE increases because the number of pores that directly traverse the set decreases. This mask also presented a good performance on the differential pressure drop making its use advisable. Conversely, this mask does not follow the trend of the higher the FE, the more difficult it is to breathe, besides presenting the smallest thickness among all masks analyzed (733.94 μm ± 8.86 μm).

Mask 3 consisted of two layers of cotton knitwear, resulting in 1057.30 μm ± 10.86 μm thickness. The meshes were manufactured following the standard interleaving of cotton filaments in two directions, providing a structure with large pores, homogeneous and periodically distanced. By overtaking both layers, unlike that observed in Mask 2, the area of the pores coincided more frequently, which led to low FE and differential pressure close to 0, which would be equivalent to breathing without wearing a mask. Therefore, the ordered structure of Mask 3 (cotton) becomes less efficient than the disordered structure of Mask 2 (non-woven). These results are similar to those observed by Davies et al.[21]

Mask 4, categorized as “neoprene,” was composed of two layers of fabric welded into a dense intermediate layer of polychloroprene foam. The filtration and differential pressure tests could not be performed in the individual layers because of the fineness of the tissue layers and the adhesion of the outer layers with the intermediate layer. However, as observed in microscopy, the small number of pores interconnected in the foam region is probably responsible for air retention. This situation results in a high FE but because of its higher thickness (2914.33 μm ± 12.13 μm) and sealed pores present high differential pressure values reducing the breathability performance. In addition, because neoprene is typically used as a thermal insulator[22] for wetsuits, this fabric may be uncomfortable due to the heat and may reduce the use time. For medium or long-term use, thermal comfort is an important parameter to consider,[23,24] especially in tropical countries.

Mask 5 was manufactured by two layers of cotton with an intermediate layer of paper towel (954.07 μm ± 12.42 μm). Tests were performed to evaluate the efficiency of the paper towel as a filter material. The results pointed out an increase of the FE by approximately 37% and slightly altered the differential pressure (less than 10%) because of the structure with few pores. The weaving pattern observed in this mask was identical to that of Mask 3; however, both layers presented smaller pores than those observed in sample 3.

Mask 6, composed of two layers of cotton fabric (thickness of the set = 966.90 μm ± 7.34 μm), presented high filtration and differential pressure values. This is related to the fact that the mesh is very closed and contains only a few pores, which confirms the correlation for cotton masks that the smaller the pores' size, the more efficient the masks are for filtering. But, conversely, it increases the pressure drop reducing the breathability.

Mask 7 is a hybrid mask of non-woven and two layers of cotton (1210.40 μm ± 10.11 μm). The non-woven showed few pores and had a stiff structure, whereas the cotton layers are more malleable and have more superficial pores. This mask and Mask 4 presented the worst differential pressure result, but an optimal filtration factor, which shows that not all material with filtration above the minimum values—70% standard according to the WHO[25]—should be used.

Mask 8 (3648.20 μm ± 6.66 μm) was the thicker analyzed in this study and is composed of a single layer of polypropylene foam. A large volume of interconnected pores results in low FE and excellent breathability, which is also influenced by the frontal seam.

Overall, the thickness analysis as FE function demonstrates that the fabric properties have little correlation with each other (R^2 = 0.1193). Based on digital microscopy, the mechanism responsible for filtration seems to be the chaotic filaments' organization that makes up the structure.

Grammage

The Brazilian organizations ANVISA and ABNT[18,19] recommend that non-professional masks should have three layers of fabric, with grammage between 20 and 40 g/m^2 per layer. However, studies have shown that masks are usually heavier than the recommendations suggest[17,26] and present a high variation between different materials.[27] This study shows that there is no correlation between grammage and both FE (Fig. 1b) and air permeability (breathability) of different materials. In addition, as shown in Fig. 1c, the higher values of grammage presented a low QF. From the analyzed samples, the neoprene mask (number 4) was the heaviest in the study, followed by Masks 1 and 6, made of polyamide and elastane, and cotton. The lightest mask studied was Mask 2, made with non-woven.

Based on the results presented by this research and the work of,[17] it is possible to conclude that grammage should not be used as a parameter of mask performance because the distribution of mass per area of fabric does not correlate to performance parameters. Based on microscopy analyzes, it is also concluded that the grammage of fabric is a function of the thickness of the strand and distance between the filaments in the mesh, both parameters that cannot easily be measured and analyzed by the general population. Furthermore, heavier fabrics might present a higher filtration efficiency; however, the user has more difficulty to breath.

Mask's performance

Fig. 1a shows the FE and the differential pressure drop of the face mask and separate layers. The graph was divided by the limits of both requirements (6 mmH_2O/cm^2 and 0.7), forming four quadrants: (1) FB, when the filtration and breathability requirements present values above the desired; (2) fB, only the requirement of breathability is met; (3) Fb, only the filtration requirement is met, and (4) fb, both requirements present values below the desired.

Masks 2, made of non-woven, and 5, made of cotton and paper towel, were the only ones that met both requirements. Both Masks 4 and 7 were classified as unbreathable.

The results indicate that there is no correlation between the two variables. Furthermore, only Mask 2 showed good FE, breathability (FB), and high QF. The results were probably affected by the pore size distribution of the samples, as proposed by Leonas and Jones.[27] Smaller pores rendered better filtration for the cotton samples; however, they also decreased breathability. Aside from that, it is not expected that common cotton fabrics have great filtering capacity for small particles, as suggested by O'Kelly.[28] However, they still might be helpful for blocking bigger particles (~10 μm)[29] and could help diminish the spread of viruses.[30]

The QF was calculated for each layer and set based on FE and pressure drop results. The results are presented in Table 2.

For the QF analyses of different layers, only the non-woven (Mask 2) presented a high value—good FE and breathability. However, combining non-woven fabrics with other fabrics reduces the QF due to the increase of pressure drop.

The results presented in Fig. 1c show that increasing the grammage by combining a set of layers with high FE, has little effect on FE of the set. However, the results indicate that it decreases breathability and, therefore, reduces global mask performance estimated by the QF indicator. This is the case of Mask 7, whose non-woven layer has 81% FE. Including two cotton layers improved FE slightly up to 92% but increased pressure drop by ~20 times, making it unbreathable. Consequently, part of the air would be breathed by the used unfiltered through the leakage in the filter−skin interface.[31] For this situation, the usual recommendation of using masks with three layers[18,19] should be revisited.

Modeling masks performance from layers properties

The estimated values obtained were close to the experimental ones, except for Masks 3 and 6.

The divergence found for Mask 3 is probably a result of a localized minor defect in the fabric mesh, which provided a preferential path air passage and decreased total filtering efficiency. The divergence found for Mask 6 can be attributed to the coincidence between the passing pores of the first mesh and the wires of the second, making it less porous. This implies that filtration behavior should not be considered constant because the movement between the two layers may influence the filtering efficiency.

Apart from the outliers, the estimated values have a high correlation with the experimental results, as shown in Fig. 3a.

The estimated values of breathability are presented in Fig. 3b as a function of the experimental results and show great correlations with each other.

Conclusions

This work analyzed the microstructure and physical characteristics of eight non-professional face masks, sold in different points of São Paulo city in June of 2020. Although this study does not cover all the Brazilian mask types and fabrics available in the market, the most representative ones were included. The results can be helpful in directing public policy and helping companies to improve the performance of the mask to prevent aerial transmission of the SARS-CoV-2. The FE and breathability were evaluated, seeking correlations between the physical parameters and the masks. The results showed no clear evidence that grammage can be used as an indicator for non-professional masks confection, as proposed by the Brazilian authorities, because no correlation with FE was found. In addition, higher grammage can reduce breathability.

The study of layers' composition and microstructure presented more suitable results for non-professional masks with proper performance. In addition, the total FE and breathability of the masks can be calculated by the properties of the individual layers.

The non-woven mask showed better QF results, combining excellent breathability because of light tissue and good FE (71%), complying with WHO recommendations (>70% for non-hospital masks). Masks made in cotton fabric, widely commercialized during the pandemic, showed a high dispersion in FE between 20% and 70%, all with two layers.

Author statements

Ethical approval

Not required since no studies were conducted with animals or patients.

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Competing interests

None declared.

Author contributions

L.N.L. contributed to data acquisition, data analysis, data interpretation, draft writing, and revision. D.C.R. contributed to data acquisition, data analysis, data interpretation, draft writing, and revision. V.K.S. contributed to data acquisition, data analysis, data interpretation, draft writing, and revision. M.A.F. contributed to data analysis, data interpretation, draft writing, and revision. F.M. contributed to data acquisition, data analysis, data interpretation, draft writing, and revision. V.M.J. contributed to revision, conception, and design of the study, resources management, and project management.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.puhe.2022.01.009.

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