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Is there an adequate alternative to commercially manufactured face masks? A comparison of various materials and forms

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SUMMARY

Background: There is a worldwide shortage of medical-grade face masks. Donning masks can play an important role in curbing the spread of SARS-CoV-2.
Aim: To conclude whether there is an effective mask for the population to wear in public that could easily be made during a medical face mask shortage using readily available materials.
Methods: We determined the effectiveness of readily available materials and models for making a face mask. The outcomes were compared with N95/FFP2/KN95 masks that entered the Netherlands in April–May 2020. Masks were tested to determine whether they filtered a minimum of 35% of 0.3-μm particles, are hydrophobic, seal on the face, are breathable, and can be washed.
Findings: Fourteen of the 25 (combinations of) materials filtered at least 35% of 0.3-μm particles. Four of the materials proved hydrophobic, all commercially manufactured filters. Two models sealed the face. Twenty-two of the 25 materials were breathable at <0.7 mbar. None of the hydrophobic materials stayed intact after washing.
Conclusions: It would be possible to reduce the reproduction rate of SARS-CoV-2 from 2.4 to below one if 39% of the population would wear a mask made from ePM_1 85% commercially manufactured filter fabric and in a duckbill form. This mask performs better than 80% of the imported N95/FFP2/KN95 masks and provides a better fit than a surgical mask. Two layers of quilt fabric with a household paper towel as filter is also a viable choice for protecting the user and the environment.

Introduction

The current SARS-CoV-2 crisis caused a worldwide shortage of medical-grade personal protective equipment, including face masks. Nevertheless, some governments, such as in Austria, Israel, Singapore, and the Czech Republic, require(d) the

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population to wear a mask when outdoors, while other governments suggest the use of face masks in public [1,2]. This contradiction has led to the improvization of face masks out of readily available materials.

Some governmental organizations provide instructions on how to make an alternative to a medical-grade face mask, such as in the Netherlands, Belgium, the USA and India [3–6]. These are all fabric-based masks. The American and Belgian models optionally hold a filter, either a coffee filter (USA) or not specified (Belgium). There are no published data available describing the protection these masks provide to the wearer and/or the enviroment.

Although there is contradictory evidence about the protective effect of masks, meta-analysis concludes that surgical and FFP2/N95 masks reduce the risk of SARS by approximately 80% [7]. We investigated the production of an alternative, effective mask for the population to wear in public that can easily be made during a crisis using readily available materials. We define effectiveness as the ability of the mask to reduce the reproduction rate (R_0) of the virus to under 1.

There are few published studies investigating the efficacy of readily available materials for face masks. One such article describes various commonly available fabrics for masks but omits information about the form of the mask and the use of additional filters [8]. The authors tested the filtration efficiencies and pressure drops for a surgical mask, vacuum cleaner bag, cotton t-shirt, scarf, tea towel, pillowcase, cotton mix, linen and silk. The two micro-organisms used for the filter efficiency tests were 0.023 μm and 0.95–1.25 μm. These tests showed that the fabrics filtered 49–90% of the micro-organisms at 0.023 μm. Quesnel described the benefits of a particular cotton mask from four-ply cotton muslin [9]. This mask showed an efficiency of 77% for particles of 0–3.3 μm. We aimed to find a mask material with an effective filtration value, that can be washed for reuse, and has the potential to reduce the R_0.

According to Tian et al. widespread mask usage in the population can halt the spread of the virus in the population [10]. They calculated the reduction factor of R_0 as:

$$(1-(\textit{efficiency of the mask}) \\ {}^*(\textit{percentage of the population that wears the mask}))^2$$

According to their theory, a partially effective mask can halt the spread of SARS-CoV-2 if a minimum population wears the mask. If we assume $R_0 = 2.4$, the minimum percentage of the population who would have to wear a mask in order to reduce R_0 to less than 1 can be calculated as 0.352 divided by mask efficiency.

There is some debate whether SARS-CoV-2 spreads through aerosols, because SARS-CoV-2 RNA has been detected in aerosols; we assumed that viable SARS-CoV-2 could travel on aerosols [11,12]. We also assumed that there is airborne transmission of this virus through breathing and talking, because this has been documented for influenza [13]. We would additionally suggest that the population wearing the mask not be limited to people who are symptomatic and coughing, as there are signs of SARS-CoV-2 transmission from pre-symptomatic patients [14,15]. Accordingly, assuming that SARS-CoV-2 travels on aerosols (or droplets) that are 0.3 μm or larger, the spread of COVID-19 can be halted if 100% of the population wears a mask that provides a minimum of 35% protection of 0.3-μm particles.

We intended to develop a mask prototype for the general population which meets the following requirements: (1) can be produced at home from widely available fabrics, including commercial air filters and materials which are available at a fabric or grocery store; (2) filters a minimum of 35% of particles at 0.3 μm; (3) has a seal on the face (at the level of an FFP2-mask); (4) is breathable; (5) is hydrophobic; (6) can be washed.

For direct comparison, we used two commonly used masks as references: an FFP2/N95 mask and an RII-surgical mask which were made conform to European standards [16,17]. FFP2 masks are recommended for aerosol-forming procedures such as open suctioning of the respiratory tract, intubation, bronchoscopy and cardiopulmonary resuscitation [18,19]. RII-surgical masks are considered sufficient for the majority of regular care for COVID-19 patients, although this is debated and there is mixed evidence [7,18]. We aimed to create a mask with a better fit than a surgical mask, because surgical masks do not seal on the face. The filtration capability of our best mask was then compared with N95/FFP2/KN95 masks that were imported during the COVID-19 crisis.

Materials and methods

We chose filters based on a literature search, on which fabrics are promoted as filters by governments, and by searching for readily available non-woven fabrics, although we are aware that woven fabrics can possibly be effective [3–5,8,20,21]. Commercial air filter fabric, made for heating, ventilation and air conditioning (HVAC) systems, were considered a viable option, because they are built to filter out particles ranging from 0.3 to 10 μm in diameter. We hypothesized that filter material of ePM_1 85% (ISO 16890) or F9 (EN 779:2012), similar to the American MERV 16 filter standards, could approach the filter capacity of an FFP2 mask [22,23]. Materials which are generally used in healthcare were avoided, since this could cause new shortages in the health care system. We hypothesized that materials could be used to make a mask as such or as an inlay filter. Materials were therefore tested by themselves and between two pieces of cotton quilt fabric. Masks were made with and without a metal nose strip.

Procedure

Step 1: Particle test

A calibrated particle counter (Solair 3100 Lighthouse, San Francisco, www.golighthouse.com, Supplementary Figure S1) counted the number of free-flowing airborne particles in a 1-min cycle with a flow rate of 1.0 cfm. The measurement was conducted on particles of sizes 0.3, 0.5, 1.0 and 5.0 μm. The closed particle chamber was specifically built to conduct these tests.

A baseline measurement was performed before every material test, during which free-flowing air was drawn into a particle chamber. The particle chamber was connected through a silicone tube to the particle counter. Material was then clamped to the top of the particle chamber and we repeated the test three times. The last measurement reflects total number of particles drawn into the particle counter through the fabric. This test was repeated three times to ensure that loose particles on the fabrics would not affect the

Table I

Particle filtration test, pressure test, and estimation of the population which needs to wear a mask of this material in order to achieve $R_0<1$

Description	Filtration value (%)					Pressure (max acceptable value set at 0.7)	% population needed to wear a mask of this material to achieve $R_0<1$[d]
	0.3 µm	0.5 µm	1 µm	3 µm	5 µm	(mbar)[c]	
IIR-surgical mask[a]	59	75	84	100	100	0.15	n/a
3M 1862 +[a]	96	98	99	99	100	0.20	37
ePM₁ 60%[b]	40	60	73	99	95	0.23	88
ePM₁ 60%[b] between quilt fabric	56	78	87	97	99	0.47	63
ePM₁ 85%[b]	90	96	98	100	100	0.31	39
ePM₁ 85%[b] between quilt fabric	94	98	99	97	97	0.72	n/a
F7[b]	41	55	65	99	100	0.07	85
F7[b] between quilt fabric	55	72	82	97	97	0.43	64
F9[b]	78	88	92	100	99	0.15	45
F9[b] between quilt fabric	77	89	94	97	97	0.50	46
M5[b]	3	6	11	90	96	0.05	>100
M5[b] between quilt fabric	19	38	54	96	97	0.39	>100
Cleaning cloth between quilt fabric	21	40	54	92	93	0.39	>100
Coffee filter (double) between quilt fabric	90	99	99	98	98	2.18	n/a
Felt 155 g between quilt fabric	20	39	55	96	97	0.36	>100
Leather	100	100	100	99	99	2.92	n/a
Microfibre fabric	59	88	95	99	99	1.50	n/a
Household paper towel (1 layer) between quilt fabric	42	70	82	95	94	0.64	85
Household paper towel (2 layers) between quilt fabric	65	90	96	98	98	1.01	n/a
Polypropelene fabric 1	10	27	41	65	75	0.41	>100
Polypropelene fabric 2	5	18	28	55	61	0.18	>100
Quilt fabric (2 layers)	16	37	55	94	95	0.31	>100
Quilt fabric (4 layers)	34	59	69	63	71	0.66	>100
Quilt fabric (6 layers)	46	74	88	98	98	0.97	n/a
Static dust cloth between quilt fabric	21	40	57	94	96	0.35	>100
Tea towel (1 layer)	5	15	14	35	36	0.05	>100
Tea towel (2 layers)	5	13	23	84	88	0.10	>100

n/a, not applicable.
[a] Reference.
[b] Commercially manufactured filter.
[c] Pressure is calculated assuming the duckbill form with the seams on the inside.
[d] only materials that passed the pressure test.

filtration measurement. We calculated the ratio of particles that passed through the material to the baseline measurement. This is an effective method for precise and fast measurements [24].

Step 2: Fit test

Mask safety depends not only on the filtration, but also on the fit on the face [16,17]. It is important that air does not enter or exit from the top, side or bottom of the mask to guarantee that the air always passes through the filter. We used an AccuFIT 9000 Respirator Fit Test apparatus (https://accutec-ihs.com/accufit-9000; Supplementary Figure S2). This machine counts the number of particles in the face mask during a series of movements, creating stress on the seal of the mask, which is compared with the ambient particulate concentration.

After validation of the device, the face mask was equipped with an inlet to a tube. A flow is created through the tube and the number of particles in the mask is counted. The fit test includes cycles for normal breathing, deep breathing, moving your head from side to side, moving your head up and down, talking out loud, and bending over [25]. The fit factor confirms the level of leakage and is calculated as a ratio of the particles inside the mask relative to the ambient concentration outside the mask. A fit factor of 100 or higher represents a good fit. All tests were carried out on one woman to ensure homogeneity in the results.

The mask prototypes were from either filter fabric only (ePM_1 85%) or filter fabric (ePM_1 85%) with cotton quilt fabric.

Different models were tested, such as folded, pleated, round, flat, and duckbill.

Step 3: Pressure test

The pressure drop over the fabric was measured to ensure that the wearer of the mask could breathe easily through the mask. A differential pressure sensor, type SDP2000-L, was attached to the particle chamber (Supplementary Figure S1). The analogue differential pressure sensor is temperature compensated, calibrated and has a resolution of 11 Pa with a repeatability of 0.3% and accuracy of 1%. We calculated the pressure as follows:

$$\Delta P = \left(\frac{\Delta P_{fabric}}{100}\right) \times \left(\frac{Area_{fabric\_sample}}{Area_{best\_mask}}\right)$$

ΔP_{mask} = pressure delta over full mask area [mbar]

ΔP_{mask} = measured pressure in particle chamber [Pa]

$Area_{fabric\_sample}$ = the surface area of the tested fabric sample $[m^2]$

$Area_{best\_mask}$ = the surface area of the best performing design $[m^2]$

Step 4: Hydrophobic test

The hydrophobic test compared the capacity of different fabrics to resist the penetration of fluids. Measuring wet particles can be seen as cross-validation of the dry particle testing.

All fabrics deemed breathable by the researcher were tested. A solution of 0.5 MacFarland *Staphylococcus epidermidis* (ATCC 12228) was sprayed on the fabrics. Subsequently, by means of a vacuum pump, air was drawn through the fabrics a rate of 1.2 L/min per cm^2 for 20 s. Culture membranes positioned underneath the fabrics were transferred on to blood agar plates. After incubation for 24 h at 37°C, results were read by two independent readers as the number of colony forming units. An ordinary laboratory paper towel was used as a control; an IIR-surgical mask served as a reference. The amount of fluid applied was unrealistically high as compared with exposure in a real-life setting.

Step 5: Wash test

We tested the commercial filters for usability after washing at 90°C.

Step 6: Determination of needed population compliance

We determined which percentage of the population would need to wear the mask for the rate of growth of disease to fall below 1. This was calculated as 0.352 divided by mask efficiency, assuming $R_0 = 2.4$. Only breathable materials were included.

Results

Step 1: Particle test

Particle tests were performed on potential mask materials and imported N95/FFP2/KN95 masks. (Table I, Supplementary

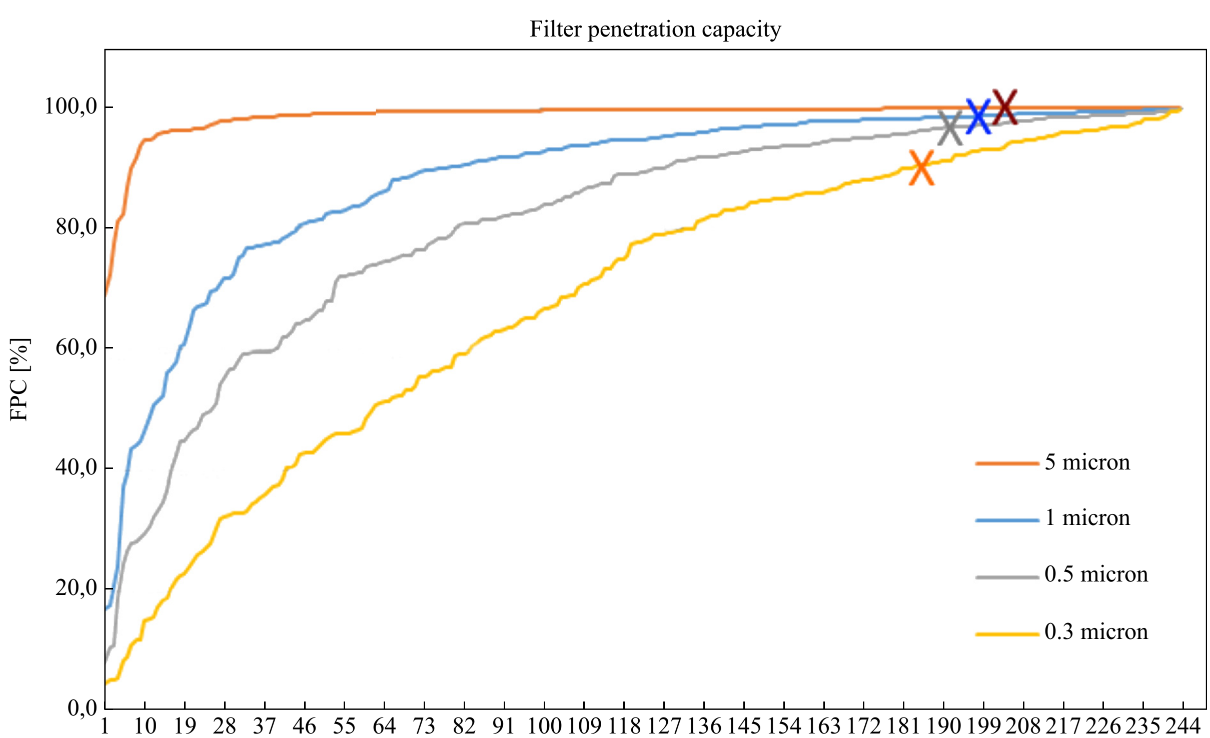

Figure 1. Filter penetration capacity (FPC) for different particle sizes of 244 different imported N95/FFP2/KN95 masks that entered the Dutch market in April and May 2020. The 'X' indicates the FPC of our best-performing model for each particle size.

Table S1) The best-performing commercially manufactured material was the ePM$_1$ 85%, either alone or between quilt fabric. Of the more readily available fabrics, leather performed the best, followed by a folded coffee filter between quilt fabric, a folded household paper towel between quilt fabric, and microfibre fabric.

Figure 1 indicates how our best-performing self-made mask performed with respect to the 244 imported N95/FFP2/KN95 masks that we measured in April–May 2020 [26]. This figure shows the particle filtration efficiency for 0.3, 0.5, 1 and 5 μm from lowest to highest. The X indicates the filtration of the ePM$_1$ 85% commercially manufactured filter.

Step 2: Fit test

Both the duckbill model with the seams on the inside and with the seams on the outside passed the fit test (Table II, Supplementary Table S2, Supplementary Figure S4). None of the models with an inserted filter into a cotton mask provided a satisfactory fit.

Step 3: Pressure test

We used the best mask from the fit test as the reference, the duckbill with the seam inside, for calculating the pressure (Supplementary Figure S3). Of the manufactured filters, the F7, F9 and M5 showed equal or less pressure than the 3M reference mask (Table I). Both the single and folded tea towels showed equal or less pressure than the 3M reference mask.

Table II
Fit quality of model (≥100 represents a good fit)

Fabric	Form	Overall fit factor
IIR-surgical mask[a]	Surgical mask	4
3M 1862+[a]	FFP2	134
ePM$_1$ 85%	American model (flat)[b] with nose strip	22
ePM$_1$ 85%	American model (flat) with nose strip and foam	57
ePM$_1$ 85%	Belgian model (pleated)[b]	15
ePM$_1$ 85%	Belgian model (pleated) with nose strip and foam[b]	18
ePM$_1$ 85%	Duckbill with seam on inside with nose strip and foam	130
ePM$_1$ 85%	Duckbill with seam on outside with nose strip and foam	120
ePM$_1$ 85%	Flat (folded) (with quilt cloth) with nose strip and foam	56
ePM$_1$ 85%	Indian model (pleated) (with quilt cloth) with nose strip	8
ePM$_1$ 85%	Indian model (pleated) with nose strip	67
ePM$_1$ 85%	Other model (pleated)[b] with nose strip	36
ePM$_1$ 85%	Round with nose strip	79

[a] Reference.
[b] The filter was inserted.

Step 4: Hydrophobic test

Results showed considerable differences between fabrics. Four of the five commercially manufactured air filters outperformed the IIR-surgical mask (Table III). None of the other readily available fabrics performed as well as the reference mask.

Step 5: Wash test

We tested all materials that we expected could be malformed from being washed at 90°C. The manufactured filters, cleaning cloth, leather, static dust cloth and felt were all malformed after washing.

Step 6: Determination of needed population compliance

The best mask from the fit test was used as the reference, the duckbill with the seam inside. In Table I, we only included fabrics which were breathable. The percentage of the population which would have to wear a mask in order to halt the spread of SARS-CoV-2 ranges from 37% to 88%, depending upon the fabric. From the masks made from manufactured filters, the percentage of the population which would need to wear a mask ranges from 39% to 88%. If people made masks from easily available fabrics from the fabric store and/or grocery store, the reproduction rate could go below 1 if 85% of the population would wear a mask from quilt fabric with a single layer household paper towel. These masks are relatively inexpensive to manufacture. We estimate the cost of the materials of a mask at approximately €0.50 (quilting cloth) to €0.60 (ePM$_1$ 85%).

Discussion

From the above measurements, we conclude that it would be possible to reduce the R_0 of SARS-CoV-2 from 2.4 to below 1 if a minimum of 39% of the population wears a mask from ePM$_1$ 85% fabric in a duckbill form. Other commercially manufactured filters could be used, but then a greater portion of the population would need to wear them in order to achieve the desired reduction in the spread of the virus. This mask provides nearly as much protection as an FFP2 mask and would provide

Table III
Hydrophobic qualities of filter fabrics (colony forming units)

Mask fabric	Tester 1	Independent tester
IIR-surgical mask[a]	150	174
ePM$_1$ 60%[b]	120	95
ePM$_1$ 85%[b]	21	34
F7[b]	44	35
F9	15	14
M5[b]	300	180
Felt (155 g)	>1000	>1000
Quilt fabric	>1000	>1000
Tea towel	800	800
Laboratory paper towel	>1000	>1000

[a] Reference.
[b] Commercially manufactured filter.

more protection to both the user and the environment than a surgical mask. We saw that the mask according to the specifications in our study is better than approximately 80% of all commercially manufactured N95/FFP2/KN95 face masks now entering the Netherlands. This mask is hydrophobic and not washable.

We also found that the two layers of quilt fabric with a household paper towel as filter can be a viable and sustainable choice for protecting the population as it is widely available and cleanable. Unfortunately, none of the mask designs in which a filter could be placed passed the fit test due to leakage, although the duckbill form could be made with quilt fabric and a paper towel. Masks made from quilt fabric and paper towel are not hydrophobic and therefore likely to be less effective. Thus 85% of the population wearing this type of mask may still be inferior to 39% wearing the ePM$_1$ 85% fabric mask.

Few tests have been published proving the efficacy of masks made from readily available materials. In a time when people are wearing improvised masks in public in order to keep themselves and others healthy, it is of utmost importance to know their effects. Our findings indicate that the omnipresent cotton mask without a filter will not achieve the necessary reduction in reproduction of the virus.

For our calculations, we used a formula to give an estimate of R_0 if mask-wearing was the only intervention. Eikenberry *et al*. created a more advanced model, dependent upon insight into when COVID-19 antibodies provide protection against COVID-19, which populations are at risk, and the infectiousness of symptomatic, pre-symptomatic and asymptomatic COVID-19 carriers [27]. Ngonghala et al. presented another model which additionally takes public health interventions into account, such as social distancing and quarantining [28]. By combining data presented in our study about the characteristics of specific face masks with local/regional data and estimates regarding the spreading of the disease, the formulas presented by Ngonghala *et al*. or Eikenberry *et al*. may provide more precise mask efficacy estimates for specific populations.

Our tests are more specific than the European standards. For testing the filtering requirements, the EN 149+A1 (FFP masks) states that material should be tested with a particle size distribution with a 0.02- to 2-μm equivalent aerodynamic diameter with a mass median diameter of 0.6 μm [17]. The EN 14683:2014 (surgical masks) requires testing with an aerosol of *Staphylococcus aureus*, which is approximately 1 μm in size [16]. At the same time, if we looked at tests used in manufactured surgical masks, we see that it is not always clear which particles sizes are used for the bacterial filtration efficiency test. The particulate filtration efficiency test, when listed, was carried out on particles from 0.1 to 5 μm [29–31]. Our tests detected particles from 0.3 μm.

European standards may not be optimal for SARS-CoV-2, which can be carried by aerosol or droplet. The WHO considers the minimum droplet size to be 0.5 μm [32]. Two size ranges of SARS-CoV-2 aerosols have been found, one from 0.25 to 1.0 μm, and another with a diameter >2.5 μm [12]. It could thus be advisable to perform filtration tests for 0.25-μm particles. This is close to our measurement of 0.3 μm.

Only the duckbill shape passed the fit test, both with the seams on the inside as on the outside. This could be partly due to the fact that the duckbill design had few seams and thus fewer places where air could enter or escape. Hypothetically some of the other models would work well if they had been glued instead of/along with sewn.

The breathability requirements for respiratory protective devices are clear in the European standards [17]. The maximum permitted resistance (mbar) differs for FFP1, FFP2, and FFP3 masks, ranging from 0.6 to 1.0 for inhalation at 30 L/min, 2.1–3.0 for 95 L/min and 3.0 for exhalation at 160 L/m. The norm for an FFP2-mask at 30 L/min is 0.7 mbar. Our test was able to measure at 28 L/min and indicated that most masks showed a pressure drop below 0.7 mbar.

Our study has some limitations. The filters used may not be representative of all filters in these classes, in particular regarding the hydrophobic characteristics. We also performed new ‘state of the art’ tests, rather than the tests described in the European standards. Furthermore, we were not able to test the filtration value at 0.25 μm, which is the assumed smallest particle size with SARS-CoV-2. Nevertheless, we consider the filtration value at 0.3 μm relevant. We also were only able to perform the pressure test at one value, whereas the European standards suggest testing the resistance at three different values.

This research should give more insight into the next steps in developing a mask for the general population. It would be prudent to repeat the tests of the masks from commercially manufactured filters after various sterilization processes. Similarly, it would be advisable to repeat the tests on the quilt fabric mask with a single layer of household paper towel, both before and after it has been washed, because there is evidence that the pores of the cotton fabric widen after washing [33]. We would also suggest fit tests with quilt cloth and a paper towel using other mask designs.

Our study strongly supports the use of commercially manufactured filters as the fabric for an alternative face mask, specifically ePM$_1$ 85% in a duckbill form. We conclude that it is possible to halt the growth of the spread of SARS-CoV-2 if 39% of the population wore a mask from this material. This material performs better than 80% of the N95/FFP2/KN95 masks entering the Netherlands.

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Conflict of interest statement
None.

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Appendix A. Supplementary data

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