Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 April 2020 doi:10.20944/preprints202004.0203.v1

Face Masks Against COVID-19: An Evidence Review

Jeremy Howard[a,c,1], **Austin Huang**[b], **Zhiyuan Li**[k], **Zeynep Tufekci**[m], **Vladimir Zdimal**[e], **Helene-Mari van der Westhuizen**[f,g], **Arne von Delft**[o,g], **Amy Price**[n], **Lex Fridman**[d], **Lei-Han Tang**[i,j], **Viola Tang**[l], **Gregory L. Watson**[h], **Christina E. Bax**[s], **Reshama Shaikh**[q], **Frederik Questier**[r], **Danny Hernandez**[p], **Larry F. Chu**[n], **Christina M. Ramirez**[h], **and Anne W. Rimoin**[t]

[a]fast.ai, 101 Howard St, San Francisco, CA 94105, US; [b]Warren Alpert School of Medicine, Brown University, 222 Richmond St, Providence, RI 02903; [c]Data Institute, University of San Francisco, 101 Howard St, San Francisco, CA 94105, US; [d]Department of Electrical Engineering & Computer Science, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139; [e]Institute of Chemical Process Fundamentals, Czech Academy of Sciences, Rozvojová 135, CZ-165 02 Praha 6, Czech Republic; [f]Department of Primary Health Care Sciences, Woodstock Road, University of Oxford, OX2 6GG, United Kingdom; [g]TB Proof, Cape Town, South Africa; [h]Department of Biostatistics, UCLA Fielding School of Public Health, 650 Charles E Young Drive, Los Angeles, CA 90095; [i]Department of Physics, Hong Kong Baptist University, Kowloon Tong, Hong Kong SAR, China; [j]Complex Systems Division, Beijing Computational Science Research Center, Haidian, Beijing 100193, China; [k]Center for Quantitative Biology, Peking University, Haidian, Beijing 100871, China; [l]Department of Information Systems, Business Statistics and Operations Management, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong SAR, China; [m]University of North Carolina at Chapel Hill; [n]School of Medicine Anesthesia Informatics and Media (AIM) Lab, Stanford University, 300 Pasteur Drive, Grant S268C, Stanford, CA 94305; [o]School of Public Health and Family Medicine, University of Cape Town, Anzio Road, Observatory, 7925, South Africa; [p]OpenAI, 3180 18th St, San Francisco, CA 94110; [q]Data Umbrella, 345 West 145th St, New York, NY 10031; [r]Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium; [s]University of Pennsylvania, 3400 Civic Center Blvd, Philadelphia, PA 19104; [t]Department of Epidemiology, UCLA Fielding School of Public Health, 650 Charles E Young Drive, Los Angeles, CA 90095

This manuscript was compiled on April 12, 2020

The science around the use of masks by the general public to impede COVID-19 transmission is advancing rapidly. Policymakers need guidance on how masks should be used by the general population to combat the COVID-19 pandemic. Here, we synthesize the relevant literature to inform multiple areas: 1) transmission characteristics of COVID-19, 2) filtering characteristics and efficacy of masks, 3) estimated population impacts of widespread community mask use, and 4) sociological considerations for policies concerning mask-wearing. A primary route of transmission of COVID-19 is likely via small respiratory droplets, and is known to be transmissible from presymptomatic and asymptomatic individuals. Reducing disease spread requires two things: first, limit contacts of infected individuals via physical distancing and contact tracing with appropriate quarantine, and second, reduce the transmission probability per contact by wearing masks in public, among other measures. The preponderance of evidence indicates that mask wearing reduces the transmissibility per contact by reducing transmission of infected droplets in both laboratory and clinical contexts. Public mask wearing is most effective at stopping spread of the virus when compliance is high. The decreased transmissibility could substantially reduce the death toll and economic impact while the cost of the intervention is low. Thus we recommend the adoption of public cloth mask wearing, as an effective form of source control, in conjunction with existing hygiene, distancing, and contact tracing strategies. We recommend that public officials and governments strongly encourage the use of widespread face masks in public, including the use of appropriate regulation.

COVID-19 | SARS-CoV-2 | Masks | Pandemic

Policymakers need urgent guidance on the use of masks by the general population as a tool in combating SARS-CoV-2, the respiratory virus that causes COVID-19. Masks have been recommended as a potential tool to tackle the COVID-19 pandemic since the initial outbreak in China (1), although usage during the outbreak varied by time and province (2). Globally, countries are grappling with translating the evidence of public mask wearing to their contexts. These policies are being developed in a complex decision-making environment, with a novel pandemic, rapid generation of new research, and exponential growth in cases and deaths in many areas. There is currently a global shortage of N95 or FFP2 respirators and surgical masks for use in hospitals. Simple cloth masks present a pragmatic solution for use by the public. This has been supported by the United States and European Centres for Disease Control. We present a literature review on the role of simple cloth masks and policies in reducing COVID-19 transmission.

1. Components to Evaluate for Public Mask Wearing

In order to identify whether public mask wearing is an appropriate policy, we need to consider these questions:

1. Do asymptomatic or presymptomatic patients pose a risk of infecting others?
2. Would a face mask likely decrease the number of people infected by an infectious mask wearer?
3. Are there alternative face covers that will not disrupt the medical supply chain, e.g. homemade cloth masks?
4. Will wearing a mask impact the probability of the wearer becoming infected themselves?
5. Does mask use reduce compliance with other recommended strategies, such as physical distancing and quarantine?

Significance Statement

Governments are evaluating the use of non-medical masks in the community amidst conflicting guidelines from health organizations. This review synthesizes available evidence to provide clarity, and advances the use of the 'precautionary principle' as a key consideration in developing policy around use of non-medical masks in public.

Jeremy Howard prepared the initial literature list; Reshama Shaikh prepared the initial literature summaries; Frederik Questier did additional literature searches and summaries; Zhiyuan Li, Violet Tang, Lei-Han Tang, and Danny Hernandez did impact modeling; Zeynep Tufekci provided sociological research and analysis; Helene-Mari van der Westhuizen and Arne von Delft provided analysis of additional impacts; Christina Bax provided review and feedback; All authors contributed to the writing.

Anne W. Rimoin is an editor of the British Medical Journal. Larry F. Chu is a member of the editorial advisory board of the British Medical Journal.

[1]To whom correspondence should be addressed. E-mail: jphoward@usfca.edu

6. Are there any other potential benefits to universal mask wearing such as reducing stigma, signaling solidarity, and increased compliance with other measures?

We will evaluate each consideration in turn.

2. Transmission Characteristics of COVID-19

A primary route of transmission of SARS-CoV-2 is likely via small droplets that are ejected when speaking, coughing or sneezing. The most common droplet size threshold has a minimum at 5 µm to 10 µm (3, 4). There is much debate about whether these droplets should sometimes be considered an aerosol (5). An added complexity is that aerosols are not consistently defined in the literature.

Although earlier studies assumed that droplets were spread mainly through coughing, a more recent analysis has found that transmission through talking may be a key vector, with louder speech creating increasing quantities and sizes of droplets, which are associated with a higher viral load (6).

SARS-CoV-2 is highly transmissible, with a replication number estimated to be approximately 2.4 (7) although estimates vary (8) and will likely change as improved measurements of asymptomatic spread become available. Many COVID-19 patients are asymptomatic, and nearly all have a pre-symptomatic incubation period ranging from 2 to 15 days, with a median length of 5.1 days (9). Patients are most infectious during the initial days of infection (10–15), when symptoms are mildest or not present. This characteristic differentiates SARS-CoV-2 (COVID-19) from SARS-CoV, as replication is activated early in the upper respiratory tract (14, 16). High viral titers of SARS-CoV-2 are reported in the saliva of COVID-19 patients. These titers have been highest at time of patient presentation and viral levels are just as high in asymptomatic or presymptomatic patients (11, 16).

A consequence of these disease characteristics is that any successful intervention policy must properly address transmission due to infectious patients that display few or no symptoms and may not realize that they are infected.

3. Filtering Capability of Masks

Masks can be made of different materials and designs (17) which influence their filtering capability. There are rigorous standards evaluating masks used in healthcare settings but these focus on personal protective equipment (PPE) efficacy, that is, the ability of the mask to protect the wearer from infectious particles. N95 (the American standard; the equivalent in Europe is FFP2) respirators are recommended for health workers conducting aerosol-generating procedures during clinical care of COVID-19 patients. While it has been shown that N95 or FFP2 respirators perform well as PPE, they can become a scarce resource during a pandemic. Toner and Waldhorn (2006) (18) point out that shortages of N95 or FFP2 respirators should be anticipated, and say that if no other masks are available, surgical masks, which will provide droplet protection, should be used. One approach that has been studied for handling N95 or FFP2 respirator shortages is sterilization and re-use, which can be effective (19).

Masks can also be used for source control, which refers to blocking droplets ejected by the wearer, as well as PPE. Although we consider both of these as important, our focus in this paper is on source control, because if everyone is wearing masks to decrease the chance that they themselves are unknowingly infecting someone, everyone ends up being more protected.

Multiple studies show the filtration effects of cloth masks relative to surgical masks. Particle sizes for speech are on the order of 1 µm (20) while typical definitions of droplet size are 5 µm-10 µm (5). Generally available household materials had between a 49% and 86% filtration rate for 0.02 µm exhaled particles whereas surgical masks filtered 89% of those particles (21). In a laboratory setting, household materials had 3% to 60% filtration rate for particles in the relevant size range, finding them comparable to some surgical masks (22). In another laboratory setup, a tea cloth mask was found to filter 60% of particles between 0.02 µm to 1 µm, where surgical masks filtered 75% (23). Dato et al (2006) (24), note that "quality commercial masks are not always accessible." They designed and tested a mask made from heavyweight T-shirts, finding that it "offered substantial protection from the challenge aerosol and showed good fit with minimal leakage".Although cloth and surgical masks are primarily targeted towards droplet particles, some evidence suggests they may have a partial effect in reducing viral aerosol shedding (25).

When considering the relevance of these studies of ingress, it's important to note that they are likely to substantially underestimate effectiveness of masks for source control. When someone is breathing, speaking, or coughing, only a tiny amount of what is coming out of their mouths is already in aerosol form. Nearly all of what is being emitted is droplets. Many of these droplets will then evaporate and turn into aerosolized particles that are 3 to 5-fold smaller. The point of wearing a mask as source control is largely to stop this process from occurring, since big droplets dehydrate to smaller aerosol particles that can float for longer in air (26).

Anfinrud et al (6) used laser light-scattering to sensitively detect droplet emission while speaking. Their analysis showed that virtually no droplets were "expelled" with a homemade mask consisting of a washcloth attached with two rubber bands around the head, while significant levels were expelled without a mask. The authors stated that "wearing any kind of cloth mouth cover in public by every person, as well as strict adherence to distancing and handwashing, could significantly decrease the transmission rate and thereby contain the pandemic until a vaccine becomes available."

An important focus of analysis for public mask wearing is droplet source control. This refers to the effectiveness of blocking droplets from an infectious person, particularly during speech, when droplets are expelled at a lower pressure and are not small enough to squeeze through the weave of a cotton mask. Many recommended cloth mask designs also include a layer of paper towel or coffee filter, which could increase filter effectiveness for PPE, but does not appear to be necessary for blocking droplet emission (6, 27, 28).

In summary, there is laboratory-based evidence that household masks have some filtration capacity in the relevant droplet size range, as well some efficacy in blocking droplets and particles from the wearer (26). That is, these masks help people keep their droplets to themselves.

4. Mask Efficacy Studies

Although no randomized controlled trials (RCT) on the use of masks as source control for SARS-CoV-2 has been published, a number of studies have attempted to indirectly estimate the efficacy of masks. Overall, an evidence review (29) finds "moderate certainty evidence shows that the use of handwashing plus masks probably reduces the spread of respiratory viruses."

The most relevant paper (30), with important implications for public mask wearing during the COVID-19 outbreak, is one that compares the efficacy of surgical masks for source control for seasonal coronavirus, influenza, and rhinovirus. With ten participants, the masks were effective at blocking coronavirus droplets of all sizes for every subject. However, masks were far less effective at blocking rhinovirus droplets of any size, or of blocking small influenza droplets. The results suggest that masks may have a significant role in source control for the current coronavirus outbreak. The study did not use COVID-19 patients, and it is not yet known whether seasonal coronavirus behaves the same as SARS-CoV-2; however, they are of the same genus, so similar behavior is likely.

Another relevant (but under-powered, with n=4) study (31) found that a cotton mask blocked 96% (reported as 1.5 log units or about a 36-fold decrease) of viral load on average, at eight inches away from a cough from a patient infected with COVID-19. If this is replicated in larger studies it would be an important result, because it has been shown (32) that "every 10-fold increase in viral load results in 26% more patient deaths" from "acute infections caused by highly pathogenic viruses".

A comparison of homemade and surgical masks for bacterial and viral aerosols (21) observed that "the median-fit factor of the homemade masks was one-half that of the surgical masks. Both masks significantly reduced the number of microorganisms expelled by volunteers, although the surgical mask was 3 times more effective in blocking transmission than the homemade mask." Research focused on aerosol exposure has found all types of masks are at least somewhat effective at protecting the wearer. Van der Sande et al (33) found that "all types of masks reduced aerosol exposure, relatively stable over time, unaffected by duration of wear or type of activity", and concluded that "any type of general mask use is likely to decrease viral exposure and infection risk on a population level, despite imperfect fit and imperfect adherence". Overall however, analysis of particle filtration is likely to underestimate the effectiveness of masks, since the fraction of particles that are emitted as aerosol (vs. droplet) is quite small (26). Analysis of seasonal coronavirus compared to rhinovirus (30) suggests that filtration of COVID-19 may be much more effective, especially for source control.

The importance of using masks for health care workers has been observed (34) in three Chinese hospitals where, in each hospital, medical staff wearing masks (mainly in quarantine areas) had no COVID-19 infections, despite being around COVID-19 patients far more often, whilst other medical staff had 10 or more infections in each of the three hospitals.

Masks seem to be effective for source control in the controlled setting of an airplane. One case report (35) describes a man who flew from China to Toronto and then tested positive for COVID-19. He was wearing a mask during the flight. The 25 people closest to him on plane/flight attendants were tested and all were negative. Nobody has been reported from that flight as getting COVID-19. Another case study involving a masked influenza patient on an airplane (36) found that "wearing a face mask was associated with a decreased risk for influenza acquisition during this long-duration flight".

Guideline development for health worker personal protective equipment have focused on whether surgical masks or N95 respirators should be recommended. Most of the research in this area focuses on influenza. At this point, it is not known to what extent findings from influenza studies apply to COVID-19 filtration. Wilkes et al (37) found that "filtration performance of pleated hydrophobic membrane filters was demonstrated to be markedly greater than that of electrostatic filters." However, even substantial differences in materials and construction do not seem to impact the transmission of droplet-borne viruses in practice, such as a meta-analysis of N95 respirators compared to surgical masks (38) that found "the use of N95 respirators compared with surgical masks is not associated with a lower risk of laboratory-confirmed influenza." Johnson et al (39) showed that "surgical and N95 masks were equally effective in preventing the spread of PCR-detectable influenza". Radonovich et al (40) found in an outpatient setting that "use of N95 respirators, compared with medical masks... resulted in no significant difference in the rates of laboratory-confirmed influenza."

One of the most frequently mentioned papers evaluating the benefits and harms of cloth masks have been by MacIntyre et al (41). Findings have been misinterpreted, and therefore justify detailed discussion here. The authors "caution against the use of cloth masks" for healthcare professionals compared to the use of surgical masks and regular procedures, based on an analysis of transmission in hospitals in Hanoi. We emphasize the setting of the study - health workers using masks to protect themselves against infection. The study compared a "surgical mask" group which received 2 new masks per day, to a "cloth mask" group that received 5 masks for the entire 4 week period and were required to wear the masks all day, to a "control group" which used masks in compliance with existing hospital protocols, which the authors describe as a "very high level of mask use". It is important to note that the authors did not have a "no mask" control group because it was deemed "unethical to ask participants to not wear a mask." The study does not inform policy pertaining to public mask wearing as compared to the absence of masks in a community setting, since there is not a "no mask" group. The results of the study show that the group with a regular supply of new surgical masks each day had significantly lower infection of rhinovirus than the group that wore a limited supply of cloth masks. This paper lends support to the use of clean, surgical masks by medical staff in hospital settings to avoid rhinovirus infection by the wearer, and is consistent with other studies that show cloth masks provide poor filtration for rhinovirus (30). Its implementation does not inform the effect of using cloth masks versus not using masks in a community setting for source control of SARS-CoV-2, which is of the same genus as seasonal coronavirus, which has been found to be effectively filtered by cloth masks in a source control setting (30).

A. Studies of Impact on Community Transmission. When evaluating the available evidence for the impact of masks on community transmission, it is critical to clarify the setting of the research study (health care facility or community), the res-

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 April 2020 doi:10.20944/preprints202004.0203.v1

piratory illness being evaluated and what reference standard was used (no mask or surgical mask). There are no RCTs that have been done to evaluate the impact of masks on community transmission during a coronavirus pandemic. While there is some evidence from influenza outbreaks, the current global pandemic poses a unique challenge. A review (42) of 67 studies including randomized controlled trials and observational studies found that simple and lowcost interventions would be useful for reducing transmission of epidemic respiratory viruses. The review recommended that "the following effective interventions should be implemented, preferably in a combined fashion, to reduce transmission of viral respiratory disease: 1. frequent handwashing with or without adjunct antiseptics; 2. barrier measures such as gloves, gowns, and masks with filtration apparatus; and 3. suspicion diagnosis with the isolation of likely cases". However, it cautioned that routine longterm implementation of some measures assessed might be difficult without the threat of an epidemic.

Seuess et al conducted an RCT (43)that suggests household transmission of influenza can be reduced by the use of non-pharmaceutical interventions, namely the use of face masks and intensified hand hygiene, when implemented early and used diligently. Concerns about acceptability and tolerability of the interventions should not be a reason against their recommendation (43). Cowling et al (44) investigated hand hygiene and face masks in an RCT that seemed to prevent household transmission of influenza virus when implemented within 36 hours of index patient symptom onset. These findings suggest that non-pharmaceutical interventions are important for mitigation of pandemic and inter-pandemic influenza.

RCT findings by Aiello et al (45) "suggest that face masks and hand hygiene may reduce respiratory illnesses in shared living settings and mitigate the impact of the influenza A (H1N1) pandemic". A randomized intervention trial (46) found that "face masks and hand hygiene combined may reduce the rate of ILI [influenza-like illness] and confirmed influenza in community settings. These non-pharmaceutical measures should be recommended in crowded settings at the start of an influenza pandemic." The authors noted that their study "demonstrated a significant association between the combined use of face masks and hand hygiene and a substantially reduced incidence of ILI during a seasonal influenza outbreak. If masks and hand hygiene have similar impacts on primary incidence of infection with other seasonal and pandemic strains, particularly in crowded, community settings, then transmission of viruses between persons may be significantly decreased by these interventions."

An observational study in Hong Kong on SARS (47) found "frequent mask use in public venues, frequent hand washing, and disinfecting the living quarters were significant protective factors (OR 0.36 to 0.58)". An important observation was that "members of the case group [infected with SARS] were less likely than members of the control group [not infected] to have frequently worn a face mask in public venues (27.9% vs. 58.7%)".

B. Implementation and Sociolological Considerations. For a novel disease where much is unknown, it is important to examine the context of studies closely and also distinguish "absence of evidence" from "evidence of absence" (2). We discuss estimates of cloth mask filtering performance in Filtering Capability of Masks and summarize modelling on population impact in Estimating Population Impacts.

Some of the concerns about public mask wearing have not been around primary evidence for the efficacy of source control, but concerns about how they will be used. We present some considerations for the translation of evidence about public mask wearing to diverse countries across the globe, outside of the parameters of a controlled research setting:

B.1. Supply chain management of N95 respirators and surgical masks. There has been a global shortage of protective equipment for health workers, with health workers falling ill and dying of occupationally acquired COVID-19 disease (48). Public messaging encouraging mask use and depleting critical supplies have been a major concern. Some regions, like South Korea and Taiwan, have decided to promote surgical mask use on a mass scale and opted to address potential stock issues through rapidly increasing production of surgical masks. In regions where surgical mask supplies are scarce, cloth masks may be a pragmatic temporary alternative to surgical masks for the public.

B.2. Sociological considerations and anticipating population-level behavior changes. It is difficult to predict the behavior change that would accompany regulations encouraging public mask use. One concern around public health messaging promoting the use of face-covering has been that members of the public may use risk compensation behavior and neglect physical distancing based on overvaluing the protection a surgical mask may offer due to an exaggerated or false sense of security (49). Similar arguments have previously been made for HIV prevention strategies (50) (51) and other safety devices and mandates such as motorcycle helmet laws (52) and seat-belts (53). However, research on these topics finds no such increase in adverse outcomes at the population level but rather improvements in safety and well-being, suggesting that even if risk compensation occurs in some individuals, that effect is dwarfed by the increased safety at the population level (53, 54). Further, even for deliberately high-risk recreational activities such as alpine skiing and snowboarding, wearing a helmet was generally associated with risk reduction oriented-behavior (55), suggesting safety devices are both compatible with and perhaps encourage safety-oriented behavior. Even for high-risk recreational activities like alpine skiing and snowboarding, helmet use has greatly reduced injury rates (56).

In general, various forms of risk compensation theories have been proposed for many different safety innovations, but have been not found to have empirical support (57) at the population level. These findings strongly suggest that, instead of withholding a preventative tool, accompanying it with accurate messaging that combines different preventative measures would display trust in the general public's ability to act responsibly and empower citizens, and risk compensation is unlikely to undo the positive benefits at the population level (58).

At the height of the 2009 influenza epidemic in Mexico City it was found (59) that mandatory mask requirements increased compliance compared to voluntary recommendations. Voluntary compliance was strongly influenced by public perception regarding the effectiveness of the recommended measures.

For many infectious diseases, including, for example, tuberculosis, health authorities recommend masks only for those

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 April 2020 doi:10.20944/preprints202004.0203.v1

infected or people who are taking care of someone infected. However, research shows that many sick people are reluctant to wear a mask if it identifies them as sick, and thus end up not wearing them at all in an effort to avoid the stigma of illness (60, 61). Stigma is a powerful force in human societies, and many illnesses come with stigma for the sick as well as fear of them, and managing the stigma is an important part of the process of controlling epidemics as stigma also leads to people avoiding treatment as well as preventive measures that would "out" their illness (62). Many health authorities have recommended wearing masks for COVID-19 only if people are sick; however, reports of people wearing masks being attacked, shunned and stigmatized have already been observed (63). Having masks worn only by the suspected/confirmed infected also has led to employers in high-risk environments like grocery stores and prisons, and even hospitals, banning employees from wearing one sometimes with the idea that it would scare the customer or the patients (64, 65). Further, in many countries, minorities suffer additional stigma and assumptions of criminality (66). In that vein, black people in the United States have reported that they were reluctant to wear masks in public during this pandemic for fear of being mistaken as criminals (67, 68). Even if it were possible to encourage only infected people to wear masks, given the lack of access to testing in many countries, it is not possible for many people to know for sure if they are infected or not (69). Thus, while this paper has shown the importance of masks for source-control – preventing asymptomatic and presymptomatic people from infecting others – it may not even be possible to have infected/sick people wear masks due to stigma, employer restrictions, or simple lack of knowledge of ones status without mask-wearing becoming universal policy.

Another important benefit of recommending universal mask wearing would be to serve as a visible signal and reminder of the pandemic, and given the importance of ritual and solidarity in human societies (70), it is plausible that visible, public signaling via mask wearing can potentially increase compliance with other health measures as well, such as keeping distance and hand-washing. Health, especially during an epidemic, is a form of public good in that everyone else's health behaviors improve the health odds of everyone else, and that it is non-rivalrous in that one person's health does not diminish the health of anyone else (71, 72). Visible signals play an important role in human societies (73). As such, signaling participation in health behaviors by wearing a mask as well as visible enforcement (for example, shops asking customers to wear masks) can increase compliance (74). Further, historically epidemics are a time of fear, confusion and helplessness (75, 76). Mask-wearing and even mask-making or distribution can provide feelings of empowerment and self-efficacy (77), which would in turn also suggest masks could increase compliance in other health-behaviors as well by increasing self-efficacy. In Hong Kong, for example, a community-driven focus on epidemic prevention started in the early days of COVID-19, and included community activists acquiring and distributing masks especially to those without resources and the elderly, even before it was officially declared a pandemic or before their own government had taken strong steps (78). Currently, Hong Kong has not only a relatively contained epidemic compared with many other countries, but a significant reduction in influenza cases as well which their health authorities attribute, among other factors, to the near-universal mask wearing and strong norms around it (79–81).

C. Universal or near-universal mask wearing. Estimating adherence to regulations for public mask wearing is a key input for modeling the impact of public mask wearing. Telephone surveys during the SARS-CoV-2 outbreak in Hong Kong reported enhanced adherence to public mask wearing as the pandemic progressed over three weeks, with 74.5% self reported mask wearing when going out increasing to 97.5%, without mandatory requirements (82). Similar surveys reported face mask use in Hong Kong during the SARS outbreak in 2003 as 79% (83), and approximately 10% during the influenza A(H1N1) pandemic in 2009 (84). This suggests that the public have enhanced awareness of their risk, and display higher adherence levels to prevention strategies than during other epidemics. Cloth masks could be an additional tool to enhance awareness of the importance of physical distancing in public places, serving as a visual reminder. Should masks be reserved solely for use in symptomatic patients, they become a symbol of illness and could lead to public stigmatization that discourages use, as has been described for patients with tuberculosis (61). Countries like the Czech Republic and Hong Kong offer interesting perspectives on the role of citizen advocacy and on the acceptability of face-covering in public.

D. Balancing potential harm of cloth masks with additional benefits for concurrent epidemic. Based on our detailed discussion above, cloth masks have not been shown to increase the risk of infection in people using them compared to not wearing any mask. While the focus of this article has been on preventing the spread of COVID-19 disease through public mask wearing, many low-middle income countries face concurrent epidemics of diseases like tuberculosis. Tuberculosis kills 1.5 million people globally per year, and in 2018, 10 million people fell ill (85). Face covering has been shown to also reduce the transmission of tuberculosis (86) and offer additional benefits to public mask wearing. Similarly, influenza transmissibility in the community was found to have declined by 44% in Hong Kong after the implementation of changes in population behaviors, including social distancing and increased mask wearing, enforced in most stores, during the COVID-19 outbreak (82).

It has been noted (87) that ensuring compliance with non-pharmaceutical interventions can be challenging: "Mask wearing is a promising non-pharmaceutical intervention to reduce risk of secondary transmission of viral URI [upper respiratory infections], but it is likely that adherence to mask wearing would occur only if there was a major pandemic that resulted in a heightened level of community concern and fear." Many regions have now passed laws to ensure compliance. The first RCT (2008) on mask use (88) "found compliance to be low, but compliance is affected by the perception of risk. In a pandemic, we would expect compliance to improve." The authors noted that "in compliant users, masks were highly efficacious."

5. Estimating Population Impacts

At the national and global scale, effective local interventions are aggregated into epidemiological parameters of disease spread. The standard epidemiological measure of spread is known as the reproduction number R_0 which parameterizes

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 12 April 2020 doi:10.20944/preprints202004.0203.v1

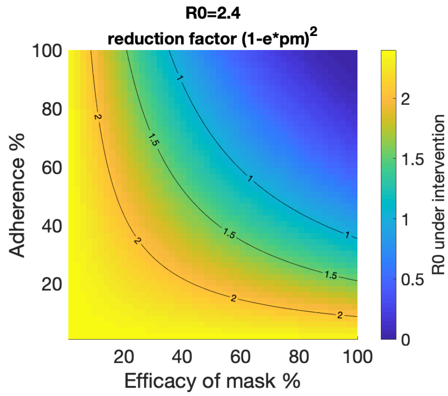

Fig. 1. Impact of public mask wearing under the full range of mask adherence and efficacy scenarios. The color indicates the resulting reproduction number R_0 from an initial R_0 of 2.4 (7).

the number of cases infected by one case,in a completely susceptible population. R_0 determines the rate of growth, with a superlinear effect. The goal of any related healthcare policy is to have an aggregate effect of reducing R_0 to below 1.0.

Efficacy of face masks within local interventions would have an aggregate effect on the reproduction number of the epidemic. What is the magnitude of such an effect? The HKBU COVID-19 Modelling Group developed a transmission model that incorporated mask wearing and mask efficacy as a factor in the model (89). They estimate reductions in the basic reproduction number R_0 under common intervention measures. For wearing masks, they find that wearing masks reduces R_0 by a factor $(1 - ep_m)^2$, where e is the efficacy of trapping viral particles inside the mask, and p_m is the percentage of the population that wears masks. When combined with contact tracing, the two effects multiply.

A conservative assessment applied to the COVID-19 estimated R_0 of 2.4 (7) might posit 50% mask usage and a 50% mask efficacy level, reducing R_0 to 1.35, an order of magnitude impact rendering spread comparable to the reproduction number of seasonal influenza. To put this in perspective, 100 cases at the start of a month becomes 31,280 cases by the month's end ($R_0 = 2.4$) vs. only 584 cases ($R_0 = 1.35$). Such a slowdown in case-load protects healthcare capacity and renders a local epidemic amenable to contact tracing interventions that can eliminate the spread entirely.

A full range of efficacy e and adherence p_m is shown with the resulting R_0 in Figure 1, illustrating regimes in which growth is halted entirely ($R_0 < 1$) as well as pessimistic regimes (e.g. due to poor implementation or population compliance) that nonetheless result in a beneficial effect in suppressing the exponential growth of the pandemic.

Yan et al (90) provide an additional example of an incremental impact assessment of respiratory protective devices using an augmented variant of a traditional SIR model in the context of influenza with N95 respirators. They showed that a sufficiently high adherence rate (~ 80% of the population) resulted in the elimination of the outbreak with most respiratory protective devices.

Qualitative comparisons of outcomes between countries (91, 92) are suggestive of policy differences leading to differences in disease spread of up to three orders of magnitude. Although between-country comparisons do not allow for causal attribution, they suggest mask wearing to be a low-risk measure with a potentially large positive impact, with many countries with widespread use of masks in public keeping deaths below one in a million.

Abaluck et al (93) extend the between-country analyses from a cost perspective, estimating the marginal benefit per cloth mask worn to range from $3,000-$6,000. They also found that "the average daily growth rate of confirmed positives is 18% in countries with no preexisting mask norms and 10% in countries with such norms." and "that the growth rate of deaths is 21% in countries with no mask norms and 11% in countries with such norms."

6. Discussion and Recommendations

Our review of the literature offers evidence in favor of widespread mask use to reduce community transmission: non-medical masks use materials that obstruct droplets of the necessary size; people are most infectious in the initial period post-infection, where it is common to have few or no symptoms (10–16); non-medical masks have been effective in reducing transmission of influenza; non-medical masks have been shown to be effective in small trials at blocking transmission of coronavirus; and places and time periods where mask usage is required or widespread have shown substantially lower community transmission.

The available evidence suggests that near-universal adoption of non-medical masks when out in public, in combination with complementary public health measures could successfully reduce effective-R to below 1.0, thereby stopping community spread. Economic analysis suggests that the impact of mask wearing could be thousands of US dollars saved per person per mask (93).

Interventions to reduce COVID-19 spread should be prioritized in order of their expected multiple on effective R divided by their cost. By this criterion experimentation with and deployment of universal masks look particularly promising. When used in conjunction with widespread testing, contact tracing, quarantining of anyone that may be infected, hand washing, and physical distancing, face masks are a valuable tool to reduce community transmission. All of these measures, through their effect on R_0, have the potential to reduce the period of lockdown required. As governments talk about relaxing lockdowns, keeping transmissions low enough to preserve health care capacity will be critical until a vaccine can be developed. Mask wearing may be critical to preventing a second wave of infections from overwhelming the health care system – further research is urgently needed here.

UNESCO states that "when human activities may lead to morally unacceptable harm that is scientifically plausible but uncertain, actions shall be taken to avoid or diminish that harm" (94). This is known as the "precautionary principle". The World Charter for Nature, which was adopted by the UN General Assembly in 1982, was the first international endorsement of the precautionary principle. It was implemented in an international treaty in the 1987 Montreal Protocol. The loss of life and economic destruction that has been seen already from COVID-19 is a "morally unacceptable harm". The positive impact of public mask wearing on this is "scientifically plausible but uncertain". This notion is reflected in Figure 1 - while researchers may reasonably disagree on the magnitude of transmissibility reduction and compliance, seemingly modest benefits can be massively beneficial in the aggregate due to the exponential character of the transmission process. Therefore, the action of ensuring widespread use of masks in the community should be taken, based on this principle (95).

Models suggest that public mask wearing is most effective at stopping spread of the virus when compliance is high. This is the same situation as we see with vaccines - the more people are vaccinated, the higher the benefit to the whole population including those who cannot be vaccinated like infants or immuno-compromised people. A common policy response to this conundrum is to ensure compliance by using laws and regulations, such as widespread state laws in the US which require vaccinations to attend school. Research shows that the strength of the mandate to vaccinate greatly influences compliance rates for vaccines and that policies that set a higher bar for vaccine exemptions result in higher vaccination rates. (96) The same approach is now being used in many jurisdictions to increase mask wearing compliance, by mandating mask use in a variety of settings (such as public transportation or grocery stores or even at all times outside the home). Early results suggest that these laws are effective at increasing compliance and slowing or stopping the spread of COVID-19 (91). We recommend that mask use requirements are implemented by governments, or when governments do not, by organizations that provide public-facing services, such as transit service providers or stores, as "no mask, no service" rules. Such mandates must be accompanied by measures to ensure access to masks, possibly including distribution and rationing mechanisms so that they do not become discriminatory but remain focused on the public health benefit. Given the value of the source control principle, especially for presymptomatic people, it is not good enough for only employees to wear masks, customers must wear masks as well.

It is also important for health authorities to provide clear guidelines for the production, use and sanitization or re-use of face masks, and consider their distribution as shortages allow. A number of countries have distributed surgical masks (South Korea, Taiwan) from early on while Japan and Singapore are now distributing cloth masks to their whole population. Clear and implementable guidelines can help increase compliance, and bring communities closer to the goal of reducing and ultimately stopping the spread of COVID-19.

Materials and Methods

A community-driven approach was used for building the paper list used in this literature review. A multidisciplinary community of researchers used online tools to review and actively discuss publications related to the question of the effectiveness and policy of public mask wearing.

ACKNOWLEDGMENTS. Thank you to Sylvain Gugger for LATEX help, and to Cam Woodsum for assistance with preparing bibtex citations.

References

1. Q Wang, C Yu, Letter to editor: Role of masks/respirator protection against 2019-novel coronavirus (COVID-19). *Infect. Control. & Hosp. Epidemiol.*, 1–7 (year?).
2. S Feng, et al., Rational use of face masks in the COVID-19 pandemic. *The Lancet Respir. Medicine* **0** (2020).
3. J Duguid, The size and the duration of air-carriage of respiratory droplets and droplet-nuclei. *Epidemiol. & Infect.* **44**, 471–479 (1946).
4. L Morawska, et al., Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. *J. Aerosol Sci.* **40**, 256–269 (2009).
5. L Bourouiba, Turbulent Gas Clouds and Respiratory Pathogen Emissions: Potential Implications for Reducing Transmission of COVID-19. *JAMA* (2020).
6. P Anfinrud, CE Bax, V Stadnytskyi, A Bax, Could sars-cov-2 be transmitted via speech droplets? *medRxiv* (2020).
7. N Ferguson, et al., Report 9: Impact of non-pharmaceutical interventions (npis) to reduce covid19 mortality and healthcare demand (2020).
8. Y Liu, AA Gayle, A Wilder-Smith, J Rocklöv, The reproductive number of covid-19 is higher compared to sars coronavirus. *J. travel medicine* (2020).
9. SA Lauer, et al., The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application. *Annals Intern. Medicine* (2020).
10. KKW To, et al., Temporal profiles of viral load in posterior oropharyngeal saliva samples and serum antibody responses during infection by SARS-CoV-2: an observational cohort study. *Lancet Infect. Dis.* **0** (2020).
11. L Zou, et al., SARS-CoV-2 Viral Load in Upper Respiratory Specimens of Infected Patients. *New Engl. J. Medicine* **382**, 1177–1179 (2020).
12. Y Bai, et al., Presumed asymptomatic carrier transmission of covid-19. *Jama* (2020).
13. J Zhang, et al., Evolving epidemiology and transmission dynamics of coronavirus disease 2019 outside Hubei province, China: a descriptive and modelling study. *The Lancet Infect. Dis.* **0** (2020).
14. N van Doremalen, et al., Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. *New Engl. J. Medicine* **0**, null (2020).
15. WE Wei, Presymptomatic Transmission of SARS-CoV-2 â Singapore, January 23âMarch 16, 2020. *MMWR. Morb. Mortal. Wkly. Rep.* **69** (2020).
16. R Wölfel, et al., Virological assessment of hospitalized patients with covid-2019. *Nature*, 1–10 (2020).
17. Brosseau, N95 Respirators and Surgical Masks | | Blogs | CDC (2009).
18. E Toner, R Waldhorn, What Hospitals Should Do to Prepare for the Influenza Pandemic. *Mary Ann Liebert Inc.* **4**, 397–402 (2006).
19. P de Man, et al., Sterilization of disposable face masks by means of standardized dry and steam sterilization processes: an alternative in the fight against mask shortages due to COVID-19 (2020).
20. S Asadi, et al., Aerosol emission and superemission during human speech increase with voice loudness. *Sci. reports* **9**, 1–10 (2019).
21. A Davies, et al., Testing the Efficacy of Homemade Masks: Would They Protect in an Influenza Pandemic? *Disaster Medicine Public Heal. Prep.* **7**, 413–418 (2013).
22. S Rengasamy, B Eimer, RE Shaffer, Simple Respiratory ProtectionEvaluation of the Filtration Performance of Cloth Masks and Common Fabric Materials Against 201000 nm Size Particles. *The Annals Occup. Hyg.* **54**, 789–798 (2010).
23. Mvd Sande, P Teunis, R Sabel, Professional and Home-Made Face Masks Reduce Exposure to Respiratory Infections among the General Population. *PLOS ONE* **3**, e2618 (2008).
24. VM Dato, D Hostler, ME Hahn, Simple Respiratory Mask. *Emerg. Infect. Dis.* **12**, 1033–1034 (2006).
25. DK Milton, MP Fabian, BJ Cowling, ML Grantham, JJ McDevitt, Influenza Virus Aerosols in Human Exhaled Breath: Particle Size, Culturability, and Effect of Surgical Masks. *PLOS Pathog.* **9**, e1003205 (2013).
26. RS Papineni, FS Rosenthal, The size distribution of droplets in the exhaled breath of healthy human subjects. *J. Aerosol Medicine* **10**, 105–116 (1997).
27. DIY Face Mask – 8 Steps in Making Protective Gear | Consumer Council (2020) [Online; accessed 8. Apr. 2020].
28. Coronavirus Disease 2019 (COVID-19) (2020) [Online; accessed 8. Apr. 2020].
29. J Burch, C Bunt, Can physical interventions help reduce the spread of respiratory viruses? *Cochrane Clin. Answers* (2020).
30. NH Leung, et al., Respiratory virus shedding in exhaled breath and efficacy of face masks. *Nat. Medicine*, 1–5 (2020).
31. S Bae, et al., Effectiveness of Surgical and Cotton Masks in Blocking SARSCoV-2: A Controlled Comparison in 4 Patients. *Annals Intern. Medicine* (2020).
32. SC Jiang, et al., Every 10-fold increase in viral load results in 26% more patient deaths: a correlation analysis. *Int J Clin Exp Med* **12**, 13712–13722 (2019).
33. M van der Sande, P Teunis, R Sabel, Professional and Home-Made Face Masks Reduce Exposure to Respiratory Infections among the General Population. *PLoS ONE* **3** (2008).
34. X Wang, Z Pan, Z Cheng, Association between 2019-nCoV transmission and N95 respirator use. *J. Hosp. Infect.* **0** (2020).
35. KL Schwartz, et al., Lack of COVID-19 Transmission on an International Flight. *CMAJ* (2020).
36. L Zhang, et al., Protection by Face Masks against Influenza A(H1N1)pdm09 Virus on Trans-Pacific Passenger Aircraft, 2009. *Emerg. Infect. Dis.* **19**, 1403–1410 (2013).
37. AR Wilkes, JE Benbough, SE Speight, M Harmer, The bacterial and viral filtration performance of breathing system filters*. *Anaesthesia* **55**, 458–465 (2000).
38. Y Long, et al., Effectiveness of N95 respirators versus surgical masks against influenza: A systematic review and meta-analysis. *J. Evidence-Based Medicine* **n/a** (2020).
39. DF Johnson, JD Druce, C Birch, ML Grayson, A quantitative assessment of the efficacy of surgical and N95 masks to filter influenza virus in patients with acute influenza infection. *Clin. Infect. Dis. An Off. Publ. Infect. Dis. Soc. Am.* **49**, 275–277 (2009).
40. LJ Radonovich, et al., N95 Respirators vs Medical Masks for Preventing Influenza Among Health Care Personnel: A Randomized Clinical Trial. *JAMA* **322**, 824–833 (2019).
41. CR MacIntyre, et al., A cluster randomised trial of cloth masks compared with medical masks in healthcare workers. *BMJ Open* **5**, e006577 (2015).
42. T Jefferson, et al., Physical interventions to interrupt or reduce the spread of respiratory viruses. *The Cochrane Database Syst. Rev.* **2011** (2011).
43. T Suess, et al., The role of facemasks and hand hygiene in the prevention of influenza transmission in households: results from a cluster randomised trial; Berlin, Germany, 2009-2011. *BMC infectious diseases* **12**, 26 (2012).
44. BJ Cowling, et al., Facemasks and hand hygiene to prevent influenza transmission in households: a cluster randomized trial. *Annals Intern. Medicine* **151**, 437–446 (2009).
45. AE Aiello, et al., Mask use, hand hygiene, and seasonal influenza-like illness among young

adults: a randomized intervention trial. *The J. Infect. Dis.* **201**, 491–498 (2010).
46. AE Aiello, et al., Facemasks, Hand Hygiene, and Influenza among Young Adults: A Randomized Intervention Trial. *PLoS ONE* **7** (2012).
47. JT Lau, H Tsui, M Lau, X Yang, SARS Transmission, Risk Factors, and Prevention in Hong Kong. *Emerg. Infect. Dis.* **10**, 587–592 (2004).
48. The Lancet, COVID-19: protecting health-care workers. *The Lancet* **395**, 922 (2020).
49. LM Brosseau, ScD, M Sietsema, P| Apr 01, 2020, COMMENTARY: Masks-for-all for COVID-19 not based on sound data (2020).
50. MM Cassell, DT Halperin, JD Shelton, D Stanton, Risk compensation: the achilles' heel of innovations in hiv prevention? *Bmj* **332**, 605–607 (2006).
51. D Rojas Castro, RM Delabre, JM Molina, Give prep a chance: moving on from the risk compensation concept. *J. Int. AIDS Soc.* **22**, e25351 (2019).
52. JV Ouellet, Helmet use and risk compensation in motorcycle accidents. *Traffic injury prevention* **12**, 71–81 (2011).
53. DJ Houston, LE Richardson, Risk compensation or risk reduction? seatbelts, state laws, and traffic fatalities. *Soc. Sci. Q.* **88**, 913–936 (2007).
54. Y Peng, et al., Universal motorcycle helmet laws to reduce injuries: a community guide systematic review. *Am. journal preventive medicine* **52**, 820–832 (2017).
55. MD Scott, et al., Testing the risk compensation hypothesis for safety helmets in alpine skiing and snowboarding. *Inj. Prev.* **13**, 173–177 (2007).
56. G Ruedl, M Kopp, M Burtscher, Does risk compensation undo the protection of ski helmet use? *Epidemiology* **23**, 936–937 (2012).
57. B Pless, Risk compensation: Revisited and rebutted. *Safety* **2**, 16 (2016).
58. A Burgess, M Horii, Risk, ritual and health responsibilisation: Japans safety blanketof surgical face mask-wearing. *Sociol. health & illness* **34**, 1184–1198 (2012).
59. BJ Condon, T Sinha, Who is that masked person: the use of face masks on mexico city public transportation during the influenza a (h1n1) outbreak. *Heal. Policy* **95**, 50–56 (2010).
60. K Abney, containing tuberculosis, perpetuating stigma: the materiality of n95 respirator masks. *Anthropol. South. Afr.* **41**, 270–283 (2018).
61. E Buregyeya, et al., Acceptability of masking and patient separation to control nosocomial tuberculosis in uganda: a qualitative study. *J. Public Heal.* **20**, 599–606 (2012).
62. G Joachim, S Acorn, Stigma of visible and invisible chronic conditions. *J. advanced nursing* **32**, 243–248 (2000).
63. DK Li, R Abdelkader, Coronavirus hate attack: Woman in face mask allegedly assaulted by man who calls her 'diseased'. *NBC News* (2020).
64. Tampa Bay nurses were told not to wear masks in hallways. Now hospitals are changing the rules. (2020) [Online; accessed 9. Apr. 2020].
65. S Malone, NY Correctional Officers Ordered Not To Wear Masks, Even If They Have Them. *Maven* (2020).
66. D Pager, H Shepherd, The sociology of discrimination: Racial discrimination in employment, housing, credit, and consumer markets. *Annu. Rev. Sociol* **34**, 181–209 (2008).
67. C Fernando Alfonso Iii, Why some people of color say they won't wear homemade masks (2020) [Online; accessed 9. Apr. 2020].
68. T Jan, Two black men say they were kicked out of Walmart for wearing protective masks. Others worry it will happen to them. *Wash. Post* (2020).
69. K Wells, Why cant I get tested? *Atlantic* (2020).
70. RE Watson-Jones, CH Legare, The social functions of group rituals. *Curr. Dir. Psychol. Sci.* **25**, 42–46 (2016).
71. P Illingworth, WE Parmet, Solidarity and health: A public goods justification. *Diametros* **43**, 65–71 (2015).
72. LC Chen, TG Evans, RA Cash, , et al., Health as a global public good. *Glob. public goods*, 284–304 (1999).
73. R BliegeBird, et al., Signaling theory, strategic interaction, and symbolic capital. *Curr. anthropology* **46**, 221–248 (2005).
74. R Van Houten, L Malenfant, B Huitema, R Blomberg, Effects of high-visibility enforcement on driver compliance with pedestrian yield right-of-way laws. *Transp. research record* **2393**, 41–49 (2013).
75. W Van Damme, W Van Lerberghe, Editorial: Epidemics and fear. *Trop. Med. Int. Heal.* **5**, 511–514 (2000).
76. MA Riva, M Benedetti, G Cesana, Pandemic fear and literature: observations from jack londons the scarlet plague. *Emerg. infectious diseases* **20**, 1753 (2014).
77. E Taal, JJ Rasker, ER Seydel, O Wiegman, Health status, adherence with health recommendations, self-efficacy and social support in patients with rheumatoid arthritis. *Patient education counseling* **20**, 63–76 (1993).
78. Coronavirus can travel twice as far as official 'safe distance', study says (2020) [Online; accessed 10. Apr. 2020].
79. CC Leung, TH Lam, KK Cheng, Mass masking in the COVID-19 epidemic: people need guidance. *The Lancet* **395**, 945 (2020).
80. J Lyons, To curb the coronavirus, hong kong tells the world masks work; city embraces widespread use of face coverings alongside other measures to slow spread of disease (2020).
81. N Liu, Hong kongs coronavirus response leads to sharp drop in flu cases. *FT.com* (2020) Name - University of Hong Kong; Chinese University of Hong Kong; Copyright - Copyright The Financial Times Limited Mar 5, 2020; Last updated - 2020-03-23; SubjectsTermNotLitGenreText - China; Hong Kong.
82. BJ Cowling, et al., Impact assessment of non-pharmaceutical interventions against COVID-19 and influenza in Hong Kong: an observational study. *medRxiv* (2020).
83. GM Leung, et al., A tale of two cities: community psychobehavioral surveillance and related impact on outbreak control in hong kong and singapore during the severe acute respiratory syndrome epidemic. *Infect. Control. & Hosp. Epidemiol.* **25**, 1033–1041 (2004).
84. BJ Cowling, et al., Community psychological and behavioral responses through the first wave of the 2009 influenza a (h1n1) pandemic in hong kong. *The J. infectious diseases* **202**, 867–876 (2010).
85. World Health Organization (WHO), Global Tuberculosis Report 2019, (World Health Organization, Geneva), Technical report (2019).
86. AS Dharmadhikari, et al., Surgical face masks worn by patients with multidrug-resistant tuberculosis: impact on infectivity of air on a hospital ward. *Am. journal respiratory critical care medicine* **185**, 1104–1109 (2012).
87. EL Larson, et al., Impact of Non-Pharmaceutical Interventions on URIs and Influenza in Crowded, Urban Households. *Public Heal. Reports* **125**, 178–191 (2010).
88. CR MacIntyre, et al., The First Randomized, Controlled Clinical Trial of Mask Use in Households to Prevent Respiratory Virus Transmission. *Int. J. Infect. Dis.* **12**, e328 (2008).
89. L Tian, et al., Calibrated intervention and containment of the covid-19 pandemic (2020).
90. J Yan, S Guha, P Hariharan, M Myers, Modeling the Effectiveness of Respiratory Protective Devices in Reducing Influenza Outbreak. *Risk Analysis* **39**, 647–661 (2019).
91. C Leffler, E Ing, CA McKeown, D Pratt, A Grzybowski, Country-wide Mortality from the Novel Coronavirus (COVID-19) Pandemic and Notes Regarding Mask Usage by the Public, Technical report (2020).
92. C Kenyon, Widespread use of face masks in public may slow the spread of SARS CoV-2: an ecological study. *medRxiv*, 2020.03.31.20048652 (2020).
93. J Abaluck, et al., The Case for Universal Cloth Mask Adoption and Policies to Increase Supply of Medical Masks for Health Workers, (Social Science Research Network, Rochester, NY), SSRN Scholarly Paper ID 3567438 (2020).
94. WC on the Ethics of Scientific Knowledge, Technology, The precautionary principle (2005).
95. T Greenhalgh, MB Schmid, T Czypionka, D Bassler, L Gruer, Face masks for the public during the covid-19 crisis. *BMJ* **369** (2020).
96. WD Bradford, A Mandich, Some state vaccination laws contribute to greater exemption rates and disease outbreaks in the united states. *Heal. Aff.* **34**, 1383–1390 (2015).