Subject: Completed Public Records Request
Date: Friday, February 5, 2021 at 3:28:44 PM Eastern Standard Time
From: Jared Larsen
To: AO Records
CC: Brady Hall
Attachments: FW: mask effectiveness.eml, Mask Mandates Impact Health Affairs 2020.pdf, Professional and home made masks resp infections general public PLOS 2008.pdf, Review of face coverings physical distancing to prevent transmission Chu et al.pdf, Role of Community Face Mask Wearing in Hong Kong Kwok-yung.pdf, Universal Masking WITH HIGHLIGHTS Kai et al.pdf, ACOEM_Use of Cloth or Disposable Face Coverings at Work.pdf, Aerosol filtration efficiency of fabrics in cloth masks Konda et al.pdf, FW_ LI Literature Service_ Face masks_ what the data say.pdf

EXTERNAL SENDER

Dear Austin,

Your public records request (below) is complete and all public records responsive to your request are attached.

Sincerely,

Jared

From: Office of the Governor <no-reply@gov.idaho.gov>
Sent: Friday, January 8, 2021 1:16 PM
To: Emily Callihan <Emily.Callihan@gov.idaho.gov>; Marissa Morrison <Marissa.Morrison@gov.idaho.gov>; Jared Larsen <Jared.Larsen@gov.idaho.gov>; Brady Hall <Brady.Hall@gov.idaho.gov>
Subject: Public Records Request received

A public records request was received with the following information:

RECORDS REQUESTED
ID-GOV-21-0012
January 8, 2021

VIA ONLINE PORTAL

Office of the Governor
700 W. Jefferson Street, Suite 228
P.O. Box 83720
Boise, Idaho 83720-0034
Via Online Portal

Re: Public Records Act Request

Dear Public Records Custodian:

Pursuant to Idaho's Public Records Act, as codified at Chapter 1 of Title 74 of the Idaho Code, I.C. T. 74, Ch. 1, American Oversight makes the following request for records.

The novel coronavirus has infected more than 21 million people and resulted in more than 365,000 deaths in the United States alone.1 In recent months, the speed and volume of infections have reached record highs across much of the country, surpassing 200,000 average new daily cases.2 Despite the months-long increase in infections, several state governments are still declining to impose or have only recently imposed public health measures such as mask mandates to mitigate the virus's spread, including in states where the rate of infections is highest.3

American Oversight seeks records with the potential to shed light on Idaho's response to the coronavirus pandemic.

Requested Records
Pursuant to Section 74-103(1) of the Idaho Code, American Oversight requests that your office produce the following records within three working days, or, if a longer period of time is needed and American Oversight is so notified, within ten working days:

1. Any final assessments, reports, analyses, recommendations, or guidance prepared by your office, other federal, state, or local offices (including the Idaho Department of Health and Welfare and the U.S. Centers for Disease Control and Prevention), or independent experts, regarding any projected or actual effects or impacts of a statewide mask mandate on the spread of COVID-19.

2. Any final assessments, reports, analyses, recommendations, or guidance prepared by your office, other federal, state, or local offices (including the Idaho Department of Health and Welfare and the U.S. Centers for Disease Control and Prevention), or independent experts, regarding any projected or actual effects of Idaho's current public health measures on the spread of COVID-19.

Please provide all responsive records from July 1, 2020, to the date the search is conducted.

Please notify American Oversight of any anticipated fees or costs in excess of $100 prior to incurring such costs or fee.

Guidance Regarding the Search & Processing of Requested Records
In connection with its request for records, American Oversight provides the following guidance regarding the scope of the records sought and the search and processing of records:

§ In conducting your search, please understand the terms "record," and "document"" in their broadest sense, to include any written, typed, recorded, graphic, printed, or audio material of any kind. We seek records of any kind, including electronic records, audiotapes, videotapes, and photographs, as well as letters, emails, facsimiles, telephone messages, voice mail messages and transcripts, notes, or minutes of any meetings, telephone conversations or discussions.
§ Our request for records includes any attachments to those records or other materials enclosed with those records when they were previously transmitted. To the extent that an email is responsive to our request, our request includes all prior messages sent or received in that email chain, as well as any attachments to the email.
§ Please search all relevant records or systems containing records regarding agency business. Do not exclude records regarding agency business contained in files, email accounts, or devices in the personal custody of your officials, such as personal email accounts or text messages. Records of official business conducted using unofficial systems or stored outside of official files are subject to Idaho's Public Records Act if they were "prepared" by your agency, including by an employee of your agency.4
§ In the event some portions of the requested records are properly exempt from disclosure, please disclose any reasonably segregable non-exempt portions of the requested records.5 If a request is denied in whole, please state specifically why it is not reasonable to segregate portions of the record for release.

§ Please take appropriate steps to ensure that records responsive to this request are not deleted by the agency before the completion of processing for this request. If records potentially responsive to this request are likely to be located on systems where they are subject to potential deletion, including on a scheduled basis, please take steps to prevent that deletion, including, as appropriate, by instituting a litigation hold on those records.
If you have any questions regarding how to construe this request for records or believe that further discussions regarding search and processing would facilitate a more efficient production of records of interest to American Oversight, please do not hesitate to contact American Oversight to discuss this request. American Oversight welcomes an opportunity to discuss its request with you before you undertake your search or incur search or duplication costs. By working together at the outset, American Oversight and your agency can decrease the likelihood of costly and time-consuming litigation in the future.
Where possible, please provide responsive material in an electronic format by email. Alternatively, please provide responsive material in native format or in PDF format on a USB drive. Please send any responsive material being sent by mail to American Oversight, 1030 15th Street NW, Suite B255, Washington, DC 20005. If it will accelerate release of responsive records to American Oversight, please also provide responsive material on a rolling basis.

Conclusion
American Oversight is a 501(c)(3) nonprofit with the mission to promote transparency in government, to educate the public about government activities, and to ensure the accountability of government officials. American Oversight uses the information gathered, and its analysis of it, to educate the public through reports, press releases, or other media. American Oversight also makes materials it gathers available on its public website and promotes their availability on social media platforms, such as Facebook and Twitter.6

We share a common mission to promote transparency in government. American Oversight looks forward to working with your agency on this request. If you do not understand any part of this request, please contact Christine H. Monahan at records@americanoversight.org or (202) 868-5244.

Sincerely,
Austin R. Evers
Executive Director
American Oversight

1 Coronavirus Map: Tracking the Global Outbreak, N.Y. Times (Jan. 8, 2021, 7:54 AM), https://www.nytimes.com/interactive/2020/world/coronavirus-maps.html?action=click&module=RelatedLinks&pgtype=Article.
2 Coronavirus in the U.S.: Latest Map and Case Count, N.Y. Times (Jan. 8, 2021, 7:54 AM) https://www.nytimes.com/interactive/2020/us/coronavirus-us-cases.html#:~:text=At%20least%202%2C923%20new%20coronavirus,the%20average%20two%20weeks%20earlier.
3 Lea Asmelash et al., Most States Now Require Face Masks to Reduce the Spread of Covid-19. These Are the Ones That Don't, CNN (updated Dec. 8, 2020, 2:17 PM), https://www.cnn.com/2020/11/09/us/biden-mask-mandate-nationwide-trnd/index.html.
4 See I.C. § 74-101(13); cf. Cowles Pub. Co. v. Kootenai Cty. Bd. of Cty. Comm'rs, 144 Idaho 259, 263 (2007).
5 I.C. § 74-112.
6 American Oversight currently has approximately 15,600 page likes on Facebook and 106,00 followers on Twitter. American Oversight, Facebook, https://www.facebook.com/weareoversight/ (last visited Jan. 4, 2021); American Oversight (@weareoversight), Twitter, https://twitter.com/weareoversight (last visited Jan. 4, 2021).

RECORDS CREATED
2020-07-01 - 2021-01-08

REQUEST TO: Receive Copies

REQUESTOR INFORMATION
Mr. Austin Evers
1030 15th Street NW
Suite B255
Washington, District of Columbia 20005

Phone: (202) 868-5244
Email: records@americanoversight.org

AMERICAN COLLEGE OF OCCUPATIONAL AND ENVIRONMENTAL MEDICINE

ACOEM Recommendations for Use of Cloth or Disposable Face Coverings in the Workplace During COVID-19

First detected last year, coronavirus disease 2019 (COVID-19) has now spread throughout the world and is found in all 50 states and in territories of the United States (U.S.). To help prevent or slow the spread of this disease, public health authorities have mandated social distancing, handwashing, and disinfection of surfaces as the key infection control techniques. Recent evidence that asymptomatic carriers of the virus can infect others, has also led the U.S. Centers for Disease Control and Prevention (CDC) and the U.S. Surgeon General to urge the use of face coverings in areas with significant transmission.

Many employees have jobs that require their physical presence at work during this pandemic including, but not limited to, public safety personnel, grocery store workers, delivery drivers, utility workers, pharmacists, etc.[1] Based on the new federal recommendations, the American College of Occupational and Environmental Medicine (ACOEM) encourages the use of face coverings in the workplace where respirators have not historically been indicated.[2] The following checklist summarizes best practices for the use of face coverings to maximize safety and stop the spread of COVID-19 to co-workers, family members, and the public.

As the science surrounding COVID-19 is rapidly changing, look to CDC and ACOEM for regular updates.

ACTION AREAS	EMPLOYERS	EMPLOYEES
WHY WEAR A FACE COVERING? *A significant portion of people with COVID-19 lack symptoms, but can transmit the virus to others. COVID-19 can spread between people interacting in close proximity – breathing and talking, not just coughing and sneezing.* *Face coverings protect others by catching the spray of droplets, and may also help prevent touching the face with contaminated hands, one way the virus is transmitted.*	❑ Provide workers with up-to-date education and training on COVID-19 risk factors and how and why to use protective behaviors/barriers (e.g., cough etiquette and care of face coverings). Training material should be clear and available in the appropriate language. ❑ Display signs that provide instructions on how to select and use face coverings.	❑ If you have any COVID-19 symptoms, STAY HOME; contact your physician and employer. Practice infection control at home to avoid exposing others. ❑ Maintain social distancing at work – at least 6 feet from co-workers and others. Do not congregate in groups. ❑ Wash your hands frequently. ❑ Disinfect high-touch surfaces as per your employer's instructions. ❑ Wear face covering if working with colleagues who cannot maintain social distance or if dealing with the public and in public spaces. Assume everyone is infected, even if they don't exhibit symptoms or if they say they feel well. ❑ If your employer does not provide a face covering, request permission to wear one of your own choice.

ID-GOV-21-0012-A-000001

CHOICE OF FACE COVERING *It is not known if certain types of face coverings (bandanas, homemade masks, disposable dust-filtering masks, etc.), are better than others in non-health-care settings, but it is likely the type of material and tightness of fit makes a difference. Consider washable multilayer, pleated cotton (but breathable) materials unless disposable face coverings are used.*	❑ Do not purchase surgical masks or N95s.[2] ❑ Offer, permit, and encourage employees whose job tasks do not require respirators to use face coverings that are not NIOSH certified and do not meet criteria of a respirator. Examples:   ❑ Recognize that some workers may not tolerate a face covering due to discomfort, claustrophobia, irritation, or difficulty breathing.	❑ A face covering is not intended to be used as respiratory protection for the wearer. ❑ Disposable face coverings may be purchased online. Cloth face coverings can be made at home. Here are two examples: 1. https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/cloth-face-cover.html 2. https://www.cdc.gov/coronavirus/2019-ncov/downloads/DIY-cloth-face-covering-instructions.pdf ❑ Face coverings must not be shared. ❑ Read and follow instructions provided by the manufacturer when applicable.
HOW TO PUT ON A FACE COVERING SAFELY *Whether using a homemade face covering or bandana or a manufactured disposable dust-filtering mask (see examples above), improperly donning a face covering will reduce its effectiveness and increase the likelihood of viral transmission.*	❑ Display signs that provide instructions on how to put face coverings on safely. ❑ Provide adequate facilities for hand washing. If available, consider alcohol-based hand sanitizers as an alternative to soap and water as appropriate.	❑ Wash your hands before putting on any face covering. ❑ If using a disposable covering, inspect to assure neither the strap nor facepiece has degraded. 1. Place covering over nose and mouth. Make sure correct side is facing out. If covering has a metal piece, shape top edge to the bridge of your nose. 2. Secure top strings or elastics behind your head and above your ears and bottom strings below your ears. Fit covering as tightly as possible while being able to breath comfortably. ❑ No matter what type of covering you are using, once you have the covering on, do NOT touch the front.
WEARING A FACE COVERING	❑ Display signs that provide instructions on how to safely use face coverings. ❑ Assure adequate availability of hand sanitizer or soap and water in areas where employees will be putting on and removing face coverings.	❑ **Before** using and **after** removing face coverings, immediately wash your hands. While wearing covering, don't touch mouth, nose, and eyes. Avoid touching face covering. ❑ Keep covering in its original location over your mouth and nose until you are ready to remove it.

		❑ If covering becomes dislodged and no longer covers your mouth and nose, follow instructions on how to remove it. ❑ If covering will be used for prolonged periods, chance of contamination increases. Therefore, remove it if it is dislodged, wet, intolerable, or if using the restroom. Follow instructions for safe removal/re-use.
REMOVING A FACE COVERING SAFELY *Improperly removing a face covering will increase the likelihood of viral transmission.*	❑ Display signs that provide instructions about how to remove face coverings safely. ❑ Assure adequate availability of hand sanitizer or soap and water where employees will be putting on and removing face coverings.	❑ WASH YOUR HANDS! Use soap and water or alcohol-based hand sanitizer. ❑ Do not touch front of face covering. Remove by grasping from back of head. ❑ Grasp the bottom ties or elastic, then the ones at the top and remove without touching the face covering. ❑ If discarding, drop face covering in a plastic trash bag. If it will be re-used, see re-use instructions. ❑ WASH YOUR HANDS! Use soap and water or alcohol-based hand sanitizer.
REUSE OF CLOTH FACE COVERINGS *Cloth face coverings can be decontaminated through laundering. However, over time, washing will likely degrade whatever protective effect the covering may have had.*	❑ If you are providing re-usable cloth face coverings to employees, assure they are instructed in proper approach for re-use.	❑ Follow instructions for putting on and removing the face covering. Place covering in a sealable plastic bag. ❑ Do not reuse until laundered. ❑ Empty bag contents into washing machine or washtub; use detergent and water as hot as material will tolerate. ❑ Dry face covering in a dryer. ❑ Face covering is now ready for reuse.
EXTENDED USE AND REUSE OF DISPOSABLE FACE COVERINGS *Ideally, if in sufficient supply, disposable filtering masks should not be reused and should be safely discarded.*[3]	❑ If a disposable face covering will be re-used, reserve it for a single individual identified by name on face covering. Provide paper bags (NOT PLASTIC) for storage. ❑ Instruct employees that for extended use over one work shift, the same disposable face covering may be used with attention to instructions for re-use.	❑ If sufficient supplies or if wet, damaged, or visibly dirty, discard face covering in a plastic trash bag after use. ❑ If reusing the disposable face covering, write your name and day of the week on the covering with indelible ink and on the paper bag before its first use. ❑ Follow instructions for safely putting on/ removing covering during work breaks, eating, smoking, or using the restroom.

The surfaces of a face covering may be contaminated and could transfer virus to the wearer upon contact with it during activities such as adjusting, improper doffing or when redonning a previously worn face covering.[4]	❑ For breaks in use, instruct workers to follow instructions for re-using the disposable face coverings during the same day. ❑ If the disposable face covering will be reused over multiple shifts, issue each worker a minimum of one disposable covering and small paper bag for its storage, for each work shift per week.[5] If it is not possible to provide 5 disposable coverings, a better alternative is to use washable ones.	❑ After removing, place in labelled paper bag. ❑ Avoid touching inside of the covering. If contact is made with the inside, discard covering and wash your hands. ❑ If the disposable covering will be re-used over multiple shifts, at the end of the shift, drop it in a paper bag labelled with your name/day of the week. Rotate disposable coverings each day of a work week; leave at least 4 days between each use for virus to die.

1. CISA. Department of Homeland Security. *Guidance on the Essential Critical Infrastructure Workforce: Ensuring Community and National Resilience in COVID-19 Response Version 2.0*. March 28, 2020. Available at: https://www.cisa.gov/sites/default/files/publications/CISA_Guidance_on_the_Essential_Critical_Infrastructure_Workforce_Version_2.0_Updated.pdf.
2. This guidance does not apply to health care workers or those whose jobs normally require use of respirators. ACOEM directs this advice to employers who permit, offer, or require cloth or disposable face coverings, potentially for prolonged period of time. Commercial and homemade disposable or cloth face coverings are not respirators. Respirators, such as N95s, are certified by the National Institute for Occupational Safety and Health to protect the person wearing them. Their use is regulated by OSHA and requires that employers put in place a Respiratory Protection Program with many elements (Standard 1910.134) see https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_id=12716&p_table=STANDARDS. **Because of insufficient supplies of N95 respirators to protect health care workers, employers should not purchase these for their workers who are at much lower risk of exposure.** This guidance is also offered in the context of a pandemic where there is a crisis in supplies of personal protective equipment, including disposable or reusable face coverings that do not meet the criteria of a respirator.
3. CDC has issued *Strategies for Optimizing the Supply of N95 Respirators* that can be referenced for guidance about the reuse of disposable filtering masks. See https://www.cdc.gov/coronavirus/2019-ncov/hcp/respirators-strategy/index.html.
4. NIOSH (https://www.cdc.gov/niosh/topics/hcwcontrols/recommendedguidanceextuse.html) an effective strategy to reduce the transfer of the virus from the disposable face covering to the wearer.
5. This guidance is based on studies that indicate that virus contamination diminishes to negligible amounts over 3 days.

About ACOEM

Founded in 1916, the American College of Occupational and Environmental Medicine (www.acoem.org) is an international society of 4,000 occupational physicians and other health care professionals. The College provides leadership to promote optimal health and safety of workers, workplaces, and environments. The College is located in Elk Grove Village, Illinois.

Contact ACOEM

American College of Occupational and Environmental Medicine
25 Northwest Point Blvd., Suite 700
Elk Grove Village, IL 60007
Telephone: 847/818-1800
E-mail: info@acoem.org
Website: www.acoem.org

From: Sara Stover <Sara.Stover@dfm.idaho.gov>
Sent: Wednesday, January 13, 2021 6:10 PM EST
To: Jared Larsen <Jared.Larsen@gov.idaho.gov>
Subject: FW: mask effectiveness
Attachment(s): "EIPH Mask Order Charts.pdf"

Sara Stover
Senior Policy Advisor | Governor Brad Little
phone: 208-854-3031
email: sara.stover@gov.idaho.gov
Facebook | Twitter | Instagram

From: Geri Rackow <grackow@eiph.idaho.gov>
Sent: Tuesday, November 3, 2020 8:46 AM
To: Sara Stover <Sara.Stover@dfm.idaho.gov>
Subject: RE: mask effectiveness

Sara,
I was able to pull this together for you….it doesn't paint a very good picture. I just pulled 4 counties – the others are all so small with cases so variable it's hard to draw any conclusion from them. At the present time, we have mask orders in effect in 7/8 of our counties. However, we do not see good compliance with the orders and we all know that unless people comply, they Order won't do any good.

Let me know if you have questions.

Geri

From: Sara Stover <Sara.Stover@dfm.idaho.gov>
Sent: Monday, November 2, 2020 12:33 PM
To: Lora Whalen <LWhalen@phd1.idaho.gov>; Carol Moehrle <CMoehrle@phd2.idaho.gov>; Zogg, Nikole <Nikole.Zogg@phd3.idaho.gov>; Russell Duke (rduke@cdhd.idaho.gov) <rduke@cdhd.idaho.gov>; Melody Bowyer - South Central Public Health Department (mbowyer@phd5.idaho.gov) <mbowyer@phd5.idaho.gov>; MMann@siph.idaho.gov; Geri Rackow <grackow@eiph.idaho.gov>
Cc: Shaw-Tulloch, Elke D. (Elke.Shaw-Tulloch@dhw.idaho.gov) <Elke.Shaw-Tulloch@dhw.idaho.gov>; Christine Hahn <christine.hahn@dhw.idaho.gov>
Subject: mask effectiveness

Do any of you have charts or graphs to show what mask use has done in any of the counties or cities in your districts when mask mandates were adopted? I think I saw one early on that Central District Health had put together when the Ada County mandate was implemented.

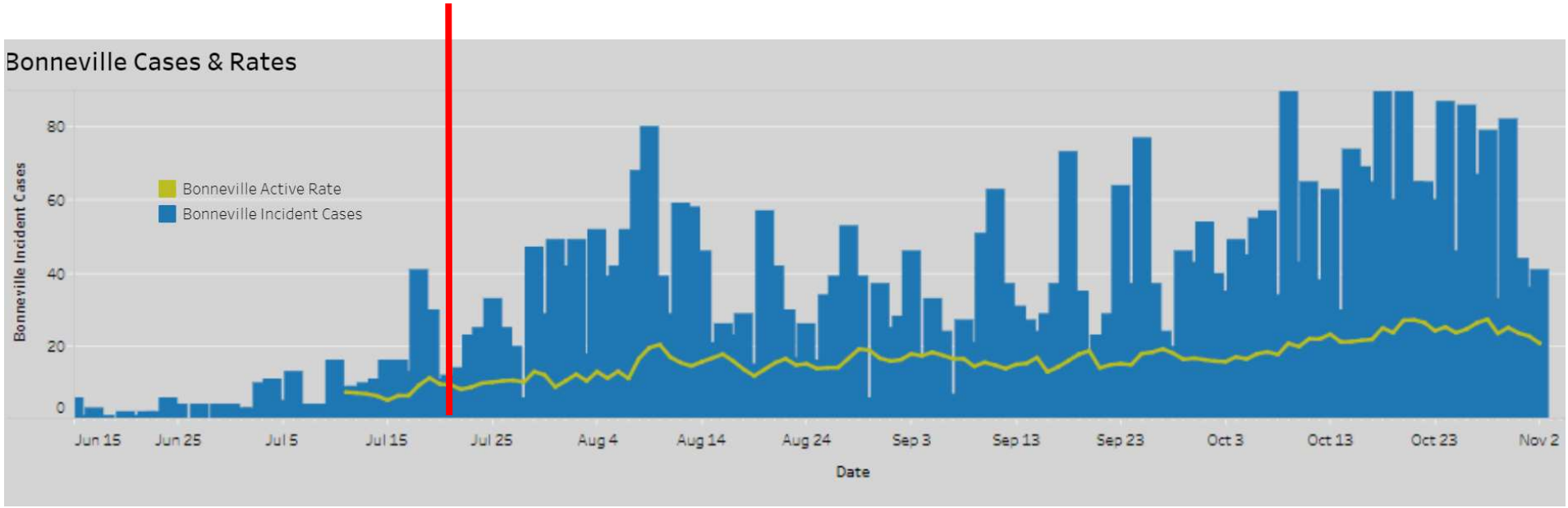
Sara Stover
Senior Policy Advisor | Governor Brad Little
phone: 208-854-3031
email: sara.stover@gov.idaho.gov
Facebook | Twitter | Instagram

Public Health Order requiring masks and limiting gatherings issued 7/21/20.

Schools in Bonneville County are requiring face coverings.

Compliance with the with Order appeared to go up initially, but waned over time.

With the recent uptick in cases in the County, anecdotal reports are that compliance has increased slightly.



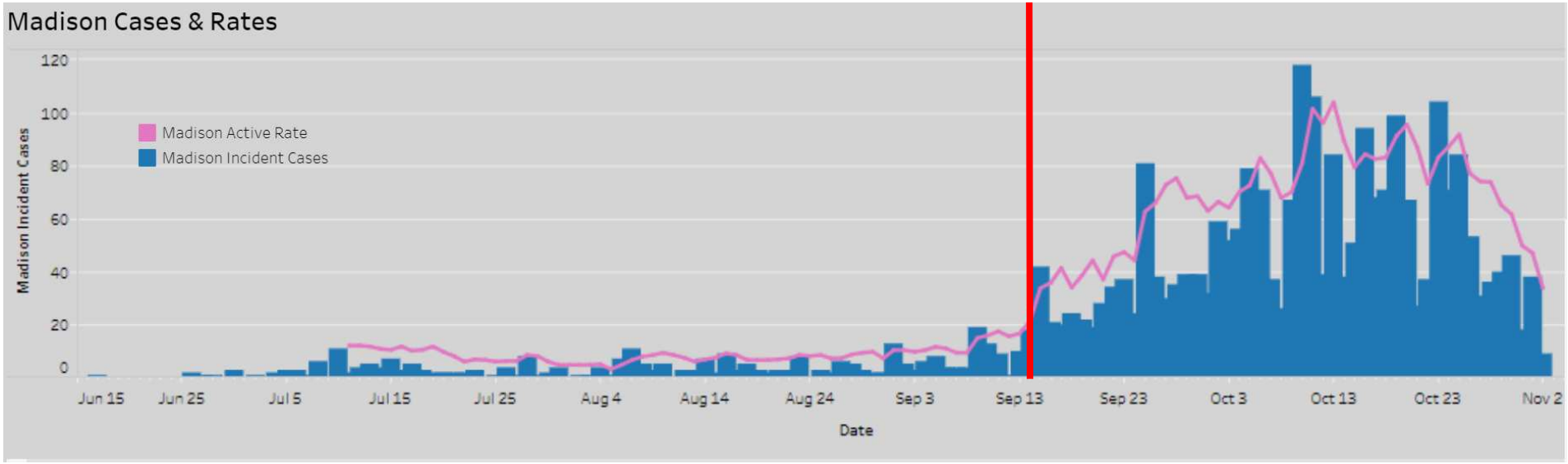
Public Health Order requiring masks and limiting gatherings issued 9/14/20.

Community compliance with Order observed to be very minimal.

K-12 schools in the County have NOT require face coverings since the start of school in late August; however, on October 11, began requiring them of teachers, and recommended them for students.

BYU-Idaho has required face coverings on campus since school started on September 14.

With the significant surge in cases in the County, on 10/8/20 the City of Rexburg began a campaign asking businesses to require masks. Level of compliance is unknown.

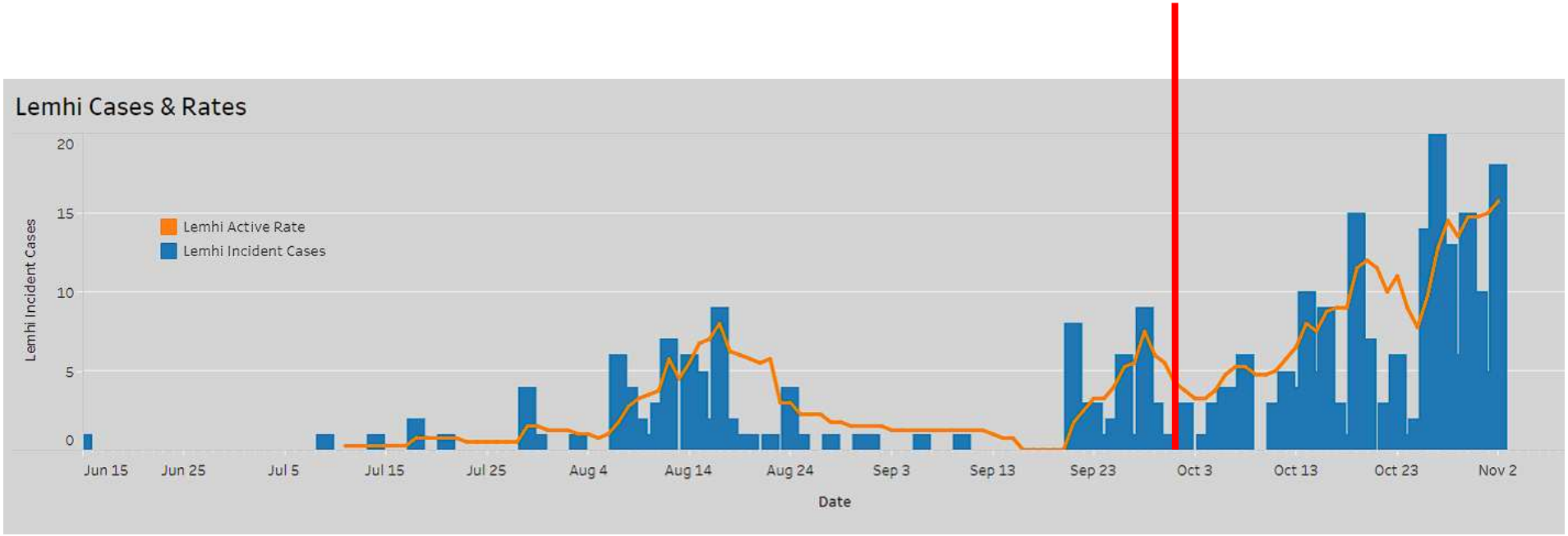


Public Health Order requiring masks and limiting gatherings issued 10/01/20.

Community compliance with Order observed to be very minimal.

Historically no support from any local elected officials throughout the pandemic—has continued with all mass gatherings.

With uptick in cases, on 10/21/20, Salmon City Council voted (4-3) to have businesses put up signage requiring masks (don't know what compliance has been). The largest retailer in the city, Saveway Market, does not support masking and is not requiring masks of employees or customers.



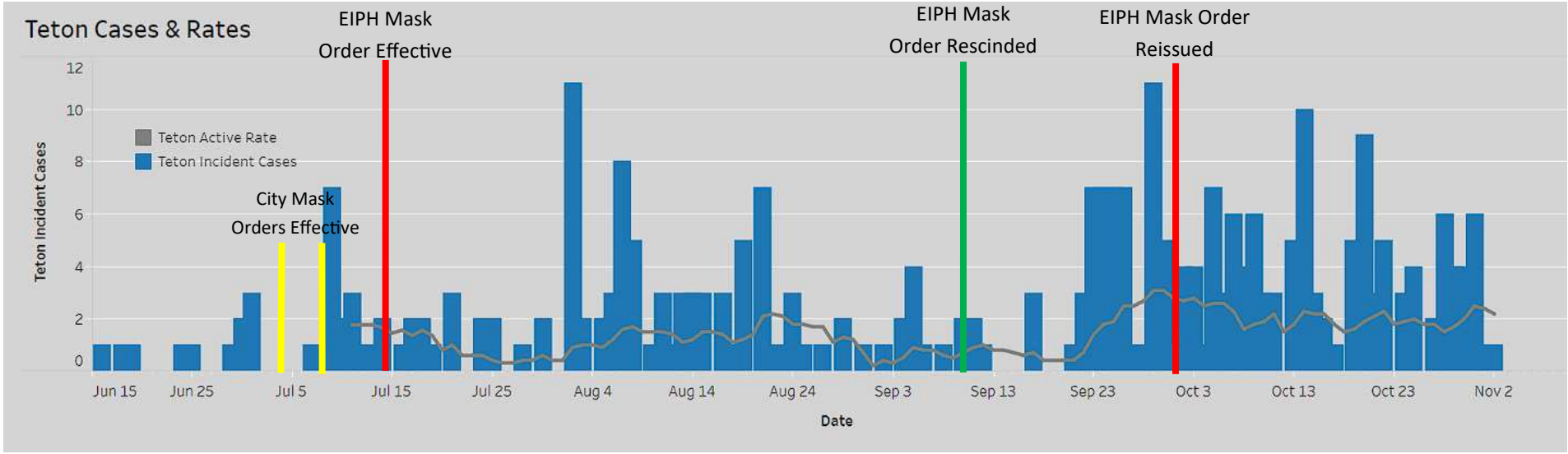
City of Driggs—Mask Order (Ordinance) in effect 7/3/20—present

City of Victor—Mask Order (Ordinance) in effect 7/8/20—present

Teton County—had an Mask Resolution, but I am not able to find a copy on their website

EIPH Public Health Order requiring masks and limiting gatherings:

- Initially issued 7/16/20
- Rescinded 9/10/20 in accordance with our Response Plan and active cases falling below a specified threshold
- Re-Issued 10/1/20—remains in effect



ACSNANO

www.acsnano.org

ARTICLE

Aerosol Filtration Efficiency of Common Fabrics Used in Respiratory Cloth Masks

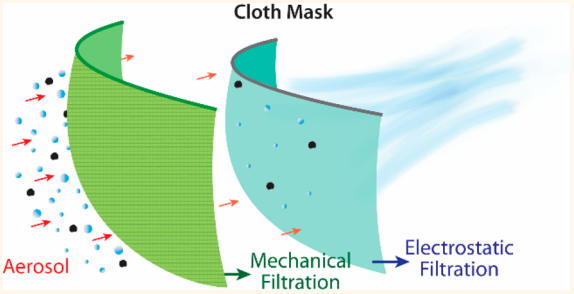
Abhiteja Konda,[⊥] Abhinav Prakash,[⊥] Gregory A. Moss, Michael Schmoldt, Gregory D. Grant, and Supratik Guha*

Cite This: https://dx.doi.org/10.1021/acsnano.0c03252

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: The emergence of a pandemic affecting the respiratory system can result in a significant demand for face masks. This includes the use of cloth masks by large sections of the public, as can be seen during the current global spread of COVID-19. However, there is limited knowledge available on the performance of various commonly available fabrics used in cloth masks. Importantly, there is a need to evaluate filtration efficiencies as a function of aerosol particulate sizes in the 10 nm to 10 μm range, which is particularly relevant for respiratory virus transmission. We have carried out these studies for several common fabrics including cotton, silk, chiffon, flannel, various synthetics, and their combinations. Although the filtration efficiencies for various fabrics when a single layer was used ranged from 5 to 80% and 5 to 95% for particle sizes of <300 nm and >300 nm, respectively, the efficiencies improved when multiple layers were used and when using a specific combination of different fabrics. Filtration efficiencies of the hybrids (such as cotton−silk, cotton−chiffon, cotton−flannel) was >80% (for particles <300 nm) and >90% (for particles >300 nm). We speculate that the enhanced performance of the hybrids is likely due to the combined effect of mechanical and electrostatic-based filtration. Cotton, the most widely used material for cloth masks performs better at higher weave densities (*i.e.*, thread count) and can make a significant difference in filtration efficiencies. Our studies also imply that gaps (as caused by an improper fit of the mask) can result in over a 60% decrease in the filtration efficiency, implying the need for future cloth mask design studies to take into account issues of "fit" and leakage, while allowing the exhaled air to vent efficiently. Overall, we find that combinations of various commonly available fabrics used in cloth masks can potentially provide significant protection against the transmission of aerosol particles.



KEYWORDS: *cloth masks, personal protection, aerosols, SARS-CoV-2, face masks, respiratory protection, COVID-19*

The use of cloth masks, many of them homemade,[1,2] has become widely prevalent in response to the 2019−2020 SARS-CoV-2 outbreak, where the virus can be transmitted *via* respiratory droplets.[3−6] The use of such masks is also an anticipated response of the public in the face of future pandemics related to the respiratory tract. However, there is limited data available today on the performance of common cloth materials used in such cloth masks,[7−12] particularly their filtration efficiencies as a function of different aerosol sizes ranging from ∼10 nm to ∼10 μm scale sizes. This is also of current significance as the relative effectiveness of different droplet sizes in transmitting the SARS-CoV-2 virus is not clear, and understanding the filtration response across a large bracketed size distribution is therefore important.[13−16] In this paper, we report the results of experiments where we measure the filtration efficiencies of a number of common fabrics, as well as selective combinations for use as hybrid cloth masks, as a function of aerosol sizes ranging from ∼10 nm to 6 μm. These include cotton, the most widely used fabric in cloth masks, as well as fabric fibers that can be electrostatically charged, such as natural silk.

Respiratory droplets can be of various sizes[17,18] and are commonly classified as aerosols (made of droplets that are <5 μm) and droplets that are greater than 5 μm.[3] Although the fate of these droplets largely depends on environmental factors such as humidity, temperature, *etc.*, in general, the larger droplets settle due to gravity and do not travel distances more than 1−2 m.[19] However, aerosols remain suspended in the air for longer durations due to their small size and play a key role in spreading infection.[14−16] The use of physical barriers such as

Received: April 18, 2020
Accepted: April 21, 2020

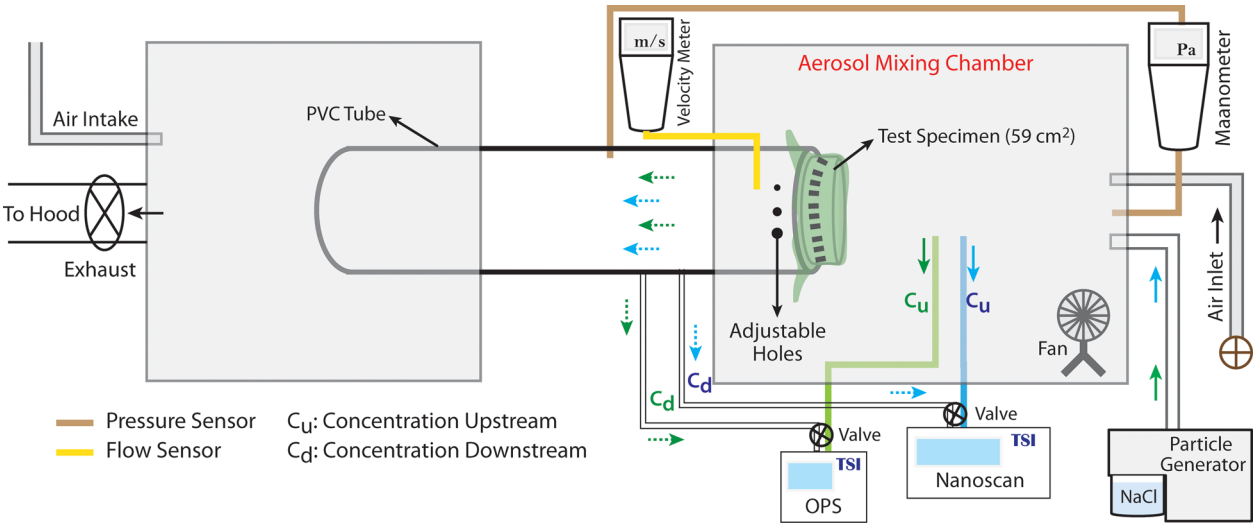


Figure 1. Schematic of the experimental setup. A polydisperse NaCl aerosol is introduced into the mixing chamber, where it is mixed and passed through the material being tested ("test specimen"). The test specimen is held in place using a clamp for a better seal. The aerosol is sampled before (upstream, C_u) and after (downstream, C_d) it passes through the specimen. The pressure difference is measured using a manometer, and the aerosol flow velocity is measured using a velocity meter. We use two circular holes with a diameter of 0.635 cm to simulate the effect of gaps on the filtration efficiency. The sampled aerosols are analyzed using particle analyzers (OPS and Nanoscan), and the resultant particle concentrations are used to determine filter efficiencies.

respiratory masks can be highly effective in mitigating this spread *via* respiratory droplets.[20−22] Filtration of aerosols follows five basic mechanisms: gravity sedimentation, inertial impaction, interception, diffusion, and electrostatic attraction.[23,24] For aerosols larger than ∼1 μm to 10 μm, the first two mechanisms play a role, where ballistic energy or gravity forces are the primary influence on the large exhaled droplets. As the aerosol size decreases, diffusion by Brownian motion and mechanical interception of particles by the filter fibers is a predominant mechanism in the 100 nm to 1 μm range. For nanometer-sized particles, which can easily slip between the openings in the network of filter fibers, electrostatic attraction predominates the removal of low mass particles which are attracted to and bind to the fibers. Electrostatic filters are generally most efficient at low velocities such as the velocity encountered by breathing through a face mask.[25]

There have been a few studies reported on the use of cloth face masks mainly during or after the Influenza Pandemic in 2009;[8−12,26] However, there is still a lack of information that includes (i) the performance of various fabrics as a function of particle size from the nanoscale to the micron sized (particularly important because this covers the ∼10 nm to ∼5 μm size scale for aerosols) and (ii) the effect of hybrid multilayer approaches for masks that can combine the benefits of different filtering mechanisms across different aerosol size ranges.[9,26] These have been the objectives of the experimental work described in this paper. In addition, we also point out the importance of fit (that leads to gaps) while using the face mask.[27,28]

The experimental apparatus (see Figure 1) consists of an aerosol generation and mixing chamber and a downstream collection chamber. The air flows from the generation chamber to the collection chamber through the cloth sample that is mounted on a tube connecting the two chambers. The aerosol particles are generated using a commercial sodium chloride (NaCl) aerosol generator (TSI Particle Generator, model #8026), producing particles in the range of a few tens of nanometers to approximately 10 μm. The NaCl aerosol based testing is widely used for testing face respirators in compliance with the NIOSH 42 CFR Part 84 test protocol.[29,30] Two different particle analyzers are used to determine particle size dimensions and concentrations: a TSI Nanoscan SMPS nanoparticle sizer (Nanoscan, model #3910) and a TSI optical particle sizer (OPS, model #3330) for measurements in the range of 10 to 300 nm and 300 nm to 6 μm, respectively.

Particles are generated upstream of the cloth sample, whose filtration properties are to be tested, and the air is drawn through the cloth using a blower fan which can be controlled in order to vary the airflow rate. Effective area of the cloth sample during the tests was ∼59 cm^2. Measurements of particle size and distribution were made by sampling air at a distance of 7.5 cm upstream and 15 cm downstream of the cloth sample. The differential pressures and air velocities were measured using a TSI digital manometer (model #AXD620) and a TSI Hot Wire anemometer (model #AVM410). The differential pressure (ΔP) across the sample material is an indicator of the comfort and breathability of the material when used as a face mask.[31] Tests were carried out at two different airflows: 1.2 and 3.2 CFM, representative of respiration rates at rest (∼35 L/min) and during moderate exertion (∼90 L/min), respectively.[32]

The effect of gaps between the contour of the face and the mask as caused by an improper fit will affect the efficiency of any face mask.[21,27,28,33] This is of particular relevance to cloth and surgical masks that are used by the public and which are generally not "fitted", unlike N95 masks or elastomeric respirators. A preliminary study of this effect was explored by drilling holes (symmetrically) in the connecting tube onto which the fabric (or a N95 or surgical mask) is mounted. The holes, in proximity to the sample (Figure 1), resulted in openings of area ∼0.5−2% of the active sample area. This, therefore, represented "leakage" of the air around the mask.

Although the detailed transmission specifics of SARS-CoV-2 virus are not well understood yet, droplets that are below 5 μm are considered the primary source of transmission in a respiratory infection,[13,15,34] and droplets that are smaller than

https://dx.doi.org/10.1021/acsnano.0c03252
ACS Nano XXXX, XXX, XXX−XXX

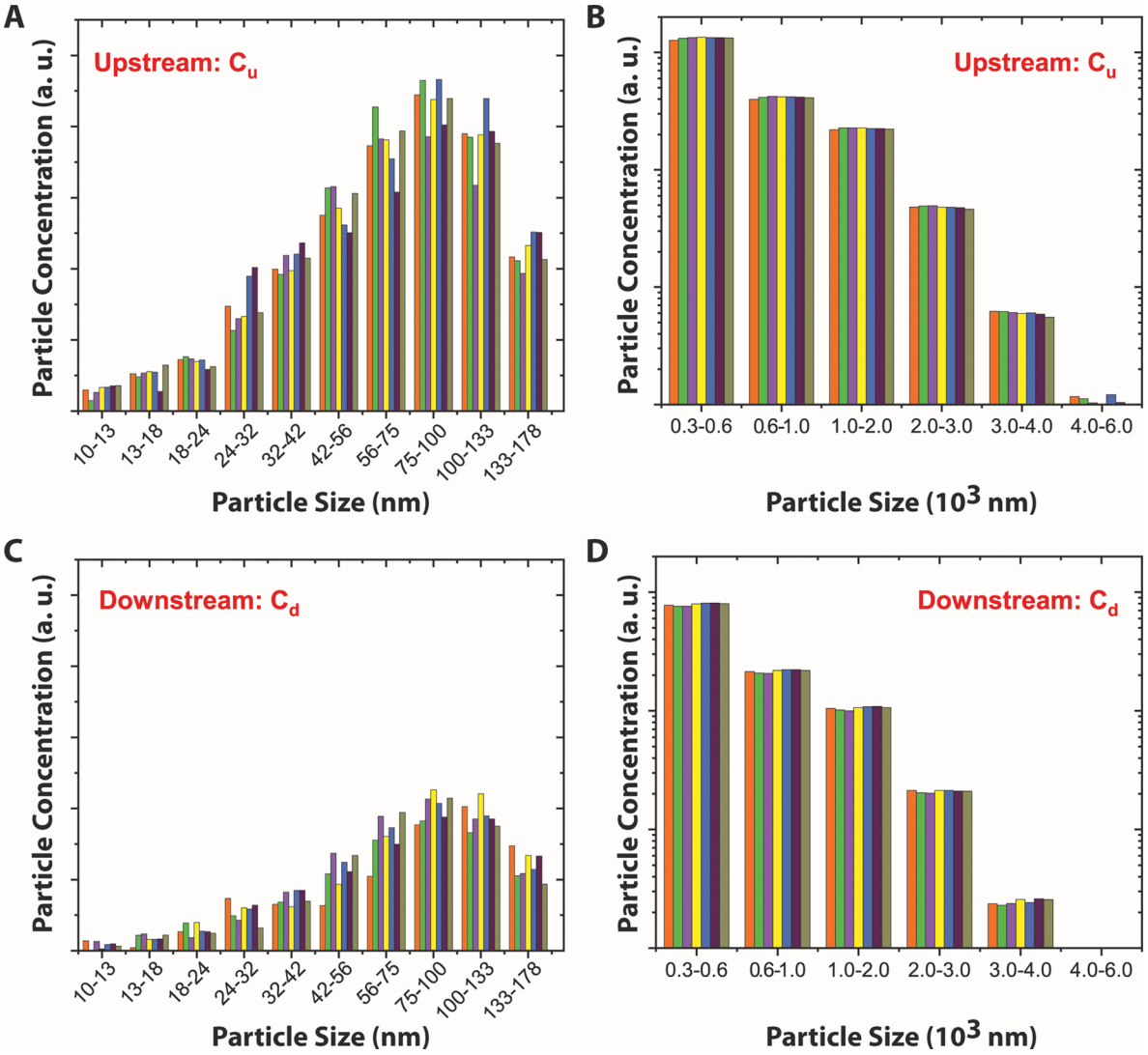


Figure 2. Particle concentration as a function of particle size at a flow rate of 1.2 CFM. Plots showing the particle concentration (in arbitrary units) upstream and downstream through a single layer of natural silk for particle sizes <300 nm (a,c) and between 300 nm and 6 μm (b,d). Each bin shows the particle concentration for at least six trials. The particle concentrations in panels (b) and (d) are given in log scale for better representation of the data. The y-axis scales are the same for panels "a" and "c"; and for panels "b" and "d".

1 μm tend to stay in the environment as aerosols for longer durations of up to 8 h.[19] Aerosol droplets containing the SARS-CoV-2 virus have been shown to remain suspended in air for ~3 h.[13,35] We have therefore targeted our experimental measurements in the important particle size range between ~10 nm and 6 μm.

We tested the performance of over 15 natural and synthetic fabrics that included materials such as cotton with different thread counts, silk, flannel, and chiffon. The complete list is provided in the Materials and Methods section. For comparison, we also tested a N95 respirator and surgical masks. Additionally, as appropriate, we tested the efficiency of multiple layers of a single fabric or a combination of multiple fabrics for hybrid cloth masks in order to explore combinations of physical filtering as well as electrostatic filtering.

RESULTS AND DISCUSSION

We determine the filtration efficiency of a particular cloth as a function of particle size (Figure 2) by measuring the concentration of the particles upstream, C_u (Figure 2a,b) and the concentration of the particle downstream, C_d (Figure 2c,d). Concentrations were measured in the size ranges of 10−178 nm (using the nanoscan tool) and 300 nm to 6 μm (using the optical particle sizer tool). The representative example in Figure 2 shows the case for a single layer of silk fabric, where the measurements of C_u and C_d were carried out at a flow rate of 1.2 CFM. Following the procedure detailed in the Materials and Methods section, we then estimated the filtration efficiency of a cloth from C_u and C_d as a function of aerosol particle size.

The results plotted in Figure 3a are the filtration efficiencies for cotton (the most common material used in cloth masks) with different thread counts (rated in threads per inch—TPI—and representative of the coarseness or fineness of the fabric). We compare a moderate (80 TPI) thread count quilter's cotton (often used in do-it-yourself masks) with a high (600 TPI) cotton fabric sample. Additionally, we also measured the transmission through a traditional cotton quilt where two 120 TPI quilter's cotton sheets sandwich a ~0.5 cm batting (90% cotton−5% polyester−5% other fibers). Comparing the two

https://dx.doi.org/10.1021/acsnano.0c03252
ACS Nano XXXX, XXX, XXX−XXX

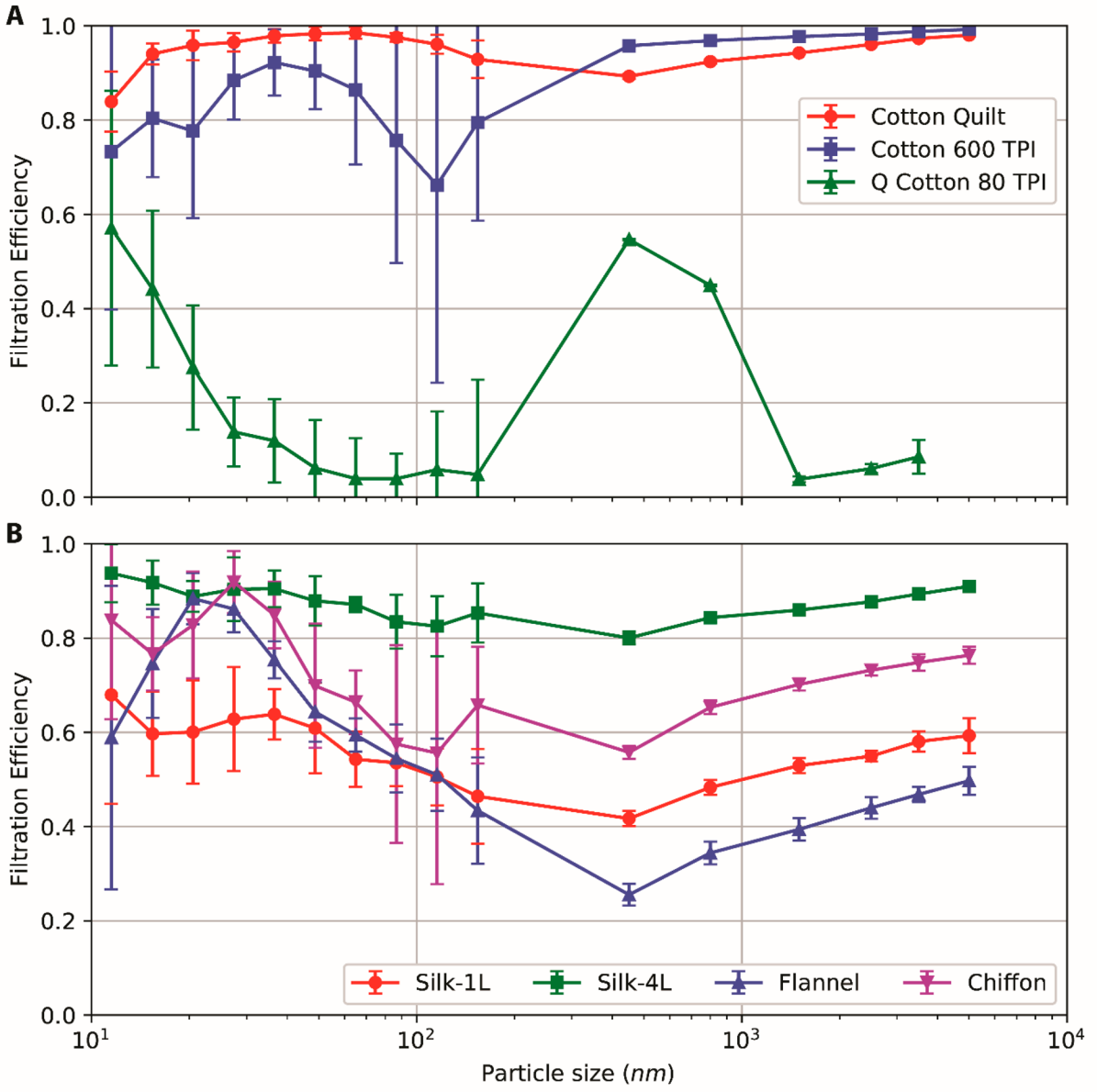


Figure 3. Filtration efficiency of individual fabrics at a flow rate of 1.2 CFM (without gap). (a) Plot showing the filtration efficiencies of a cotton quilt consisting of two 120 threads per inch (TPI) cotton sheets enclosing a ~0.5 cm thick cotton batting, 80 TPI quilters cotton (Q Cotton 80 TPI), and a 600 TPI cotton (cotton 600 TPI). (b) Plot showing the filtration efficiencies of one layer of natural silk (Silk-1L), four layers of natural silk (Silk-4L), one layer of flannel, and one layer of chiffon. The error bars on the <300 nm measurements are higher, particularly for samples with high filtration efficiencies because of the small number of particles generated in this size range, the relatively poorer counting efficiency of the detector at <300 nm particle size, and the very small counts downstream of the sample. The sizes of the error bars for some of the data points (>300 nm) are smaller than the symbol size and hence not clearly visible.

cotton sheets with different thread counts, the 600 TPI cotton is clearly superior with >65% efficiency at <300 nm and >90% efficiency at >300 nm, which implies a tighter woven cotton fabric may be preferable. In comparison, the single-layer 80 TPI cotton does not perform as well, with efficiencies varying from ~5 to ~55% depending on the particle size across the entire range. The quilt, a commonly available household material, with a fibrous cotton batting also provided excellent filtration across the range of particle sizes (>80% for <300 nm and >90% for >300 nm).

Electrostatic interactions are commonly observed in various natural and synthetic fabrics.[36,37] For instance, polyester woven fabrics can retain more static charge compared to natural fibers or cotton due to their lower water adsorption properties.[36] The electrostatic filtering of aerosols have been well studied.[38] As a result, we investigated three fabrics expected to possess moderate electrostatic discharge value: natural silk, chiffon (polyester−Spandex), and flannel (cotton−polyester).[36] The results for these are shown in Figure 3b. In the case of silk, we made measurements through one, two, and four layers of the fabric as silk scarves are often wrapped in multiple layers around the face (the results for two layers of silk are presented in Figure S1 (Supporting Information) and omitted from this figure). In all of these cases, the performance in filtering nanosized particles <300 nm is superior to performance in the 300 nm to 6 μm range and particularly effective below ~30 nm, consistent with the expectations from the electrostatic effects of these materials. Increasing the number of layers (as

https://dx.doi.org/10.1021/acsnano.0c03252
ACS Nano XXXX, XXX, XXX−XXX

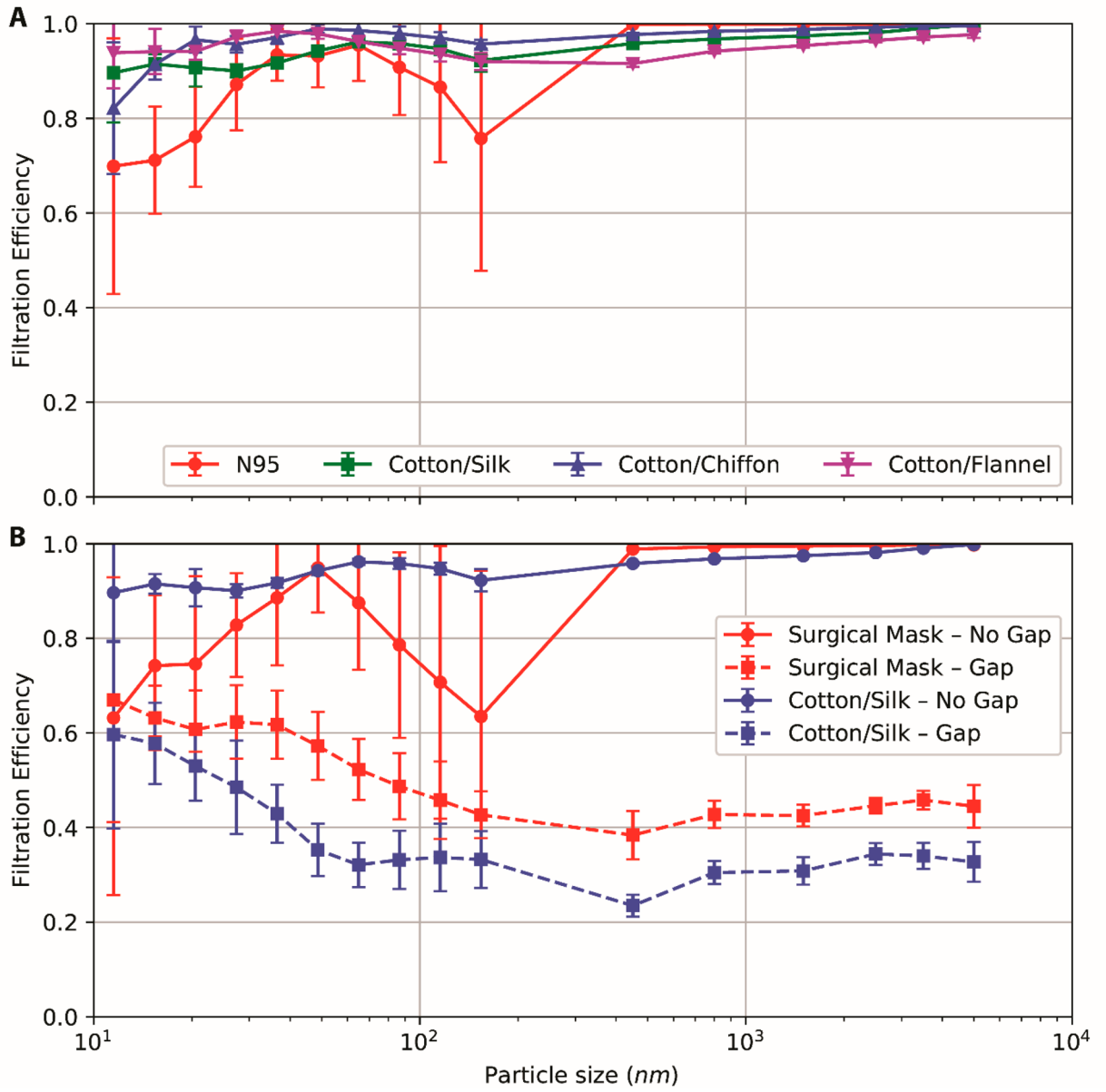


Figure 4. Filtration efficiency of hybrid fabrics at a flow rate of 1.2 CFM. (a) Plot showing the filtration efficiencies without gap for an N95 respirator and a combination of different fabrics: 1 layer of 600 threads per inch (TPI) cotton and 2 layers of silk (cotton/silk), 1 layer of 600 TPI cotton and 2 layers of chiffon (cotton/chiffon), and 1 layer of 600 TPI cotton and 1 layer of flannel (cotton/flannel). (b) Plot showing the filtration efficiencies of a surgical mask and cotton/silk with (dashed) and without a gap (solid). The gap used is ~1% of the active mask surface area. The error bars on the <300 nm measurements are higher, particularly for samples with high filtration efficiencies because of the small number of particles generated in this size range, the relatively poorer counting efficiency of the detector at <300 nm particle size, and the very small counts downstream of the sample. The sizes of the error bars for some of the data points (>300 nm) are smaller than the symbol size and hence not clearly visible.

shown for silk in Figure 3b), as expected, improves the performance. We performed additional experiments to validate this using the 600 TPI cotton and chiffon (Figure S1). We note that the performance of a four-layer silk composite offers >80% filtration efficiency across the entire range, from 10 nm to 6 μm.

In Figure 4a, we combine the nanometer-sized aerosol effectiveness (for silk, chiffon, and flannel) and wearability (of silk and chiffon because of their sheer nature) with the overall high performance of the 600 TPI cotton to examine the filtration performance of hybrid approaches. We made measurements for three variations: combining one layer 600 TPI cotton with two layers of silk, two layers of chiffon, and one layer of flannel. The results are also compared with the performance of a standard N95 mask. All three hybrid combinations performed well, exceeding 80% efficiency in the <300 nm range, and >90% in the >300 nm range. These cloth hybrids are slightly inferior to the N95 mask above 300 nm, but superior for particles smaller than 300 nm. The N95 respirators are designed and engineered to capture more than 95% of the particles that are above 300 nm,[39,40] and therefore, their underperformance in filtering particles below 300 nm is not surprising.

It is important to note that in the realistic situation of masks worn on the face without elastomeric gasket fittings (such as the commonly available cloth and surgical masks), the

https://dx.doi.org/10.1021/acsnano.0c03252
ACS Nano XXXX, XXX, XXX−XXX

Table 1. Filtration Efficiencies of Various Test Specimens at a Flow Rate of 1.2 CFM and the Corresponding Differential Pressure (ΔP) across the Specimen[a]

	flow rate: 1.2 CFM		
	filter efficiency (%)		pressure differential
sample/fabric	<300 nm average ± error	>300 nm average ± error	ΔP (Pa)
N95 (no gap)	85 ± 15	99.9 ± 0.1	2.2
N95 (with gap)	34 ± 15	12 ± 3	2.2
surgical mask (no gap)	76 ± 22	99.6 ± 0.1	2.5
surgical mask (with gap)	50 ± 7	44 ± 3	2.5
cotton quilt	96 ± 2	96.1 ± 0.3	2.7
quilter's cotton (80 TPI), 1 layer	9 ± 13	14 ± 1	2.2
quilter's cotton (80 TPI), 2 layers	38 ± 11	49 ± 3	2.5
flannel	57 ± 8	44 ± 2	2.2
cotton (600 TPI), 1 layer	79 ± 23	98.4 ± 0.2	2.5
cotton (600 TPI), 2 layers	82 ± 19	99.5 ± 0.1	2.5
chiffon, 1 layer	67 ± 16	73 ± 2	2.7
chiffon, 2 layers	83 ± 9	90 ± 1	3.0
natural silk, 1 layer	54 ± 8	56 ± 2	2.5
natural silk, 2 layers	65 ± 10	65 ± 2	2.7
natural silk, 4 layers	86 ± 5	88 ± 1	2.7
hybrid 1: cotton/chiffon	97 ± 2	99.2 ± 0.2	3.0
hybrid 2: cotton/silk (no gap)	94 ± 2	98.5 ± 0.2	3.0
hybrid 2: cotton/silk (gap)	37 ± 7	32 ± 3	3.0
hybrid 3: cotton/flannel	95 ± 2	96 ± 1	3.0

[a]The filtration efficiencies are the weighted averages for each size range—less than 300 nm and more than 300 nm.

presence of gaps between the mask and the facial contours will result in "leakage" reducing the effectiveness of the masks. It is well recognized that the "fit" is a critical aspect of a high-performance mask.[27,28,33,41] Earlier researchers have attempted to examine this qualitatively in cloth and other masks through feedback on "fit" from human trials.[11,12] In our case, we have made a preliminary examination of this effect *via* the use of cross-drilled holes on the tube holding the mask material (see Figure 1) that represents leakage of air. For example, in Figure 4b, we compare the performance of the surgical mask and the cotton/silk hybrid sample with and without a hole that represents about ∼1% of the mask area. Whereas the surgical mask provides moderate (>60%) and excellent (close to 100%) particle exclusion below and above 300 nm, respectively, the tests carried out with the 1% opening surprisingly resulted in significant drops in the mask efficiencies across the entire size range (60% drop in the >300 nm range). In this case, the two holes were ∼0.635 cm in diameter and the mask area was ∼59 cm^2. Similar trends in efficiency drops are seen in the cotton/silk hybrid sample, as well. Hole size also had an influence on the filtration efficiency. In the case of an N95 mask, increasing hole size from 0.5 to 2% of the cloth sample area reduced the weighted average filtration efficiency from ∼60 to 50% for a particle of size <300 nm. It is unclear at this point whether specific aerodynamic effects exacerbate the "leakage" effects when simulated by holes. Its determination is outside the scope of this paper. However, our measurements at both the high flow (3.2 CFM) and low flow (1.2 CFM) rates show substantial drop in effectiveness when holes are present. The results in Figures 2−4 highlight materials with good performance. Several fabrics were tested that did not provide strong filtration protection (<30%), and examples include satin and synthetic silk (Table S1). The filtration efficiencies of all of the samples that we measured at both 1.2 CFM and 3.2 CFM are detailed in the Supporting Information (Figures S2−S4).

In Table 1, we summarize the key findings from the various fabrics and approaches that we find promising. Average filtration efficiencies (see Materials and Methods section for further detail) in the 10−178 nm and 300 nm to 6 μm range are presented along with the differential pressures measured across the cloths, which represents the breathability and degree of comfort of the masks. The average differential pressure across all of the fabrics at a flow rate of 1.2 CFM was found to be 2.5 ± 0.4 Pa, indicating a low resistance and represent conditions for good breathability (Table 1).[31] As expected, we observed an increase in the average differential pressures for the higher flow rate (3.2 CFM) case (Table S1).

Guidance. We highlight a few observations from our studies for cloth mask design:

Fabric with tight weaves and low porosity, such as those found in cotton sheets with high thread count, are preferable. For instance, a 600 TPI cotton performed better than an 80 TPI cotton. Fabrics that are porous should be avoided.

Materials such as natural silk, a chiffon weave (we tested a 90% polyester−10% Spandex fabric), and flannel (we tested a 65% cotton−35% polyester blend) can likely provide good electrostatic filtering of particles. We found that four layers of silk (as maybe the case for a wrapped scarf) provided good protection across the 10 nm to 6 μm range of particulates.

Combining layers to form hybrid masks, leveraging mechanical and electrostatic filtering may be an effective approach. This could include high thread count cotton combined with two layers of natural silk or chiffon, for instance. A quilt consisting of two layers of cotton sandwiching a cotton−polyester batting also worked well. In all of these cases, the filtration efficiency was >80% for <300 nm and >90% for >300 nm sized particles.

The filtration properties noted in (i) through (iii) pertain to the intrinsic properties of the mask material and do not take into account the effect of air leaks that arise due to improper

https://dx.doi.org/10.1021/acsnano.0c03252
ACS Nano XXXX, XXX, XXX−XXX

"fit" of a mask on the user's face. It is critically important that cloth mask designs also take into account the quality of this "fit" to minimize leakage of air between the mask and the contours of the face, while still allowing the exhaled air to be vented effectively. Such leakage can significantly reduce mask effectiveness and are a reason why properly worn N95 masks and masks with elastomeric fittings work so well.

CONCLUSIONS

In conclusion, we have measured the filtration efficiencies of various commonly available fabrics for use as cloth masks in filtering particles in the significant (for aerosol-based virus transmission) size range of ~10 nm to ~6 μm and have presented filtration efficiency data as a function of aerosol particle size. We find that cotton, natural silk, and chiffon can provide good protection, typically above 50% in the entire 10 nm to 6.0 μm range, provided they have a tight weave. Higher threads per inch cotton with tighter weaves resulted in better filtration efficiencies. For instance, a 600 TPI cotton sheet can provide average filtration efficiencies of 79 ± 23% (in the 10 nm to 300 nm range) and 98.4 ± 0.2% (in the 300 nm to 6 μm range). A cotton quilt with batting provides 96 ± 2% (10 nm to 300 nm) and 96.1 ± 0.3% (300 nm to 6 μm). Likely the highly tangled fibrous nature of the batting aids in the superior performance at small particle sizes. Materials such as silk and chiffon are particularly effective (considering their sheerness) at excluding particles in the nanoscale regime (<~100 nm), likely due to electrostatic effects that result in charge transfer with nanoscale aerosol particles. A four-layer silk (used, for instance, as a scarf) was surprisingly effective with an average efficiency of >85% across the 10 nm −6 μm particle size range. As a result, we found that hybrid combinations of cloths such as high threads-per-inch cotton along with silk, chiffon, or flannel can provide broad filtration coverage across both the nanoscale (<300 nm) and micron scale (300 nm to 6 μm) range, likely due to the combined effects of electrostatic and physical filtering. Finally, it is important to note that openings and gaps (such as those between the mask edge and the facial contours) can degrade the performance. Our findings indicate that leakages around the mask area can degrade efficiencies by ~50% or more, pointing out the importance of "fit". Opportunities for future studies include cloth mask design for better "fit" and the role of factors such as humidity (arising from exhalation) and the role of repeated use and washing of cloth masks. In summary, we find that the use of cloth masks can potentially provide significant protection against the transmission of particles in the aerosol size range.

MATERIALS AND METHODS

Materials. All of the fabrics used as well as the surgical masks and N95 respirators tested are commercially available. We used 15 different types of fabrics. This included different types of cotton (80 and 600 threads per inch), cotton quilt, flannel (65% cotton and 35% polyester), synthetic silk (100% polyester), natural silk, Spandex (52% nylon, 39% polyester, and 9% Spandex), satin (97% polyester and 3% Spandex), chiffon (90% polyester and 10% Spandex), and different polyester and polyester−cotton blends. Specific information on the composition, microstructure, and other parameters can be found in the Supporting Information (Table S2).

Polydisperse Aerosol Generation. A polydisperse, nontoxic NaCl aerosol was generated using a particle generator and introduced into the mixing chamber along with an inlet for air. The aerosol is then mixed in the mixing chamber with the help of a portable fan. The particle generator produces particles sizes in the ranges of 10 nm to 10 μm.

Detection of Aerosol Particles. The particles were sampled both upstream (C_u, before the aerosol passes through the test specimen) and downstream (C_d, after the aerosol passes through the test specimen) for 1 min. The samples collected from the upstream and downstream are separately sent to the two particle sizers to determine a particle concentration (pt/cc). Each sample is tested seven times following the minimum sample size recommended by the American Industrial Hygiene Association exposure assessment sampling guidelines.[42] We observed a significantly lower particle count in the upper size distribution for both of the data sets, that is, for particles greater than 178 nm for the data from the TSI Nanoscan analyzer and greater than 6 μm for the data from TSI OPS analyzer. We exclude the data above these thresholds for all of the studies reported due to the extremely low counts. We categorize our data based on these two particle analyzers—individually the two plots (Figure 2a,b) show two size distributions—particles smaller than 300 nm and particles larger than 300 nm. Two different flow rates of 1.2 CFM (a face velocity of 0.1 m/s) and 3.2 CFM (a face velocity of 0.26 m/s) were used that corresponded to rates observed at rest to moderate activity, respectively. The velocity of the aerosol stream was measured at ~5 cm behind where the test specimen would be mounted using a velocity meter.

Differential Pressure. The differential pressure (ΔP) across the test specimen was measured ~7.5 cm away on either side of the material being tested using a micromanometer. The ΔP value is an estimate of the breathability of the fabric.

Data Analysis. The particle concentrations from seven consecutive measurements were recorded and divided into multiple bins—10 for nanoparticle sizer (dimensions in nm: 10−13, 13−18, 18−24, 24−32, 32−42, 42−56, 56−75, 75−100, 100−133, 133−178) and 6 for optical particle sizer (dimensions in μm: 0.3−0.6, 0.6−1.0, 1.0−2.0, 2.0−3.0, 3.0−4.0, 4.0−6.0). The seven measurements for each bin were subjected to one iteration of the Grubbs' test with a 95% confidence interval to remove at most one outlier per bin. This improves the statistical viability of the data. Following Grubbs' test, average concentrations were used to calculate the filtration efficiencies as described below.

Filtration Efficiency. The filtration efficiency (FE) of different masks was calculated using the following formula:

$$\mathrm{FE} = \frac{C_u - C_d}{C_u}$$

where C_u and C_d are the mean particle concentrations per bin upstream and downstream, respectively. To account for any possible drifts in the aerosol generation, we measured upstream concentrations before and after the downstream measurement and used the average of these two upstream values to calculate C_u (for runs that did not include a gap). We do not measure upstream concentration twice when the run included a gap. The error in FE was calculated using the quadrature rule of error propagation. Due to noise in the measurements, some FE values were below 0, which is unrealistic. As such, negative FE values were removed from consideration in figures and further calculations. In addition to the FE curves, we computed an aggregate filter efficiency for each test specimen. To do this, we took a weighted average of FE values weighted by the bin width for the two particle size ranges (<300 nm and >300 nm). These values are reported in Table 1 and Table S1.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsnano.0c03252.

Filtration efficiencies for various fabrics tested at two different flow rates and the effect of layering on the filtration efficiencies of chiffon, silk, and 600 TPI cotton; detailed information on various fabrics used (PDF)

https://dx.doi.org/10.1021/acsnano.0c03252
ACS Nano XXXX, XXX, XXX−XXX

AUTHOR INFORMATION

Corresponding Author

Supratik Guha − *Pritzker School of Molecular Engineering, University of Chicago, Chicago, Illinois 60637, United States; Argonne National Laboratory, Lemont, Illinois 60439, United States;* orcid.org/0000-0001-5071-8318; Phone: (914)-325-5147; Email: guha@uchicago.edu

Authors

Abhiteja Konda − *Center for Nanoscale Materials, Argonne National Laboratory, Lemont, Illinois 60439, United States;* orcid.org/0000-0003-3362-0583

Abhinav Prakash − *Center for Nanoscale Materials, Argonne National Laboratory, Lemont, Illinois 60439, United States; Pritzker School of Molecular Engineering, University of Chicago, Chicago, Illinois 60637, United States;* orcid.org/0000-0002-8899-0568

Gregory A. Moss − *Worker Safety & Health Division, Argonne National Laboratory, Lemont, Illinois 60439, United States*

Michael Schmoldt − *Center for Nanoscale Materials and Worker Safety & Health Division, Argonne National Laboratory, Lemont, Illinois 60439, United States*

Gregory D. Grant − *Pritzker School of Molecular Engineering, University of Chicago, Chicago, Illinois 60637, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsnano.0c03252

Author Contributions

[⊥]A.K. and A.P. contributed equally.

Funding

Department of Defense Vannevar Bush Fellowship Grant No. N00014-18-1-2869.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

Use of the Center for Nanoscale Materials, an Office of Science user facility, was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357. S.G. acknowledges the Vannevar Bush Fellowship under the program sponsored by the Office of the Undersecretary of Defense for Research and Engineering [OUSD (R&E)] and the Office of Naval Research as the executive manager for the grant. A.K. acknowledges and thanks Prof. Anindita Basu for helpful discussion and support.

REFERENCES

(1) Ma, N.; Jeffrey, S. S. How to Sew a Fabric Face Mask. *Science* **2020**, *367*, 1424.

(2) Centers for Disease Control and Prevention. Coronavirus Disease 2019 (COVID-19). *Use of Cloth Face Coverings to Help Slow the Spread of COVID-19*; CS316353B, available at https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/diy-cloth-face-coverings.html, 2020; pp 1−3.

(3) Kutter, J. S.; Spronken, M. I.; Fraaij, P. L.; Fouchier, R. A.; Herfst, S. Transmission Routes of Respiratory Viruses Among Humans. *Curr. Opin. Virol.* **2018**, *28*, 142−151.

(4) Stelzer-Braid, S.; Oliver, B. G.; Blazey, A. J.; Argent, E.; Newsome, T. P.; Rawlinson, W. D.; Tovey, E. R. Exhalation of Respiratory Viruses by Breathing, Coughing, and Talking. *J. Med. Virol.* **2009**, *81*, 1674−1679.

(5) Milton, D. K.; Fabian, M. P.; Cowling, B. J.; Grantham, M. L.; McDevitt, J. J. Influenza Virus Aerosols in Human Exhaled Breath: Particle Size, Culturability, and Effect of Surgical Masks. *PLoS Pathog.* **2013**, *9*, No. e1003205.

(6) National Academies of Sciences. Medicine. *Rapid Expert Consultation on the Possibility of Bioaerosol Spread of SARS-CoV-2 for the COVID-19 Pandemic*; The National Academies Press: Washington, DC, 2020; p 3.

(7) National Academies of Sciences. Medicine. *Rapid Expert Consultation on the Effectiveness of Fabric Masks for the COVID-19 Pandemic*; The National Academies Press: Washington, DC, 2020; p 8.

(8) MacIntyre, C. R.; Seale, H.; Dung, T. C.; Hien, N. T.; Nga, P. T.; Chughtai, A. A.; Rahman, B.; Dwyer, D. E.; Wang, Q. A Cluster Randomised Trial of Cloth Masks Compared With Medical Masks in Healthcare Workers. *BMJ. Open* **2015**, *5*, No. e006577.

(9) Shakya, K. M.; Noyes, A.; Kallin, R.; Peltier, R. E. Evaluating the Efficacy of Cloth Facemasks in Reducing Particulate Matter Exposure. *J. Exposure Sci. Environ. Epidemiol.* **2017**, *27*, 352−357.

(10) Rengasamy, S.; Eimer, B.; Shaffer, R. E. Simple Respiratory Protection–Evaluation of the Filtration Performance of Cloth Masks and Common Fabric Materials Against 20−1000 nm Size Particles. *Ann. Occup. Hyg.* **2010**, *54*, 789−798.

(11) Davies, A.; Thompson, K. A.; Giri, K.; Kafatos, G.; Walker, J.; Bennett, A. Testing the Efficacy of Homemade Masks: Would They Protect in an Influenza Pandemic? *Disaster Med. Public Health Prep.* **2013**, *7*, 413−418.

(12) van der Sande, M.; Teunis, P.; Sabel, R. Professional and Home-Made Face Masks Reduce Exposure to Respiratory Infections Among the General Population. *PLoS One* **2008**, *3*, No. e2618.

(13) van Doremalen, N.; Bushmaker, T.; Morris, D. H.; Holbrook, M. G.; Gamble, A.; Williamson, B. N.; Tamin, A.; Harcourt, J. L.; Thornburg, N. J.; Gerber, S. I.; Lloyd-Smith, J. O.; de Wit, E.; Munster, V. J. Aerosol and Surface Stability of SARS-CoV-2 as Compared With SARS-CoV-1. *N. Engl. J. Med.* **2020**, *382*, 1564.

(14) Morawska, L.; Cao, J. Airborne Transmission of SARS-Cov-2: The World Should Face the Reality. *Environ. Int.* **2020**, *139*, 105730.

(15) Wang, J.; Du, G. COVID-19 May Transmit Through Aerosol. *Ir. J. Med. Sci.* **2020**, 1−2.

(16) Santarpia, J. L.; Rivera, D. N.; Herrera, V.; Morwitzer, M. J.; Creager, H.; Santarpia, G. W.; Crown, K. K.; Brett-Major, D.; Schnaubelt, E.; Broadhurst, M. J.; Lawler, J. V.; Reid, S. P.; Lowe, J. J. Transmission Potential of SARS-CoV-2 in Viral Shedding Observed at the University of Nebraska Medical Center. 2020, *medRxiv*; https://10.1101/2020.03.23.20039446 (accessed 2020-04-04).

(17) Zhang, H.; Li, D.; Xie, L.; Xiao, Y. Documentary Research of Human Respiratory Droplet Characteristics. *Procedia Eng.* **2015**, *121*, 1365−1374.

(18) World Health Organization. Annex C - Respiratory droplets. In *Natural Ventilation for Infection Control in Health-Care Settings*; Atkinson, J., Chartier, Y., Pessoa-Silva, C. L., Jensen, P., Li, Y., Seto, W. H., Eds.; World Health Organization: Geneva, 2009; pp 77−82.

(19) Morawska, L. Droplet Fate in Indoor Environments, or Can We Prevent the Spread of Infection? *Indoor Air* **2006**, *16*, 335−347.

(20) Ching, W.-H.; Leung, M. K. H.; Leung, D. Y. C.; Li, Y.; Yuen, P. L. Reducing Risk of Airborne Transmitted Infection in Hospitals by Use of Hospital Curtains. *Indoor Built Environ.* **2008**, *17*, 252−259.

(21) Lai, A. C. K.; Poon, C. K. M.; Cheung, A. C. T. Effectiveness of Facemasks to Reduce Exposure Hazards for Airborne Infections Among General Populations. *J. R. Soc., Interface* **2012**, *9*, 938−948.

(22) Leung, N. H. L.; Chu, D. K. W.; Shiu, E. Y. C.; Chan, K.-H.; McDevitt, J. J.; Hau, B. J. P.; Yen, H.-L.; Li, Y.; Ip, D. K. M.; Peiris, J. S. M.; Seto, W.-H.; Leung, G. M.; Milton, D. K.; Cowling, B. J. Respiratory Virus Shedding in Exhaled Breath and Efficacy of Face Masks. *Nat. Med.* **2020**, DOI: 10.1038/s41591-020-0843-2.

(23) Hinds, W. C. 9 - Filtration. In *Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles*, 2nd ed.; John Wiley & Sons: New York, 1999; pp 182−205.

(24) Vincent, J. H. 21 - Aerosol Sample Applications and Field Studies. In *Aerosol Sampling. Science, Standards, Instrumentation and*

Applications; Vincent, J. H., Ed.; John Wiley & Sons: New York, 2007; pp 528−529.
(25) Colbeck, I.; Lazaridis, M. 5 - Filtration Mechanisms. In *Aerosol Science: Technology and Applications*, 1st ed.; Colbeck, I., Lazaridis, M., Eds.; John Wiley & Sons: New York, 2014; pp 89−118.
(26) Jung, H.; Kim, J.; Lee, S.; Lee, J.; Kim, J.; Tsai, P.; Yoon, C. Comparison of Filtration Efficiency and Pressure Drop in Anti-Yellow Sand Masks, Quarantine Masks, Medical Masks, General Masks, and Handkerchiefs. *Aerosol Air Qual. Res.* **2014**, *14*, 991−1002.
(27) Holton, P. M.; Tackett, D. L.; Willeke, K. Particle Size-Dependent Leakage and Losses of Aerosols in Respirators. *Am. Ind. Hyg. Assoc. J.* **1987**, *48*, 848−854.
(28) Rengasamy, S.; Eimer, B. C. Nanoparticle Penetration Through Filter Media and Leakage Through Face Seal Interface of N95 Filtering Facepiece Respirators. *Ann. Occup. Hyg.* **2012**, *56*, 568−580.
(29) Rengasamy, S.; Zhuang, Z.; Niezgoda, G.; Walbert, G.; Lawrence, R.; Boutin, B.; Hudnall, J.; Monaghan, W. P.; Bergman, M.; Miller, C.; Harris, J.; Coffey, C. A Comparison of Total Inward Leakage Measured Using Sodium Chloride (NaCl) and Corn Oil Aerosol Methods for Air-Purifying Respirators. *J. Occup. Environ. Hyg.* **2018**, *15*, 616−627.
(30) Electronic Code of Federal Regulations (eCFR), Title 42: Public Health, Part 84—Approval of Respiratory Protective Devices. *Code of Federal Regulations*, April 2020.
(31) Lord, J. 35—The Determination of the Air Permeability of Fabrics. *J. Text. I.* **1959**, *50*, T569−T582.
(32) Silverman, L.; Lee, G.; Plotkin, T.; Sawyers, L. A.; Yancey, A. R. Air Flow Measurements on Human Subjects With and Without Respiratory Resistance at Several Work Rates. *AMA Arch. Ind. Hyg. Occup. Med.* **1951**, *3*, 461−478.
(33) Grinshpun, S. A.; Haruta, H.; Eninger, R. M.; Reponen, T.; McKay, R. T.; Lee, S.-A. Performance of an N95 Filtering Facepiece Particulate Respirator and a Surgical Mask During Human Breathing: Two Pathways for Particle Penetration. *J. Occup. Environ. Hyg.* **2009**, *6*, 593−603.
(34) Wells, W. F. Airborne Contagion and Air Hygiene: An Ecological Study of Droplet Infections. *J. Am. Med. Assoc.* **1955**, *159*, 90.
(35) Huang, H.; Fan, C.; Li, M.; Nie, H.-L.; Wang, F.-B.; Wang, H.; Wang, R.; Xia, J.; Zheng, X.; Zuo, X.; Huang, J. COVID-19: A Call for Physical Scientists and Engineers. *ACS Nano* **2020**, DOI: 10.1021/acsnano.0c02618.
(36) Perumalraj, R. Characterization of Electrostatic Discharge Properties of Woven Fabrics. *J. Textile Sci. Eng.* **2015**, *06*, 1000235.
(37) Frederick, E. R. Fibers, Filtration and Electrostatics - A Review of the New Technology. *J. Air Pollut. Control Assoc.* **1986**, *36*, 205−209.
(38) Sanchez, A. L.; Hubbard, J. A.; Dellinger, J. G.; Servantes, B. L. Experimental Study of Electrostatic Aerosol Filtration at Moderate Filter Face Velocity. *Aerosol Sci. Technol.* **2013**, *47*, 606−615.
(39) Bałazy, A.; Toivola, M.; Adhikari, A.; Sivasubramani, S. K.; Reponen, T.; Grinshpun, S. A. Do N95 Respirators Provide 95% Protection Level Against Airborne Viruses, and How Adequate are Surgical Masks? *Am. J. Infect. Control* **2006**, *34*, 51−57.
(40) Balazy, A.; Toivola, M.; Reponen, T.; Podgorski, A.; Zimmer, A.; Grinshpun, S. A. Manikin-Based Performance Evaluation of N95 Filtering-Facepiece Respirators Challenged With Nanoparticles. *Ann. Occup. Hyg.* **2005**, *50*, 259−269.
(41) National Academies of Sciences. Medicine. *Reusable Elastomeric Respirators in Health Care: Considerations for Routine and Surge Use*; The National Academies Press: Washington, DC, 2019; p 226.
(42) Bullock, W. H.; Ignacio, J. S. *A Strategy for Assessing and Managing Occupational Exposures*; AIHA Press, American Industrial Hygiene Association, 2006.

NOTE ADDED AFTER ASAP PUBLICATION

The units in Figure 2 were corrected April 27, 2020.

https://dx.doi.org/10.1021/acsnano.0c03252
ACS Nano XXXX, XXX, XXX−XXX

From: COREY SURBER <Corey.Surber@saintalphonsus.org>
Sent: Thursday, October 15, 2020 3:06 PM
To: jagenbroad@senate.idaho.gov; gburgoyne@senate.idaho.gov; Lori Den Hartog <LDenHartog@senate.idaho.gov>; jellis@house.idaho.gov; Fred Martin <fmartin@senate.idaho.gov>; Representative Lauren Necochea <LNecochea@house.idaho.gov>; Representative Ilana Rubel <IRubel@house.idaho.gov>; 'cwinder@senate.idaho.gov' <cwinder@senate.idaho.gov>; Representative Melissa Wintrow <MWintrow@house.idaho.gov>; Sara Stover <Sara.Stover@dfm.idaho.gov>; 'ryoungblood@house.idaho.gov' <ryoungblood@house.idaho.gov>
Subject: FW: LI Literature Service: Face masks: what the data say

Thank you all for attending our legislative virtual town hall with CEO Odette Bolano this morning. Odette asked that I pass the article below along that she mentioned during her comments. Have a wonderful and safe weekend, everyone!

Corey Surber | MHS
Director, State Advocacy
Saint Alphonsus Health System
1055 N. Curtis Rd., Boise, ID 83706
Office: 208-367-7078 | Cell: 208-859-2207
Corey.Surber@saintalphonsus.org
#SaintAlsForLife

From: Odette C. Bolano <Odette.Bolano@saintalphonsus.org>
Sent: Thursday, October 15, 2020 11:51 AM
To: 'Jeremy Pisca' <jpisca@rischpisca.com>; COREY SURBER <Corey.Surber@saintalphonsus.org>
Subject: FW: LI Literature Service: Face masks: what the data say

Here you go…

Face masks: what the data say

The science supports that face coverings are saving lives during the coronavirus pandemic, and yet the debate trundles on. How much evidence is enough?

Nature

By Lynne Peeples
October 6, 2020

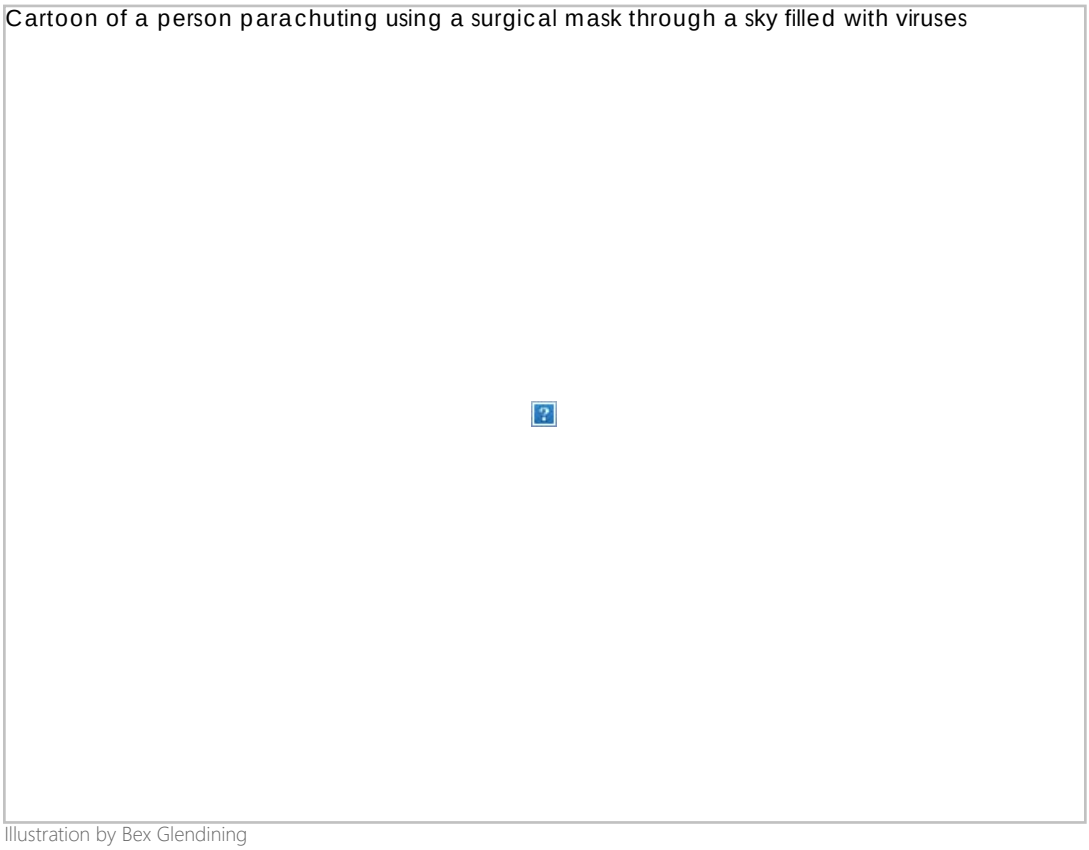


Illustration by Bex Glendining

When her Danish colleagues first suggested distributing protective cloth face masks to people in Guinea-Bissau to stem the spread of the coronavirus, Christine Benn wasn't so sure.

"I said, 'Yeah, that might be good, but there's limited data on whether face masks are actually effective,'" says Benn, a global-health researcher at the University of Southern Denmark in Copenhagen, who for decades has co-led public-health campaigns in the West African country, one of the world's poorest.

That was in March. But by July, Benn and her team had worked out how to possibly provide some needed data on masks, and hopefully help people in Guinea-Bissau. They distributed thousands of locally produced cloth face coverings to people as part of a randomized controlled trial that might be the world's largest test of masks' effectiveness against the spread of COVID-19.

Face masks are the ubiquitous symbol of a pandemic that has sickened 35 million people and killed more than 1 million. In hospitals and other health-care facilities,

the use of medical-grade masks clearly cuts down transmission of the SARS-CoV-2 virus. But for the variety of masks in use by the public, the data are messy, disparate and often hastily assembled. Add to that a divisive political discourse that included a US president disparaging their use, just days before being diagnosed with COVID-19 himself. “People looking at the evidence are understanding it differently,” says Baruch Fischhoff, a psychologist at Carnegie Mellon University in Pittsburgh, Pennsylvania, who specializes in public policy. “It’s legitimately confusing.”

To be clear, the science supports using masks, with recent studies suggesting that they could save lives in different ways: research shows that they cut down the chances of both transmitting and catching the coronavirus, and some studies hint that masks might reduce the severity of infection if people do contract the disease.

But being more definitive about how well they work or when to use them gets complicated. There are many types of mask, worn in a variety of environments. There are questions about people’s willingness to wear them, or wear them properly. Even the question of what kinds of study would provide definitive proof that they work is hard to answer.

“How good does the evidence need to be?” asks Fischhoff. “It’s a vital question.”

Beyond gold standards

At the beginning of the pandemic, medical experts lacked good evidence on how SARS-CoV-2 spreads, and they didn’t know enough to make strong public-health recommendations about masks.

The standard mask for use in health-care settings is the N95 respirator, which is designed to protect the wearer by filtering out 95% of airborne particles that measure 0.3 micrometres (μm) and larger. As the pandemic ramped up, these respirators quickly fell into short supply. That raised the now contentious question: should members of the public bother wearing basic surgical masks or cloth masks? If so, under what conditions? “Those are the things we normally [sort out] in clinical trials,” says Kate Grabowski, an infectious-disease epidemiologist at Johns Hopkins School of Medicine in Baltimore, Maryland. “But we just didn’t have time for that.”

So, scientists have relied on observational and laboratory studies. There is also indirect evidence from other infectious diseases. “If you look at any one paper — it’s not a slam dunk. But, taken all together, I’m convinced that they are working,” says Grabowski.

Confidence in masks grew in June with news about two hair stylists in Missouri who tested positive for COVID-191. Both wore a double-layered cotton face covering or surgical mask while working. And although they passed on the infection to members

of their households, their clients seem to have been spared (more than half reportedly declined free tests). Other hints of effectiveness emerged from mass gatherings. At Black Lives Matter protests in US cities, most attendees wore masks. The events did not seem to trigger spikes in infections[2], yet the virus ran rampant in late June at a Georgia summer camp, where children who attended were not required to wear face coverings[3]. Caveats abound: the protests were outdoors, which poses a lower risk of COVID-19 spread, whereas the campers shared cabins at night, for example. And because many non-protesters stayed in their homes during the gatherings, that might have reduced virus transmission in the community. Nevertheless, the anecdotal evidence "builds up the picture", says Theo Vos, a health-policy researcher at the University of Washington in Seattle.

More-rigorous analyses added direct evidence. A preprint study[4] posted in early August (and not yet peer reviewed), found that weekly increases in per-capita mortality were four times lower in places where masks were the norm or recommended by the government, compared with other regions. Researchers looked at 200 countries, including Mongolia, which adopted mask use in January and, as of May, had recorded no deaths related to COVID-19. Another study[5] looked at the effects of US state-government mandates for mask use in April and May. Researchers estimated that those reduced the growth of COVID-19 cases by up to 2 percentage points per day. They cautiously suggest that mandates might have averted as many as 450,000 cases, after controlling for other mitigation measures, such as physical distancing.

"You don't have to do much math to say this is obviously a good idea," says Jeremy Howard, a research scientist at the University of San Francisco in California, who is part of a team that reviewed the evidence for wearing face masks in a preprint article that has been widely circulated[6].

But such studies do rely on assumptions that mask mandates are being enforced and that people are wearing them correctly. Furthermore, mask use often coincides with other changes, such as limits on gatherings. As restrictions lift, further observational studies might begin to separate the impact of masks from those of other interventions, suggests Grabowski. "It will become easier to see what is doing what," she says.

Although scientists can't control many confounding variables in human populations, they can in animal studies. Researchers led by microbiologist Kwok-Yung Yuen at the University of Hong Kong housed infected and healthy hamsters in adjoining cages, with surgical-mask partitions separating some of the animals. Without a barrier, about two-thirds of the uninfected animals caught SARS-CoV-2, according to the paper[7] published in May. But only about 25% of the animals protected by mask material got infected, and those that did were less sick than their mask-free neighbours (as measured by clinical scores and tissue changes).

The findings provide justification for the emerging consensus that mask use protects the wearer as well as other people. The work also points to another potentially game-changing idea: “Masking may not only protect you from infection but also from severe illness,” says Monica Gandhi, an infectious-disease physician at the University of California, San Francisco.

Gandhi co-authored a paper[8] published in late July suggesting that masking reduces the dose of virus a wearer might receive, resulting in infections that are milder or even asymptomatic. A larger viral dose results in a more aggressive inflammatory response, she suggests.

She and her colleagues are currently analysing hospitalization rates for COVID-19 before and after mask mandates in 1,000 US counties, to determine whether the severity of disease decreased after public masking guidelines were brought in.

The idea that exposure to more virus results in a worse infection makes “absolute sense”, says Paul Digard, a virologist at the University of Edinburgh, UK, who was not involved in the research. “It’s another argument for masks.”

Gandhi suggests another possible benefit: if more people get mild cases, that might help to enhance immunity at the population level without increasing the burden of severe illness and death. “As we’re awaiting a vaccine, could driving up rates of asymptomatic infection do good for population-level immunity?” she asks.

Back to ballistics

The masks debate is closely linked to another divisive question: how does the virus travel through the air and spread infection?

The moment a person breathes or talks, sneezes or coughs, a fine spray of liquid particles takes flight. Some are large — visible, even — and referred to as droplets; others are microscopic, and categorized as aerosols. Viruses including SARS-CoV-2 hitch rides on these particles; their size dictates their behaviour.

Droplets can shoot through the air and land on a nearby person’s eyes, nose or mouth to cause infection. But gravity quickly pulls them down. Aerosols, by contrast, can float in the air for minutes to hours, spreading through an unventilated room like cigarette smoke.

What does this imply for the ability of masks to impede COVID-19 transmission? The virus itself is only about 0.1 μm in diameter. But because viruses don’t leave the body on their own, a mask doesn’t need to block particles that small to be effective. More relevant are the pathogen-transporting droplets and aerosols, which range from about 0.2 μm to hundreds of micrometres across. (An average human hair has a diameter of about 80 μm.) The majority are 1–10 μm in diameter and can linger in

the air a long time, says Jose-Luis Jimenez, an environmental chemist at the University of Colorado Boulder. “That is where the action is.”

Scientists are still unsure which size of particle is most important in COVID-19 transmission. Some can’t even agree on the cut-off that should define aerosols. For the same reasons, scientists still don’t know the major form of transmission for influenza, which has been studied for much longer.

Many believe that asymptomatic transmission is driving much of the COVID-19 pandemic, which would suggest that viruses aren’t typically riding out on coughs or sneezes. By this reasoning, aerosols could prove to be the most important transmission vehicle. So, it is worth looking at which masks can stop aerosols.

All in the fabric

Even well-fitting N95 respirators fall slightly short of their 95% rating in real-world use, actually filtering out around 90% of incoming aerosols down to 0.3 µm. And, according to unpublished research, N95 masks that don’t have exhalation valves — which expel unfiltered exhaled air — block a similar proportion of outgoing aerosols. Much less is known about surgical and cloth masks, says Kevin Fennelly, a pulmonologist at the US National Heart, Lung, and Blood Institute in Bethesda, Maryland.

In a review[9] of observational studies, an international research team estimates that surgical and comparable cloth masks are 67% effective in protecting the wearer.

In unpublished work, Linsey Marr, an environmental engineer at Virginia Tech in Blacksburg, and her colleagues found that even a cotton T-shirt can block half of inhaled aerosols and almost 80% of exhaled aerosols measuring 2 µm across. Once you get to aerosols of 4–5 µm, almost any fabric can block more than 80% in both directions, she says.

Multiple layers of fabric, she adds, are more effective, and the tighter the weave, the better. Another study[10] found that masks with layers of different materials — such as cotton and silk — could catch aerosols more efficiently than those made from a single material.

Benn worked with Danish engineers at her university to test their two-layered cloth mask design using the same criteria as for medical-grade ventilators. They found that their mask blocked only 11–19% of aerosols down to the 0.3 µm mark, according to Benn. But because most transmission is probably occurring through particles of at least 1 µm, according to Marr and Jimenez, the actual difference in effectiveness between N95 and other masks might not be huge.

Eric Westman, a clinical researcher at Duke University School of Medicine in Durham, North Carolina, co-authored an August study11 that demonstrated a method for testing mask effectiveness. His team used lasers and smartphone cameras to compare how well 14 different cloth and surgical face coverings stopped droplets while a person spoke. “I was reassured that a lot of the masks we use did work,” he says, referring to the performance of cloth and surgical masks. But thin polyester-and-spandex neck gaiters — stretchable scarves that can be pulled up over the mouth and nose — seemed to actually reduce the size of droplets being released. “That could be worse than wearing nothing at all,” Westman says.

Some scientists advise not making too much of the finding, which was based on just one person talking. Marr and her team were among the scientists who responded with experiments of their own, finding that neck gaiters blocked most large droplets. Marr says she is writing up her results for publication.

“There’s a lot of information out there, but it’s confusing to put all the lines of evidence together,” says Angela Rasmussen, a virologist at Columbia University’s Mailman School of Public Health in New York City. “When it comes down to it, we still don’t know a lot.”

Minding human minds

Questions about masks go beyond biology, epidemiology and physics. Human behaviour is core to how well masks work in the real world. “I don’t want someone who is infected in a crowded area being confident while wearing one of these cloth coverings,” says Michael Osterholm, director of the Center for Infectious Disease Research and Policy at the University of Minnesota in Minneapolis.

US baseball players wore masks while playing during the 1918 influenza epidemic.Credit: Underwood And Underwood/LIFE Images Collection/Getty

Perhaps fortunately, some evidence[12] suggests that donning a face mask might drive the wearer and those around them to adhere better to other measures, such as social distancing. The masks remind them of shared responsibility, perhaps. But that requires that people wear them.

Across the United States, mask use has held steady around 50% since late July. This is a substantial increase from the 20% usage seen in March and April, according to data from the Institute for Health Metrics and Evaluation at the University of Washington in Seattle (see go.nature.com/30n6kxv). The institute's models also predicted that, as of 23 September, increasing US mask use to 95% — a level observed in Singapore and some other countries — could save nearly 100,000 lives in the period up to 1 January 2021.

"There's a lot more we would like to know," says Vos, who contributed to the analysis. "But given that it is such a simple, low-cost intervention with potentially such a large impact, who would not want to use it?"

Further confusing the public are controversial studies and mixed messages. One study[13] in April found masks to be ineffective, but was retracted in July. Another,

published in June14, supported the use of masks before dozens of scientists wrote a letter attacking its methods (see go.nature.com/3jpvxpt). The authors are pushing back against calls for a retraction. Meanwhile, the World Health Organization (WHO) and the US Centers for Disease Control and Prevention (CDC) initially refrained from recommending widespread mask usage, in part because of some hesitancy about depleting supplies for health-care workers. In April, the CDC recommended that masks be worn when physical distancing isn't an option; the WHO followed suit in June.

There's been a lack of consistency among political leaders, too. US President Donald Trump voiced support for masks, but rarely wore one. He even ridiculed political rival Joe Biden for consistently using a mask — just days before Trump himself tested positive for the coronavirus, on 2 October. Other world leaders, including the president and prime minister of Slovakia, Zuzana Caputová and Igor Matovic, sported masks early in the pandemic, reportedly to set an example for their country.

Denmark was one of the last nations to mandate face masks — requiring their use on public transport from 22 August. It has maintained generally good control of the virus through early stay-at-home orders, testing and contact tracing. It is also at the forefront of COVID-19 face-mask research, in the form of two large, randomly controlled trials. A research group in Denmark enrolled some 6,000 participants, asking half to use surgical face masks when going to a workplace. Although the study is completed, Thomas Benfield, a clinical researcher at the University of Copenhagen and one of the principal investigators on the trial, says that his team is not ready to share any results.

Benn's team, working independently of Benfield's group, is in the process of enrolling around 40,000 people in Guinea-Bissau, randomly selecting half of the households to receive bilayer cloth masks — two for each family member aged ten or over. The team will then follow everyone over several months to compare rates of mask use with rates of COVID-like illness. She notes that each household will receive advice on how to protect themselves from COVID-19 — except that those in the control group will not get information on the use of masks. The team expects to complete enrolment in November.

Several scientists say that they are excited to see the results. But others worry that such experiments are wasteful and potentially exploit a vulnerable population. "If this was a gentler pathogen, it would be great," says Eric Topol, director of the Scripps Research Translational Institute in La Jolla, California. "You can't do randomized trials for everything — and you shouldn't." As clinical researchers are sometimes fond of saying, parachutes have never been tested in a randomized controlled trial, either.

But Benn defends her work, explaining that people in the control group will still

benefit from information about COVID-19, and they will get masks at the end of the study. Given the challenge of manufacturing and distributing the masks, “under no circumstances”, she says, could her team have handed out enough for everyone at the study’s outset. In fact, they had to scale back their original plans to enrol 70,000 people. She is hopeful that the trial will provide some benefits for everyone involved. “But no one in the community should be worse off than if we hadn’t done this trial,” she says. The resulting data, she adds, should inform the global scientific debate.

For now, Osterholm, in Minnesota, wears a mask. Yet he laments the “lack of scientific rigour” that has so far been brought to the topic. “We criticize people all the time in the science world for making statements without any data,” he says. “We’re doing a lot of the same thing here.”

Nevertheless, most scientists are confident that they can say something prescriptive about wearing masks. It’s not the only solution, says Gandhi, “but I think it is a profoundly important pillar of pandemic control”. As Digard puts it: “Masks work, but they are not infallible. And, therefore, keep your distance.”

By Wei Lyu and George L. Wehby

Community Use Of Face Masks And COVID-19: Evidence From A Natural Experiment Of State Mandates In The US

DOI: 10.1377/hlthaff.2020.00818
HEALTH AFFAIRS 39,
NO. 8 (2020): 1419–1425

ABSTRACT **State policies mandating public or community use of face masks or covers in mitigating the spread of coronavirus disease 2019 (COVID-19) are hotly contested. This study provides evidence from a natural experiment on the effects of state government mandates for face mask use in public issued by fifteen states plus Washington, D.C., between April 8 and May 15, 2020. The research design is an event study examining changes in the daily county-level COVID-19 growth rates between March 31 and May 22, 2020. Mandating face mask use in public is associated with a decline in the daily COVID-19 growth rate by 0.9, 1.1, 1.4, 1.7, and 2.0 percentage points in 1–5, 6–10, 11–15, 16–20, and 21 or more days after state face mask orders were signed, respectively. Estimates suggest that as a result of the implementation of these mandates, more than 200,000 COVID-19 cases were averted by May 22, 2020. The findings suggest that requiring face mask use in public could help in mitigating the spread of COVID-19.**

Wei Lyu is a research associate in the Department of Health Management and Policy, College of Public Health, University of Iowa, in Iowa City, Iowa.

George L. Wehby (george-wehby@uiowa.edu) is a professor in the Department of Health Management and Policy, College of Public Health, at the University of Iowa, and a research associate at the National Bureau of Economic Research.

One of the most contentious issues being debated worldwide in the response to the coronavirus disease 2019 (COVID-19) pandemic is the value of wearing masks or face coverings in public settings.[1] A key factor fueling the debate is the limited direct evidence thus far on how much widespread community use would affect COVID-19 spread. However, there is now substantial evidence of asymptomatic transmission of COVID-19.[2,3] For example, a recent study of antibodies in a sample of customers in grocery stores in New York State reported an infection rate of 14.0 percent by March 29 (projected to represent more than 2.1 million cases), which substantially exceeds the number of confirmed COVID-19 cases.[4] Moreover, all public health authorities call on symptomatic people to wear masks to reduce transmission risk. Even organizations that at the time of our study had not yet recommended widespread community use of face masks for COVID-19 mitigation (that is, everyone without symptoms should use a face mask outside of their home), such as the World Health Organization, strongly recommend that symptomatic individuals wear them.[5] Because mask wearing by infected people can reduce transmission risk, and because of the high proportion of asymptomatic infected individuals and transmissions, there appears to be a strong case for the effectiveness of widespread use of face masks in reducing the spread of COVID-19. However, there is no direct evidence thus far on the magnitude of such effects, especially at a population level.

Researchers have been reviewing evidence from previous randomized controlled trials for other respiratory illnesses, examining mask use and types among people at higher risk of contracting infections (such as health care workers or people in infected households). Systematic reviews and meta-analyses of such studies have provided suggestive, although generally weak, evidence.[6] The estimates from the meta-analyses

based on randomized controlled trials suggest declines in transmission risk for influenza or influenza-like illnesses to mask wearers, although estimates are mostly statistically insignificant possibly because of small sample sizes or design limitations, especially those related to assessing compliance.[7–9] There is also a relationship between increased adherence to mask use, specifically, and effectiveness of reducing transmission to mask wearers: In one randomized study of influenza transmission in infected households in Australia, transmission risk for mask wearers was lower with greater adherence.[10] Further, the evidence is mixed from randomized studies on types of masks and risk for influenza-like illness transmission to mask wearers; for example, a recent systematic review and meta-analysis comparing N-95 respirators versus surgical masks found a statistically insignificant decline in influenza risk with N-95 respirators.[11]

Positions on widespread face mask use have differed worldwide but are changing over time. In the US, public health authorities did not recommend widespread face mask use in public at the start of the pandemic. The initially limited evidence on asymptomatic transmission and concern about mask shortages for the health care workforce and people caring for patients contributed to that initial decision. On April 3, 2020, the Centers for Disease Control and Prevention (CDC) issued new guidance advising everyone to wear cloth face covers in public areas where close contact with others is unavoidable, citing new evidence on virus transmission from asymptomatic or presymptomatic people.[12] Guidelines differ between countries, and some, including Germany, France, Italy, Spain, China, and South Korea, have mandated the use of face masks in public.[13–16]

This study adds complementary evidence to the literature on the impacts of widespread community use of face masks on COVID-19 spread from a natural experiment based on whether or not US states had mandated the use of face masks in public for COVID-19 mitigation as of May 2020. Fifteen states plus Washington, D.C., issued mandates for face mask use in public between April 8 and May 15.

We identified the effects of state mandates for the use of face masks in public on the daily COVID-19 growth rate, using an event study that examined the effects over different periods. We considered the impact of mandates for mask use targeted only to employees in some work settings, as opposed to communitywide mandates. This evidence is critical, as states and countries worldwide begin to shift to "reopening" their economies and as foot traffic increases. Mandating the public use of masks has become a socially and politically contentious issue, with multiple protests and even acts of violence directed against masked employees and those asking customers to wear face masks.[17] Face cover recommendations and mandates are part of the current set of measures, following earlier social distancing measures such as school and nonessential business closures, bans on large gatherings, and shelter-in-place orders being considered by states and local governments, especially as regions of the country reopen. For example, during Virginia's phase one reopening, begun May 22, 2020, everyone in the state was required to wear a face mask in public where people congregate.[18] Even though more states have issued such orders since the study was completed, it is critical to provide direct evidence on this question not only for public health authorities and governments but also for educating the public.

Study Data And Methods

DATA We collected information on statewide face cover mandate orders from public data sets on such policies and from searching and reviewing all state orders issued between April 1 and May 21, 2020. Our study focused on state executive orders or directives signed by governors that mandate use. Recommendations or guidelines from state departments of public health were not included, as these largely follow the CDC guidelines and might not necessarily add further information or impact. See online appendix A for a more detailed description of the data sources and measuring of the mandates.[19]

States differ in whether or not they require their citizens to wear face masks (covers) to limit COVID-19 spread. Between April 8 and May 15, governors of fifteen states and the mayor of Washington, D.C., signed orders mandating all individuals who can medically tolerate the wearing of a face mask do so in public settings (for example, public transportation, grocery stores, pharmacies, or other retail stores) where maintaining six feet of "social distance" might not always be practicable. These sixteen jurisdictions also have specific mandates requiring employees in certain professions to wear masks at all times while working.

In addition to these sixteen jurisdictions, twenty additional states have employee-only mandates (but no community mandate) requiring that some employees (for example, close-contact service providers such as in barber shops and nail salons) wear a face mask at all times while providing services. The face mask defined in these orders primarily refers to cloth face coverings or nonmedical masks. The state orders

strongly discourage the use of any medical or surgical masks and N-95 respirators, which should be reserved for health care workers and first responders. The orders also clearly specify that the face masks are not a replacement for any other social distancing protocols. More information on dates and links to these state orders are in appendix exhibit A1 and appendices D and E.[19] Fifteen states had not yet issued community or employee mandates when we performed the study.

The main model used publicly available daily county-level data of confirmed COVID-19 cases from March 25 through May 21.[20] The data covered all states plus Washington, D.C., and the analytical sample included 2,930 unique counties plus New York City (five boroughs combined). See appendix A for a more detailed description of COVID-19 data.[19]

STATISTICAL ANALYSIS We employed an event study, which is generally similar to a difference-in-differences design, to examine whether statewide mandates to wear face masks in public affect the spread of COVID-19 based on the state variations noted earlier. This design allowed us to estimate the effects in the context of a natural experiment, comparing the pre-post mandate changes in COVID-19 spread in the states with mandates versus changes in COVID-19 spread in the states that did not pass these mandates, over time. The model also tested whether states issuing these mandates had differential pre-event trends in COVID-19 rates before they were issued. This is a critical assumption of the validity of an event study that must be upheld under testing. In addition, the model allowed us to control for a wide range of time-invariant differences between states and counties, such as population density and socioeconomic and demographic factors, plus time-variant differences between states and counties, such as other mitigation and social distancing policies, in addition to state-level COVID-19 testing rates.

We estimated the effects of face cover mandates on the daily county-level COVID-19 growth rate, which is the difference in the natural log of cumulative COVID-19 cases on a given day minus the natural log of cumulative cases in the prior day, multiplied by 100.[21] This measure gives the daily growth rate in percentage points.

The reference period for estimating the face cover mandate effects was 1–5 days before signing the order. We examined how effects change over five post-event periods: 1–5, 6–10, 11–15, 16–20, and 21 or more days. The model also tested for pre-event trends over the course of 6–10, 11–15, and 16 or more days before signing the mandate. For all counties in the analytical sample, the main model included daily data from March 31 (seven days before the first state signed a face cover mandate) through May 22. The models were estimated by least squares weighted by the county's 2019 population with heteroscedasticity-robust and state-clustered standard errors.

As noted earlier, all of the fifteen states plus Washington, D.C., that mandated face cover use in public also mandated employee mask use. To assess the effects of employee face cover mandates, we employed another event study model that focused solely on the employee face cover mandate as the policy intervention. In this analysis, we excluded the sixteen jurisdictions that enacted both public and employee face cover mandates and focused on the twenty states that enacted an employee-only mandate and the fifteen states with neither a public nor an employee mandate.

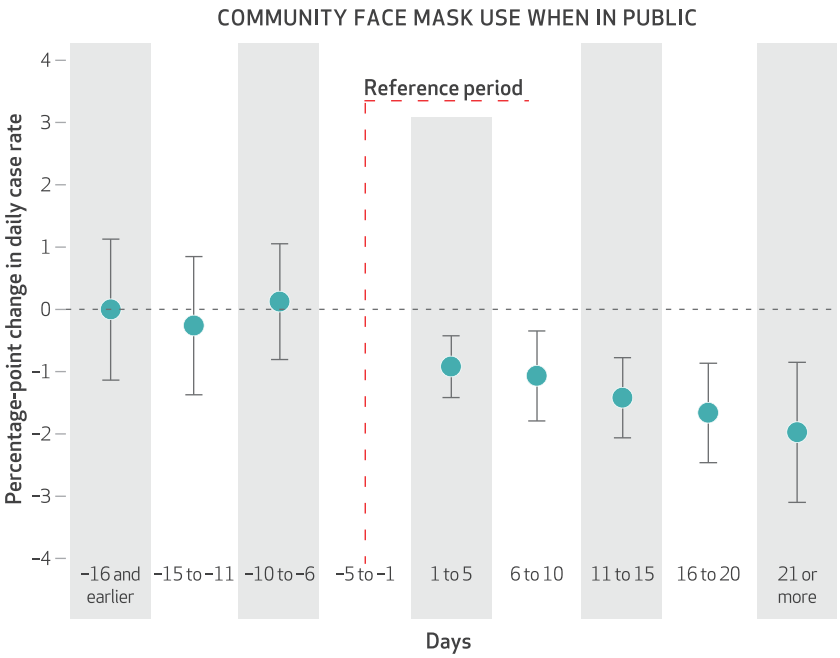
LIMITATIONS We were unable to measure face cover use in the community (that is, compliance with the mandate). As such, the estimates represent the intent-to-treat effects of these mandates—that is, their effects as passed and not the individual-level effect of wearing a face mask in public on one's own COVID-19 risk. Related, we did not measure enforcement of the mandates, which might affect compliance. We also did not have data on county-level mandates for wearing face masks in public. In some states without state-level mandates at the time of our study, such as California,[22] Texas,[23] and Colorado,[24] multiple counties had enacted such mandates. These county-level mandates did not bias the intent-to-treat estimates of effects of state-level mandates as actually passed, but they added local-level heterogeneity not directly accounted for in the model. We did examine the robustness of estimates to the exclusion of some of these states. Finally, we were able to examine only confirmed COVID-19 cases. However, there is evidence of a higher infection rate in the community than is reflected in the number of confirmed cases.[25]

Study Results

EFFECTS OF MANDATES FOR FACE COVERING IN PUBLIC Exhibit 1 plots the event study estimates of effects of state mandates for community face covering in public on the county-level daily growth rate of COVID-19 cases, with 95 percent confidence intervals, obtained from the main regression model (in appendix B),[19] using county-level daily data from March 31 through May22; appendix exhibit C1 (column 1) reports the exact estimates. The effects are shown over the course of five periods after signing the orders, relative to the five days before signing (which is the reference period). Also shown

EXHIBIT 1

Event study estimates of the effects of states mandating community face mask use in public on the daily county-level growth rate of COVID-19 cases, 2020



SOURCE Authors' analysis of US county-level COVID-19 case data between March 31 and May 22, 2020. **NOTES** Event study estimates (dots) and 95% confidence intervals (bars) of the effects of states mandating community use of face covers or masks when people are in public on the county-level daily growth rate of COVID-19 cases over different periods before and after the mandate order was signed. The reference period was the first five days before the mandate order was signed. The model controlled for major COVID-19 mitigation policies as time-varying (closure of K–12 schools, county-level or statewide shelter-in-place orders, nonessential business closure, closure of restaurants for dining in, closure of gyms or movie theaters), COVID-19 tests per 100,000 people, county fixed effects, and day fixed effects. The model was estimated by least squares weighted by the county 2019 population, and the standard errors were robust to heteroscedasticity and clustered at the state level.

are estimated differences in daily COVID-19 growth rates between states with and without the mandates over the course of three periods before the reference period.

There was a significant decline in daily COVID-19 growth rate after the mandating of face covers in public, with the effect increasing over time after the orders were signed. Specifically, the daily case rate declined by 0.9, 1.1, 1.4, 1.7, and 2.0 percentage points within 1–5, 6–10, 11–15, 16–20, and 21 or more days after signing, respectively. All of these declines were statistically significant ($p < 0.05$ or less). In contrast, the pre-event trends in COVID-19 case growth rates were small and statistically insignificant.

We also projected the number of averted COVID-19 cases with the mandates for face mask use in public by comparing actual cumulative daily cases with daily cases predicted by the model if none of the states had enacted the public face cover mandate at the time they did (see details in appendix B).[19] The main model estimates suggested that because of these mandates, 230,000–450,000 cases may have been averted by May 22. Estimates of averted cases should be viewed cautiously and only as general approximations.

ROBUSTNESS CHECKS We estimated multiple extensions of the main event study model to assess the robustness of estimates to different model specifications and sample choices. These checks started the event study on March 26; added flexible controls for social distancing measures, state reopening measures, employee face mask use mandates, and county-specific time trends; and allowed time trends to vary by sociodemographic indicators. Other checks used the mandate effective date instead of the signing date, used hyperbolic sine transformation to account for zero cases, included states as the unit instead of counties, included only urban counties, and excluded some states without state-level mandates but with multiple counties having local mandates. The detailed description and results of these robustness checks are in appendix C.[19] The results were robust across these checks; effects were smaller when we used the effective dates instead of the signing dates, which differ by about two to three days, on average, suggesting earlier compliance, and when we used states as the unit of analysis. But the estimates remained meaningful and statistically significant in all checks.

EFFECTS OF EMPLOYEE-ONLY FACE COVER MANDATES As noted earlier, we also directly assessed the effects of states mandating only that certain employees wear face masks. Twenty states issued employee use mandates but not community use mandates. We reestimated the event study model described earlier for an employee-only mandate including those twenty states (issued between April 17 and May 9) and the fifteen states without mandates, and excluding the sixteen jurisdictions that issued both public and employee use mandates. Exhibit 2 plots the event study estimates of changes in county-level daily COVID-19 growth rates with the employee-only face cover mandates and their 95 percent confidence intervals. All pre- and postmandate estimates were small and insignificant. Overall, these results indicate no evidence of declines in daily COVID-19 growth rates with employee-only mandates.

Discussion

Around the world, governments have been fighting COVID-19 spread through a mix of policies and mitigation measures such as school and nonessential business closures and shelter-in-place orders. Some countries have also recommended or mandated widespread community use of face

masks as a mitigation measure. However, the effectiveness of this measure is highly debated. The debate and uncertainty are fueled by the limited direct empirical evidence available on the magnitude of the effects of widespread face mask use in public on COVID-19 mitigation. There is a critical need for empirical evidence on the magnitude of these effects from natural experiments.[8] This evidence is especially relevant as governments reopen their economies and loosen social distancing restrictions while new infections continue to occur and while there is no vaccine or widely accessible or effective treatments in sight.

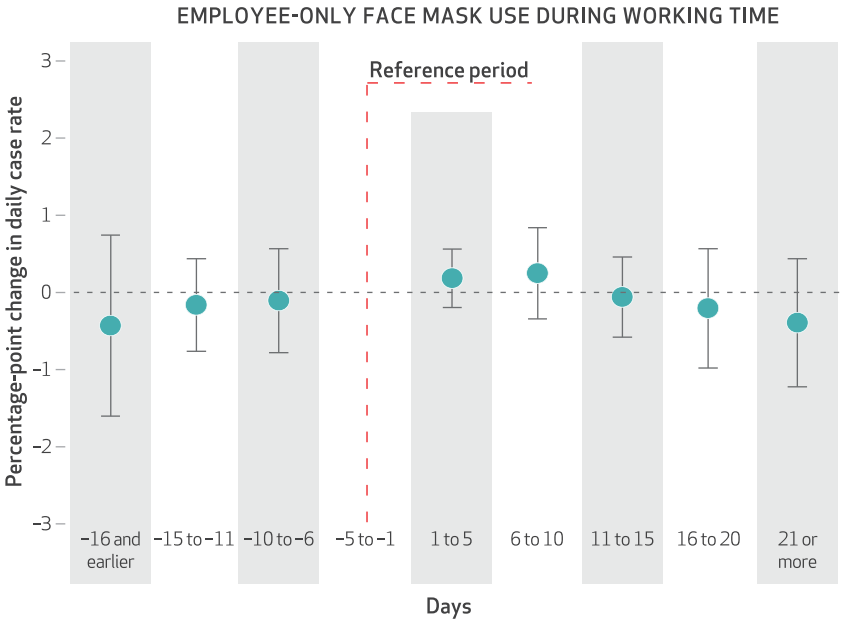
The study provides direct evidence on the effectiveness of widespread community use of face masks from a natural experiment that evaluated the effects of state government mandates in the US for face mask use in public on COVID-19 spread. Fifteen states plus Washington, D.C., mandated face mask use between April 8 and May 15. Using an event study that examined daily changes in county-level COVID-19 growth rates, the study found that mandating public use of face masks was associated with a reduction in the COVID-19 daily growth rate. Specifically, we found that the average daily county-level growth rate decreases by 0.9, 1.1, 1.4, 1.7, and 2.0 percentage points in 1–5, 6–10, 11–15, 16–20, and 21 or more days after signing, respectively.

These estimates are not small; they represent nearly 16 percent to 19 percent of the effects of other social distancing measures (school closures; bans on large gatherings; shelter-in-place orders; and closures of restaurants, bars, and entertainment venues) after similar periods from their enactment.[21] The estimates suggest that the effectiveness of and benefits from these mandates increase over time. By May 22, 2020, the estimates suggest that 230,000–450,000 COVID-19 cases may have been averted on the basis of when states passed these mandates. Again, the estimates of averted cases should be viewed cautiously, as they are sensitive to assumptions and different approaches to transforming the changes in the daily growth rate estimates to cases.

The early declines in the daily growth rate over the course of five days after signing the order are broadly consistent with the timing of the effects of other social distancing measures such as business closures.[21] Although the median incubation period is estimated to be around five days,[26] there is a wide range from 2.2 days (2.5th percentile) to 11.5 days (97.5th percentile), which suggests that for many people, symptoms may appear relatively early. Further, people may become aware of the mandates early through governors' briefings and related media reports, or they may be anticipating them.

EXHIBIT 2

Event study estimates of effects of states mandating only employee use of face masks during working time on daily county-level growth rate of COVID-19 cases



SOURCE Authors' analysis of US county-level COVID-19 case data between March 31 and May 22, 2020. **NOTES** Event study estimates (dots) and 95% confidence intervals (bars) of the effects of states mandating employee use of face covers or masks on the county-level daily growth rate of COVID-19 cases over different periods before and after the mandate order was signed. This model excluded fifteen states plus Washington, D.C., that made the use of face covering mandatory for both the general public and employees. The reference period was the first five days before the mandate order was signed. The model controlled for major COVID-19 mitigation policies as time-varying (closure of K–12 schools, county-level or statewide shelter-in-place orders, nonessential business closure, closure of restaurants for dining in, and closure of gyms or movie theaters), COVID-19 tests per 100,000 people, county fixed effects, and day fixed effects. The model was estimated by least squares weighted by the county 2019 population, and the standard errors were robust to heteroscedasticity and clustered at state level.

There is no evidence of differential pre-mandate COVID-19 trends with respect to issuing these mandates. The estimates represent the intent-to-treat effects of the statewide face cover mandates as passed, conditional on other national and local measures. In that way, the effects are independent of the CDC national guidance to wear face masks that was issued April 3, 2020.[12] These effects were robust to several model checks. The study provides evidence from a natural experiment on the effectiveness of mandating public use of face masks in mitigating the spread of COVID-19. We found no evidence for effects of states mandating employee face mask use, perhaps because many businesses themselves already required their employees to wear masks.[27,28] In that case, mandating employee mask use reinforce what many businesses already choose to do on their own.

Although the intent-to-treat estimates are of interest for understanding the effectiveness of

these policies in limiting COVID-19 spread at the community and population levels, understanding how their effects change with compliance and enforcement strategies is important for designing effective policies. Our study has built the first step in estimating the overall effect of these policies as enacted. However, these policies vary in their strictness and the consequences of noncompliance. The mandates generally require wearing a face mask in public whenever the social distance cannot be maintained. States such as Delaware, Maryland, Massachusetts, and Maine clarify what "public" areas are (for example, indoor space in retail establishments, outdoor space in busy parking lots and waiting areas for take-out services, semi-enclosed areas such as at public transportation stops, and enclosed spaces such as in taxis and other public transportation). The language on enforcement and penalties for noncompliance also vary. In states such as Delaware, Hawaii, Maryland, and Massachusetts, the face mask orders state that they have the force and effect of law, with a willful violation subject to a criminal offense with penalties. For example, the order in Maryland states that "a person who knowingly and willfully violates this order is guilty of a misdemeanor and on conviction is subject to imprisonment not exceeding one year or a fine not exceeding $5,000 or both."[29] In contrast, the orders of other states such as Connecticut, Maine, and Pennsylvania, although clearly mandating the wearing of a face mask in public, do not appear to clearly specify that violations of the order are subject to criminal offense or penalties. Future work should examine whether and how differences in strictness and enforcement modify the effects of these mandates.

Compliance and enforcement may also differ across contextual factors (such as other social distancing measures, workforce distribution, population demographics, and socioeconomic and cultural factors). In that regard, it is important to clarify that the suggested benefits from mandating face mask use are not substitutes for other social distancing measures; the effects are conditional on the other enacted social distancing measures and how communities are complying with them. It is also important to extend the evidence into additional measures of exposure to the virus in the community as data become available, such as from serological testing for antibodies. Finally, future work can examine effects on deaths, which lag cases and change not only with the number of cases but also with case severity.

Conclusion

The study provides evidence that US states mandating the use of face masks in public had a greater decline in daily COVID-19 growth rates after issuing these mandates compared with states that did not issue mandates. These effects were observed conditional on other existing social distancing measures and were independent of the CDC recommendation to wear face covers issued April 3, 2020. As international and state governments begin to relax social distancing restrictions, and considering the high likelihood of a second COVID-19 wave in the fall and winter of 2020,[30] requiring the use of face masks in public could help in reducing COVID-19 spread. ■

An unedited version of this article was published online June 16, 2020, as a Fast Track Ahead Of Print article. That version is available in the online appendix.

NOTES

1 Feng S, Shen C, Xia N, Song W, Fan M, Cowling BJ. Rational use of face masks in the COVID-19 pandemic. Lancet Respir Med. 2020;8(5):434–6.

2 Furukawa NW, Brooks JT, Sobel J. Evidence supporting transmission of severe acute respiratory syndrome coronavirus 2 while presymptomatic or asymptomatic. Emerg Infect Dis. 2020;26(7).

3 Mizumoto K, Kagaya K, Zarebski A, Chowell G. Estimating the asymptomatic proportion of coronavirus disease 2019 (COVID-19) cases on board the Diamond Princess cruise ship, Yokohama, Japan, 2020. Euro Surveill. 2020;25(10):2000180.

4 Rosenberg ES, Tesoriero JM, Rosenthal EM, Chung R, Barranco MA, Styer LH, et al. Cumulative incidence and diagnosis of SARS-CoV-2 infection in New York. MedRxiv [serial on the Internet]. 2020 May 29 [cited 2020 Jun 11]. Available from: https://www.medrxiv.org/content/10.1101/2020.05.25.20113050v1

5 World Health Organization. Advice on the use of masks in the context of COVID-19: interim guidance [Internet]. Geneva: WHO; 2020 Apr 6 [cited 2020 Jun 11]. Available from: https://apps.who.int/iris/handle/10665/331693

6 Greenhalgh T, Schmid MB, Czypionka T, Bassler D, Gruer L. Face masks for the public during the covid-19 crisis. BMJ. 2020;369:m1435.

7 Brainard JS, Jones N, Lake I, Hooper L, Hunter P. Facemasks and similar barriers to prevent respiratory illness such as COVID-19: a rapid systematic review. MedRxiv [serial on the Internet]. 2020 Apr 6 [cited 2020 Jun 11]. Available from: https://www.medrxiv.org/content/

10.1101/2020.04.01.20049528v1
8 Jefferson T, Jones M, Al Ansari LA, Bawazeer G, Beller E, Clark J, et al. Physical interventions to interrupt or reduce the spread of respiratory viruses. Part I—face masks, eye protection, and person distancing: systematic review and meta-analysis. MedRxiv [serial on the Internet]. 2020 Apr 7 [cited 2020 Jun 11]. Available from: https://www.medrxiv.org/content/10.1101/2020.03.30.20047217v2
9 Xiao J, Shiu EYC, Gao H, Wong JY, Fong MW, Ryu S, et al. Nonpharmaceutical measures for pandemic influenza in nonhealthcare settings—personal protective and environmental measures. Emerg Infect Dis. 2020;26(5):967–75.
10 MacIntyre CR, Cauchemez S, Dwyer DE, Seale H, Cheung P, Browne G, et al. Face mask use and control of respiratory virus transmission in households. Emerg Infect Dis. 2009;15(2):233–41.
11 Long Y, Hu T, Liu L, Chen R, Guo Q, Yang L, et al. Effectiveness of N95 respirators versus surgical masks against influenza: a systematic review and meta-analysis. J Evid Based Med. 2020;13(2):93–101.
12 Centers for Disease Control and Prevention. Recommendation regarding the use of cloth face coverings, especially in areas of significant community-based transmission [Internet]. Atlanta (GA): CDC; [last updated 2020 Apr 3; cited 2020 Jun 11]. Available from: https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/cloth-face-cover.html
13 Pleitgen F, Schmidt N. Germans face fines of up to $5,000 as wearing a face mask becomes mandatory. CNN [serial on the Internet]. [Last updated 2020 Apr 27; cited 2020 Jun 11]. Available from: https://www.cnn.com/2020/04/27/europe/germany-face-mask-mandatory-grm-intl/index.html
14 Bostock B. France has made wearing face masks compulsory in public, while maintaining a controversial ban on burqas and niqabs. Business Insider [serial on the Internet]. 2020 May 11 [cited 2020 Jun 11]. Available from: https://www.businessinsider.com/france-face-masks-compulsory-burqas-niqabs-banned-criticism-muslims-2020-5
15 Duncan C. Coronavirus: Spain makes face masks compulsory on public transport as country begins to ease strict lockdown. The Independent [serial on the Internet]. 2020 May 2 [cited 2020 Jun 11]. Available from: https://www.independent.co.uk/news/world/europe/coronavirus-face-masks-spain-public-transport-lockdown-pedro-sanchez-a9496031.html
16 Which countries have made wearing face masks compulsory? Al Jazeera News [serial on the Internet]. 2020 Jun 3 [cited 2020 Jun 11]. Available from: https://www.aljazeera.com/news/2020/04/countries-wearing-face-masks-compulsory-200423094510867.html
17 Tensions over masks, social distancing lead to violent altercations, shooting death, pipe bomb threats. Kaiser Health News [serial on the Internet]. 2020 May 5 [cited 2020 Jun 11]. Available from: https://khn.org/morning-breakout/tensions-over-masks-social-distancing-lead-to-violent-altercations-shooting-death-pipe-bomb-threats/
18 Commonwealth of Virginia. Office of the Governor, executive order number 63 (2020) [Internet]. Richmond (VA): Office of the Governor; 2020 May 26 [cited 2020 Jun 11]. Available from: https://www.governor.virginia.gov/media/governorvirginiagov/executive-actions/EO-63-and-Order-Of-Public-Health-Emergency-Five---Requirement-To-Wear-Face-Covering-While-Inside-Buildings.pdf
19 To access the appendix, click on the Details tab of the article online.
20 New York Times. An ongoing repository of data on coronavirus cases and deaths in the U.S. GitHub [serial on the Internet]. 2020 [cited 2020 Jun 11]. Available from: https://github.com/nytimes/covid-19-data
21 Courtemanche C, Garuccio J, Le A, Pinkston J, Yelowitz A. Strong social distancing measures in the United States reduced the COVID-19 growth rate. Health Aff (Millwood). 2020;39(7):1237–46.
22 News NBC. Face masks to become part of life in California, but the rules vary. NBC Los Angeles [serial on the Internet]. 2020 May 8 [cited 2020 Jun 11]. Available from: https://www.nbclosangeles.com/news/local/california-face-mask-rules-coronavirus-covid-19/2359246/
23 Nix MG, Huebinger J, Segura O Jr. Face covering guidelines for businesses operating in Texas [Internet]. Brandon (FL): Holland & Knight; 2020 Apr 30 [cited 2020 Jun 11]. Available from: https://www.hklaw.com/en/insights/publications/2020/04/face-covering-guidelines-for-businesses-operating-in-texas
24 Sebastian M. These Colorado cities and counties require masks be worn in public places. Denver Post [serial on the Internet]. 2020 May 4 [cited 2020 Jun 11]. Available from: https://www.denverpost.com/2020/05/04/colorado-denver-mask-required-orders/
25 Bendavid E, Mulaney B, Sood N, Shah S, Ling L, Bromley-Dulfano R, et al. COVID-19 antibody seroprevalence in Santa Clara County, California. MedRxiv [serial on the Internet]. 2020 Apr 30 [cited 2020 Jun 11]. Available from: https://www.medrxiv.org/content/10.1101/2020.04.14.20062463v2
26 Lauer SA, Grantz KH, Bi Q, Jones FK, Zheng Q, Meredith HR, et al. The incubation period of coronavirus disease 2019 (COVID-19) from publicly reported confirmed cases: estimation and application. Ann Intern Med. 2020;172(9):577–82.
27 Peterson H. Walmart is now requiring all US employees to wear face masks and will encourage customers to wear them while shopping. Business Insider [serial on the Internet]. 2020 Apr 17 [cited 2020 Jun 11]. Available from: https://www.businessinsider.com/walmart-requires-face-masks-workers-urges-shoppers-to-wear-them-2020-4
28 Rice B. Costco, Delta, United: list of businesses requiring employees or customers to wear face masks. Enquirer [serial on the Internet]. 2020 May 1 [cited 2020 Jun 11]. Available from: https://www.cincinnati.com/story/news/2020/05/01/face-masks-chipotle-walmart-sams-club-among-businesses-requiring/3055849001/
29 State of Maryland, Executive Department. Order of the governor of the state of Maryland, number 20-04-15-01 [Internet]. Annapolis (MD): State of Maryland; 2020 Apr 15 [cited 2020 Jun 11]. Available from: https://governor.maryland.gov/wp-content/uploads/2020/04/Masks-and-Physical-Distancing-4.15.20.pdf
30 Sun LH. CDC director warns second wave of coronavirus is likely to be even more devastating. Washington Post [serial on the Internet]. 2020 Apr 21 [cited 2020 Jun 11]. Available from: https://www.washingtonpost.com/health/2020/04/21/coronavirus-secondwave-cdcdirector/

OPEN ACCESS Freely available online

PLoS one

Professional and Home-Made Face Masks Reduce Exposure to Respiratory Infections among the General Population

Marianne van der Sande[1]*, Peter Teunis[1,2], Rob Sabel[3]

1 National Institute for Public Health and the Environment (RIVM), Bilthoven, Netherlands, **2** Hubert Department of Global Health, Rollins School of Public Health, Emory University, Atlanta, Georgia, United States of America, **3** Netherlands Organisation for Applied Scientific Research (TNO), Rijswijk, Netherlands

Abstract

Background: Governments are preparing for a potential influenza pandemic. Therefore they need data to assess the possible impact of interventions. Face-masks worn by the general population could be an accessible and affordable intervention, if effective when worn under routine circumstances.

Methodology: We assessed transmission reduction potential provided by personal respirators, surgical masks and home-made masks when worn during a variety of activities by healthy volunteers and a simulated patient.

Principal Findings: All types of masks reduced aerosol exposure, relatively stable over time, unaffected by duration of wear or type of activity, but with a high degree of individual variation. Personal respirators were more efficient than surgical masks, which were more efficient than home-made masks. Regardless of mask type, children were less well protected. Outward protection (mask wearing by a mechanical head) was less effective than inward protection (mask wearing by healthy volunteers).

Conclusions/Significance: Any type of general mask use is likely to decrease viral exposure and infection risk on a population level, in spite of imperfect fit and imperfect adherence, personal respirators providing most protection. Masks worn by patients may not offer as great a degree of protection against aerosol transmission.

Citation: van der Sande M, Teunis P, Sabel R (2008) Professional and Home-Made Face Masks Reduce Exposure to Respiratory Infections among the General Population. PLoS ONE 3(7): e2618. doi:10.1371/journal.pone.0002618

Editor: Madhukar Pai, McGill University, Canada

Received January 25, 2008; **Accepted** May 20, 2008; **Published** July 9, 2008

Funding: The study was funded by the Netherlands Ministry of Health, Welfare and Sports. The sponsor had no role in design and conduct of the study, in the collection, analysis and interpretation, nor in the preparation, review or approval of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: marianne.van.der.sande@rivm.nl

Introduction

With a potential influenza pandemic looming, governments need to decide how they can best use available resources to protect their people against severe illness and death, and to mitigate health and social effects for society as a whole. Much research is being devoted to develop optimal strategies for the use of (pre)pandemic vaccines and of anti-virals. There are only limited data to assess the potential effectiveness of non-pharmaceutical interventions to reduce the risk of transmission, including the effect of different kinds of face-masks worn by the general public or by patients.

Respiratory infections such as influenza are transmitted through infectious particles, small enough to be suspended in air [1]. Influenza transmission can occur via large droplets, which only remain suspended in the air for a short period of time thus requiring close contact, and can occur via small airborne particles, which remain suspended in air for considerable longer periods of time, and can thus be transmitted over larger distances [2]. Furthermore, some transmission may occur via direct contact with respiratory secretions such as on hands and surfaces [2].

Interruption of transmission may allow containment of major outbreaks, like pandemic influenza. Opportunistic data collected during the SARS epidemic in Asia suggested that population-wide use of face masks may significantly decrease transmission of not only SARS but also influenza [3,4,5,6,7]. As part of pandemic preparedness, many are contemplating the contribution wide-spread use of masks could have [8,9]. As this has major implications for resource allocation and for communication, there is great need for data to guide such decisions and make them evidence-based.

Protective effects of face masks have been studied extensively, but usually this involved personal respirators for professionals under idealized conditions, because of specific applications, for instance in military or occupational uses, involving protection of specifically trained personnel. This is different from deployment of masks in the general population during an outbreak of an infectious disease, where anyone may encounter the infectious micro-organism, implying much greater heterogeneity, in training levels (experience and understanding), goodness of fit of a mask, and activities interfering with mask use and thus reducing potential reduction of transmission. The protective effect of masks is created through a combined effect of the transmission blocking potential of the material, the fit and related air leakage of the mask, and the degree of adherence to proper wearing and disposal of masks. Personal respirators such as those worn by staff attending TB

patients, are used primarily to protect the wearer, and are designed to fit to the face with as tight a seal as possible. Their efficiency is graded on the degree of protection the material offers, assuming a perfect fit and optimal compliance. In contrast, surgical masks, as commonly worn in the operating theatre, are primarily used to protect the environment from the respiratory droplets produced by the wearer. With these masks, facial fit is much looser. The fit of home made masks, which could be e.g. made of a tea cloth or other comparable material available in the home, is likely to be even looser. Thus personal respirators confer a higher degree of protection than surgical masks, and these are again likely to give a higher degree of protection than home-made masks. In professional situations, ample time might be available prior to use to ensure a perfect fit and to give extensive counselling on adherence, but it is unlikely this will apply to the general population in case of a pandemic. It is possible that the discomfort in wearing associated with a certain type of masks will lead to reduced adherence and thus to a loss in overall protectiveness [10,11]. Indeed a review among health care workers could not determine whether personal respirators conferred better protection for the health care workers than surgical masks [10].

To investigate the levels of protection, and their variation, wearing of face masks could convey to untrained subjects we designed a study in which healthy volunteers would be wearing different types of professional and home-made masks during a selection of activities, in different conditions (inward protection). We also assessed the protection different types of masks could convey when worn by a simulated infectious patient (outward protection). Resulting quantitative descriptions of distributions of protection factors may be used for assessing the importance of mask use in respiratory disease transmission.

Methods

Design and description of the study

Three different experiments were undertaken to assess 1) short-term protection for different types of masks worn during 10–15 minutes by the same volunteer following a standardized protocol, 2) long-term protection of a specific mask worn continuously by a volunteer for 3 hours during regular activities, and 3) effectiveness of different types of mask in preventing outgoing transmission by a simulated infectious subject. Inward protection was defined as the effect of mask wearing to protect the wearer from the environment; outward protection was defined as the effect of a mask on protecting the environment from the generation of airborne particles by a patient (or in this case a mechanical head).

In the first short-term experiment, 28 healthy adult volunteers were recruited, as well as 11 children between 5 and 11 years of age. Each volunteer followed the same protocol wearing a Filtering Facepiece against Particles (FFP)-2 mask 1872V® (3M); which is the European equivalent of a N95 mask, a surgical mask (1818 Tie-On®, 3M; with a filtering efficiency of around 95% for particles of sizes between 0.02 μm to 1 μm; http://jada.ada.org/cgi/content/full/136/7/877) and a home-made mask (made of TD Cerise Multi® teacloths, Blokker). In this standard protocol, the volunteer was asked to perform five successive tasks in a fixed sequence 1.5 minute of duration each: no activity-sit still, nod head ("yes"), shake head ("no"), read aloud a standard text, stationary walk. In this sequence of activities, the respiratory rate is gradually increased. Throughout this exercise, the concentration of particles was measured on both sides of the mask through a receptor fixed on the facial and on the external side. These were connected to a portable counter of all free floating particles in the air via an electrostatic particle classifier and counter, the Portacount®. The Portacount® can register particles floating in the air with sizes between 0.02 μm to 1 μm, covering most of the size range of infectious respiratory aerosols [12]. Total inward leakage (TIL) percentage was calculated by dividing the concentrations on the outside and on the inside (TIL = (concentration inside/concentration outside)×100); the calculated quantitative protection factor was the inverse of the leakage (PF = (TIL/100)$^{-1}$). To ensure small numbers of particles produced by the volunteers would not affect measurements, we checked that at least 10,000 particles per cm^3 particles of this size class (0.02 μm–1 μm) were present in the room which were produced by a number of lit candles. (Figure 1)

In the second long-term experiment, 22 volunteers, all adults, 10 men, 12 women, were divided into 3 groups. Each group wore a single type of mask for a period of three hours, being either a FFP2 mask (4 males, 4 females), a surgical mask (3 males, 4 females) or a home-made mask (3 males, 4 females), similar to the masks used in the short-term experiment described above. At the beginning and end of each three-hour period, full series of measurements were taken using the standardised protocol as described for the short-term experiment, and during the three hour period while wearing the masks, participants reported back at regular intervals for a short measurement during rest (absence of activity). For the remainder of the period, participants carried on with their usual daily activities. During regular activities in between measurements, the probes of the masks were plugged which did not involve dislodging of the masks.

Figure 1. Protection factor of home-made mask being measured by Portacount in volunteer. Volunteer with home-made mask made of tea cloth. Note the candles in the foreground and the other mask types in the background.
doi:10.1371/journal.pone.0002618.g001

Table 1. Median (IQR) protection factor by mask, by activity, by age category.

		no activity	nodding	shaking	reading	walking
Tea cloth	Adults	2.5 (2.1–2.9)	2.2 (1.9–2.5)	2.2 (1.9–2.7)	3.2 (2.5–3.9)	2.4 (2.1–3.3)
	children	2.2 (1.5–2.2)	1.9 (1.5–2.3)	1.9 (1.4–2.3)	2.2 (1.8–3.7)	2.2 (1.8–2.4)
Surgical mask	Adults	4.1 (3.1–7.2)	4.7 (3.4–7.3)	5.1 (3.2–7.6)	5.3 (4.3–8.0)	4.2 (3.1–5.7)
	children	3.2 (2.2–4.1)	3.4 (2.7–5.2)	3.6 (2.7–4.3)	4.9 (4.0–5.3)	3.6 (2.4–4.2)
FFP2 mask	Adults	113 (26–210)	82 (45–179)	91 (23–187)	66 (29–107)	99 (19–169)
	children	18 (6.1–165)	13 (3.8–41)	18 (4.0–54)	35 (8.6–91)	15 (5.1–176)

IQR = interquartile range

doi:10.1371/journal.pone.0002618.t001

In the final experiment, we assessed the effectiveness of different types of masks in reducing outgoing transmission from an infectious subject shedding aerosolised particles. This was simulated by fitting the different types of masks to an artificial test head, which was connected to PC-driven respirator (Bacou® LAMA AMP, Modelref 1520307). Breathing frequency was varied to mimic different respiratory rates (15, 25 and 40/minute). Only expiration was simulated; twice for each mask at each respiratory rate. The breathing flow was defined as (respiratory rate/minute x volume per breath (2 litres)) resulting in a breathing flow of 30, 50 and 80 litres per minute, which correlates with light (walking), medium (marching with backpack) and strenuous (running) activities [13]. Concentrations of particles were measured as described above by a TSI Portacount Respirator Fit tester, model 8020, measuring outward protection, rather than inward protection.

All volunteers received written information prior to the experiments and gave oral informed consent. For the children also a parent gave oral informed consent, and a parent remained present during the experiments. The Dutch Central Committee on Research Involving Human Subjects (CCMO) informed us in writing that this project did not need to be assessed by an Ethics committee.

Data analysis

Protection factors (PF) calculated from measurements of particle concentration by Portacount® devices were reported as the ratio of particle concentrations outside and inside the mask. This is a similar concept to the fit factor as used by the US Occupational Safety and Health Administration (http://www.osha.gov/pls/oshaweb/owadisp.show_document). Therefore, a higher PF is better and PF = 1 means complete absence of protection. For statistical analysis, the following transformation was used:

$$x = \text{logit}\left(\frac{1}{PF}\right)$$

The inverse of the PF (1/PF) can be interpreted as a probability (that any particle succeeds in moving through the barrier the mask provides). The logit transformation is a standard transformation to transform the probability scale (0,1) to the real axis (-infinity, +infinity) to allow standard regression techniques (including ANOVA) to test the effects of co-variables (mask type, age class, sex, activity, duration of use) on transformed PFs in a linear model, using the statistical application R (version 2.5.0). The p-values are based on testing the ratio of mean squares for a factor (like 'mask') and the mean square of errors (random fluctuations), assuming that ratio is F-distributed. Whenever the p-value (the probability of a greater value of the tested ratio) is greater than 0.05, the ratio is considered significantly different from 1 (= indifference) at the 95% level.

Results

Short term inward protection experiment

All masks provided protection against transmission by reducing exposure during all types of activities, for both children and adults (Table 1). Within each category of masks, the degree of protection varied by age category and to a lesser extent by activity. We observed no difference between men and women. Surgical masks provided about twice as much protection as home made masks, the difference a bit more marked among adults. FFP2 masks provided adults with about 50 times as much protection as home made masks, and 25 times as much protection as surgical masks. The increase in protection for children was less marked, about 10 times as much protection by FFP2 versus home-made masks and 6 times as much protection as surgical masks.

In these short term experiments, adjusting for covariates, face mask type had a strongly significant independent effect on protection ($p<0.001$). Children were significantly less protected than adults ($p<0.001$). There was no significant impact of activity on protection.

Long term inward protection experiment

As in the short term experiment, mask type was a strong determinant of protection (Table 2). Protection factors for each type of mask were similar to the protection factors measured in the short term experiments for adults. There was considerable variability between volunteers. The median protection factors measured over a 3 hour period increased for those wearing home-made masks, decreased for those wearing FFP2 masks, and did not show a consistent pattern for those wearing a surgical mask (Figure 2), but overall protection factors calculated per type of mask were stable over time, and did not change statistically significant with prolonged wearing. Overall, protection factors were relatively stable over time for each individual (ANOVA $p = 0.4$). Males and females did not have significantly different protection factors (ANOVA $p = 0.9$). As in the short term experiment, protection conferred by surgical masks was higher than protection given by a home-made mask, and protection provided by a FFP2 masks was again markedly higher than protection provided by a surgical mask. As in the short term experiment, more strenuous activities (reading and walking) tended to increase the protection of the home-made mask and to a lesser extent of the surgical mask, and decreased the protection by the FFP2 mask, but there was no overall significant effect of type of activity on PF (ANOVA $p = 0.1$).

Table 2. Median (IQR) protection factors at start and end of long term-experiment, by mask, by activity.

		no activity	nodding	shaking	reading	walking
Tea cloth	Start	2.8 (2.5–3.1)	2.4 (2.3–2.6)	2.5 (2.3–2.8)	3.4 (2.9–3.7)	2.4 (2.2–3.1)
	End	3.2 (2.7–3.4)	2.7 (2.5–3.0)	2.9 (2.6–3.4)	4.3 (3.5–5.2)	2.9 (2.8–2.9)
Surgical mask	Start	3.9 (3.4–6.1)	3.6 (3.1–7.1)	3.8 (3.7–7.3)	6.5 (4.3–7.2)	4.6 (2.9–6.4)
	End	4.4 (3.2–7.4)	4.5 (3.4–7.2)	4.1 (3.3–7.8)	5.9 (4.2–6.5)	3.9 (3.3–6.7)
FFP2 mask	Start	141 (34–196)	100 (26–156)	132 (54–265)	84 (47–194)	79 (10–167)
	End	53 (31–339)	48 (36–116)	42 (23–177)	92 (29–202)	43 (16–185)

IQR = interquartile range
doi:10.1371/journal.pone.0002618.t002

Outward protection experiment

In a final experiment, retention of particles expelled inside the masks was studied. Here again, mask type was strongly correlated with (transformed) protection factors. Protection factors for all type of masks were considerably lower than those observed for inward protection. The home-made masks only provided marginal protection, while protection offered by a surgical mask and an FFP2 mask did not differ (figure 3).

The simulated breathing frequency did not significantly affect the measured protection factors. Adjusting for covariates, mask type and particle concentration, but not flow rate, were significant factors for protection in the reverse flow experiment.

Discussion

In our experiments, the main determinant of the magnitude of protection factors measured by masks was the type of mask, which can be seen as a proxy for potential reduction in infectious disease transmission. The duration of wear and the type of activity did not have a significant impact on exposure reduction. Thus, the expected superior protection conferred by a professional FFP2 mask compared to a surgical mask or a home-made mask was maintained when these FFP2 masks were worn by healthy lay people in spite of the increased risk of a poor fit and significant behavioural leakage.

Children were significantly less protected from exposure than adults, which might be related to an inferior fit of the masks on their smaller faces. Although we observed a high degree of individual variability in the degree of protection conferred as reflected in the wide interquartile ranges of the measured PFs, no systematic difference was found between men and women, suggesting a poorer fit only has a noticeable impact on protection when the mismatch between face and mask is considerable. All types of masks provided a much higher degree of exposure protection against inward transmission of particles, then in preventing outward transmission by a mechanical head as a proxy for an infected patient exposing the environment.

Data from professional users suggest a decrease in protection over time due to a reduction in fibre charges [13]. In our data, this effect was not significantly present, although a tendency towards reduced protection over time was seen for the FFP2 masks. Also, our study showed a high degree of individual variation in exposure protection. This is important as it reflects the presence of many different sources of variation, behavioural as well as anatomical, which can also be expected to be present if the general population would be requested to wear face masks in case of a pandemic. Furthermore, we do not know from these experiments whether reduced exposure has a linear or non-linear relationship to the reduction of infection risk.

Although this could imply that individual subjects may not always be optimally protected, from a public health point of view, any type of general face mask usage can still decrease viral transmission. Also, it is important not to focus on a single intervention in case of a pandemic, but to integrate all effective interventions for optimal protection.

Surprisingly, the protection conferred by each of the masks appeared stable over time and was not dependent on activity. This suggests that leakage associated with suboptimal fit and compliance was stable over time. The tendency towards improved protection of the poorer fitting masks with increased activities such as reading, might be attributable to reduced leakage when breathing through the mouth rather than the nose, which could give some overpressure and thus reduce inward leakage. We had assumed that compliance would decrease during the three hours of continuous wearing, in particular with more strenuous activities. Indeed, among professionals like cullers, there have been some anecdotal reports that FFP3 masks were associated with poorer compliance than FFP2 masks in wearing. Where a reduction in protection was found with the FFP2 mask, the reverse was seen for the home-made mask. It is possible that the experimental situation, sufficient motivation to endure a relatively limited time of discomfort, and the absence of physically challenging activities, has provided more stable protection than might be found in real-life situations. However, overall these experiments show that significant protection against influenza transmission upon exposure can be conveyed also for lay people, including children, in spite of imperfect fit and imperfect adherence.

It is also clear that home-made masks such as teacloths may still confer a significant degree of protection, albeit less strong than surgical masks or FFP2 masks. Home made masks however would not suffer from limited supplies, and would not need additional resources to provide at large scale. Home made masks, and to a lesser degree surgical masks, are unlikely to confer much protection against transmission of small particles like droplet nuclei, but as the reproduction number of influenza may not be very high [14] a small reduction in transmissibility of the virus may be sufficient for reducing the reproduction number to a value smaller than 1 and thus extinguishing the epidemic [15]. Greater reduction in transmissibility may be achieved if transmission is predominantly carried by larger droplets. In a typical human cough half of the droplets may be small (<10 μm), but these comprise only a small fraction ($2.5*10^{-6}$) of the expelled volume [12]. Smaller droplets may however more easily penetrate the smaller bronchi and be more effective in transmission [1]. A more detailed analysis of aerosol and droplet inoculation and infectivity may provide better insight into the impact of either transmission mode on population spread.

The difference in measured protection against inward and outward protection is remarkable, and cannot be explained from

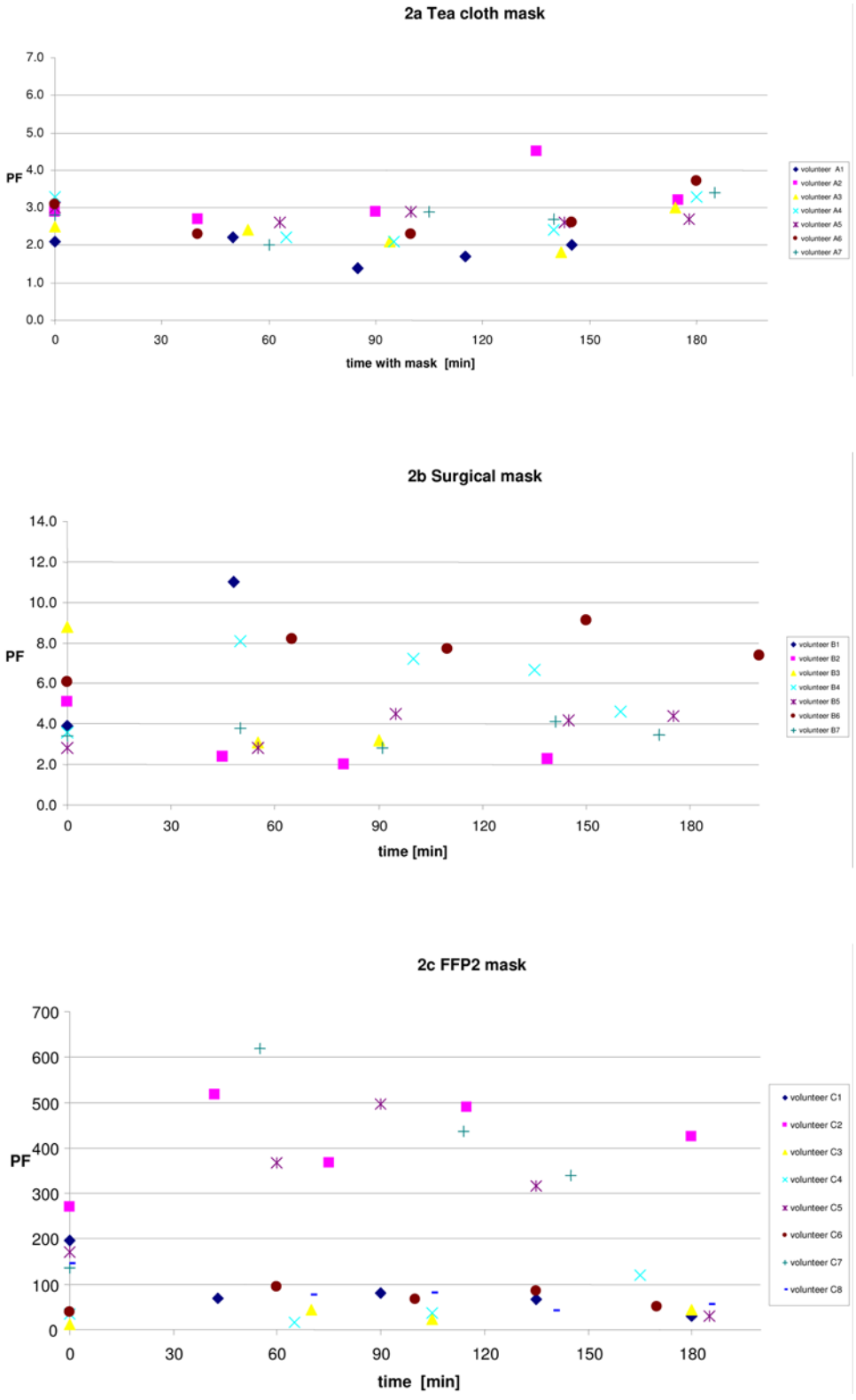


Figure 2. Protection factors over time per volunteer by type of mask worn. Please note different scale on Y-axis!
doi:10.1371/journal.pone.0002618.g002

the available data as we only measured the overall effect. A differential effect on the amount of leakage seems most plausible. At the same time, we cannot exclude that wearing of face masks, even FFP2 or surgical masks by patients might still significantly reduce transmission. However, the observed limited particle retention in our experiments may still be an overestimate of protection, as it may for instance be challenging to enforce adherence to mask wearing by a patient who is short of breath.

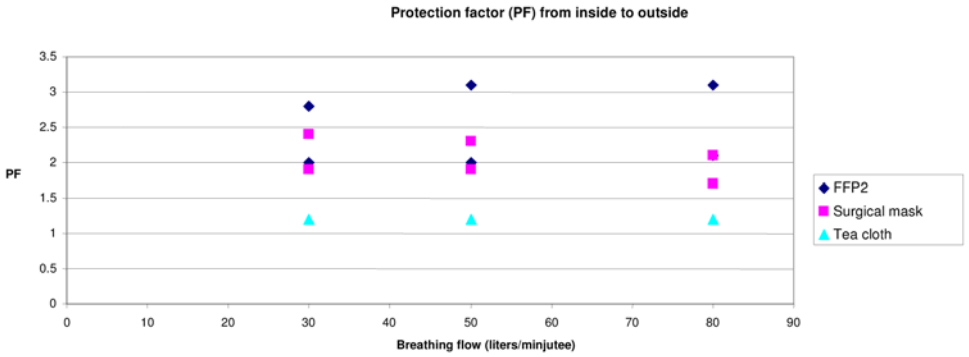


Figure 3. Outward protection factors at a range of breathing flows for a mechanical head with different types of masks, with two meaurements per mask at each breathing flow. PFs for teacloth did not differ during the repeated measurement at each breathing flow, so light blue triangles overlap in figure.
doi:10.1371/journal.pone.0002618.g003

Wearing of masks by caregivers might be more feasible and more effective, in particular where additional preventive measures are in place as well for caregivers.

Furthermore, we should bear in mind that this is an experimental study, with relatively small numbers of volunteers, which limits the generalisability of some of our findings. E.g., for masks to have any impact during an actual pandemic, people may need to be wearing masks during several weeks with many shorter or longer mask-free periods. Furthermore, the PFs may be an over- or underestimation of the actual protection conferred. And although our simulated patient varied its breathing frequency, we have not assessed the impact of e.g. coughing or sneezing on outward transmission through a mask.

A recent analysis of the 1918 epidemic, noted that cities where strict interventions were implemented early on to prevent transmission, were overall worse-off than cities where some degree of transmission occurred early on [16]. Given the need for the population to acquire sufficient natural immunity over time, it can not be excluded that the amount of protection conferred by home made masks might sufficiently reduce viral exposure to impact on transmission during the early waves, while allowing people enough exposure to start mounting an efficient immune response. Further field studies are needed to assess acceptability and effectiveness of masks worn by people from the general population. Also, experimental data are needed to develop dose-response models which may improve understanding of determinants of transmission. A cost-effectiveness analysis might give further insights in the relative benefits of home made masks.

Acknowledgments

We thank Nicole Brienen for preparatory literature searches, Rob Schimmel and Tineke Albers for support in conducting the experiments, and all volunteers. Volunteers in figure 1 gave written permission for reproduction.

Author Contributions

Conceived and designed the experiments: Mv PT RS. Performed the experiments: Mv PT RS. Analyzed the data: Mv PT RS. Contributed reagents/materials/analysis tools: PT RS. Wrote the paper: Mv.

References

1. Tellier R (2006) Review of aerosol transmission of influenza A virus. Emerging Infectious Diseases 12: 1657–62.
2. Brankston G, Gitterman G, Hirji J, Lemieux C, Gardam M (2007) Transmission of influenza A in human beings. Lancet Infectious Diseases 7: 257–265.
3. Lau JTF, Tsui H, Lau M, Yang X (2004) SARS transmission, risk factors and prevention in Hong Kong. Emerging Infectious Diseases 10: 587–92.
4. Lo JYC, Tsang THF, Leung Y, Yeung EYH, Wu T, et al. (2005) Respiratory infections during SARS outbreak, Hong Kong, 2003. Emerging Infectious Diseases 15: 1738–41.
5. Wilder-Smith A, Low JGH (2005) Risk of respiratory infections in health care workers: lesson on infection control emerge from the SARS outbreak. Southeast Asian Journal of Tropical Medicine and Public Health 36: 481–488.
6. Wu J, Xu F, Zhou W, Feikin DR, Lin C-Y, et al. (2004) Risk factors for SARS among persons without known contact with SARS patients, Beijing, China. Emerging Infectious Diseases 10: 210–16.
7. Tang CS, Wong CY (2004) Factors influencing the wearing of facemasks to prevent the severe acute respiratory syndrome among adult Chinese in Hong Kong. Preventive Medicine 39: 1187–93.
8. World Health Organisation Writing Group (2006) Nonpharmaceutical Interventions for Pandemic Influenza, International Measures. Emerging Infectious Diseases 12: 81–87.
9. World Health Organisation Writing Group (2006) Non-pharmaceutical Interventions for Pandemic Influenza, National and Community Measures. Emerging Infectious Diseases 12: 88–94.
10. Gamage B, Moore D, Copes R, Yassi A, Bryce E (2005) Protecting health care workers from SARS and other respiratory pathogens: a review of the infection control literature. American Journal of Infection Control 33: 114–121.
11. Pourbohloul B, Meyers L, Skowronski D, Krajden M, Patrick D, et al. (2005) Modelling control strategies of respiratory pathogens. Emerging Infectious Diseases 11: 1249–56.
12. Nicas M, Nazaroff WW, Hubbard A (2005) Towards understanding the risk of secondary airborne infection: emission of respirable pathogens. Journal of Occupational and Environmental Hygiene 2: 143–154.
13. Balazy A, Toivola M, Adhikari A, Sivasubramani S, Reponen T, et al. (2006) Do N95 respirators provide 95% protection level against airborne viruses, and how adequate are surgical masks? American Journal of Infection Control 34: 51–57.
14. Mills CE, Robins JM, Lipsitch M (2004) Transmissibility of 1918 pandemic influenza. Nature 432: 904–06.
15. Diekman O, Heesterbeek JAP (2000) Mathematical epidemiology of infectious diseases. Model building, analysis and interpretation. Wiley Series of Mathematical and Computational Biology. Chichester: John Wiley and Sons.
16. Bootsma MC, Ferguson NM (2007) The effect of public health measures on the 1918 influenza pandemic in US cities. Proc Natl Acad Sci USA 7588–93.

Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis

*Derek K Chu, Elie A Akl, Stephanie Duda, Karla Solo, Sally Yaacoub, Holger J Schünemann, on behalf of the COVID-19 Systematic Urgent Review Group Effort (SURGE) study authors**

Summary

Background Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) causes COVID-19 and is spread person-to-person through close contact. We aimed to investigate the effects of physical distance, face masks, and eye protection on virus transmission in health-care and non-health-care (eg, community) settings.

Methods We did a systematic review and meta-analysis to investigate the optimum distance for avoiding person-to-person virus transmission and to assess the use of face masks and eye protection to prevent transmission of viruses. We obtained data for SARS-CoV-2 and the betacoronaviruses that cause severe acute respiratory syndrome, and Middle East respiratory syndrome from 21 standard WHO-specific and COVID-19-specific sources. We searched these data sources from database inception to May 3, 2020, with no restriction by language, for comparative studies and for contextual factors of acceptability, feasibility, resource use, and equity. We screened records, extracted data, and assessed risk of bias in duplicate. We did frequentist and Bayesian meta-analyses and random-effects meta-regressions. We rated the certainty of evidence according to Cochrane methods and the GRADE approach. This study is registered with PROSPERO, CRD42020177047.

Findings Our search identified 172 observational studies across 16 countries and six continents, with no randomised controlled trials and 44 relevant comparative studies in health-care and non-health-care settings (n=25 697 patients). Transmission of viruses was lower with physical distancing of 1 m or more, compared with a distance of less than 1 m (n=10 736, pooled adjusted odds ratio [aOR] 0·18, 95% CI 0·09 to 0·38; risk difference [RD] –10·2%, 95% CI –11·5 to –7·5; moderate certainty); protection was increased as distance was lengthened (change in relative risk [RR] 2·02 per m; $p_{interaction}$=0·041; moderate certainty). Face mask use could result in a large reduction in risk of infection (n=2647; aOR 0·15, 95% CI 0·07 to 0·34, RD –14·3%, –15·9 to –10·7; low certainty), with stronger associations with N95 or similar respirators compared with disposable surgical masks or similar (eg, reusable 12–16-layer cotton masks; $p_{interaction}$=0·090; posterior probability >95%, low certainty). Eye protection also was associated with less infection (n=3713; aOR 0·22, 95% CI 0·12 to 0·39, RD –10·6%, 95% CI –12·5 to –7·7; low certainty). Unadjusted studies and subgroup and sensitivity analyses showed similar findings.

Interpretation The findings of this systematic review and meta-analysis support physical distancing of 1 m or more and provide quantitative estimates for models and contact tracing to inform policy. Optimum use of face masks, respirators, and eye protection in public and health-care settings should be informed by these findings and contextual factors. Robust randomised trials are needed to better inform the evidence for these interventions, but this systematic appraisal of currently best available evidence might inform interim guidance.

Funding World Health Organization.

Published Online
June 1, 2020
https://doi.org/10.1016/S0140-6736(20)31142-9

See Online/Comment
https://doi.org/10.1016/S0140-6736(20)31183-1

*Study authors are listed in the appendix and at the end of the Article

Department of Health Research Methods, Evidence and Impact (D K Chu MD, S Duda MSc, K Solo MSc, Prof E A Akl MD, Prof H J Schünemann MD), **and Department of Medicine** (D K Chu, Prof H J Schünemann), **McMaster University, Hamilton, ON, Canada; The Research Institute of St Joe's Hamilton, Hamilton, ON, Canada** (D K Chu); **Department of Internal Medicine** (Prof E A Akl), **and Clinical Research Institute** (Prof E A Akl, S Yaacoub MPH), **American University of Beirut, Beirut, Lebanon; and Michael G DeGroote Cochrane Canada and GRADE Centres, Hamilton, ON, Canada** (Prof H J Schünemann)

Correspondence to:
Prof Holger J Schünemann, Michael G DeGroote Cochrane Canada and McMaster GRADE Centres, McMaster University, Hamilton, ON L8N 3Z5, Canada
schuneh@mcmaster.ca

See Online for appendix

Introduction

As of May 28, 2020, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has infected more than 5·85 million individuals worldwide and caused more than 359 000 deaths.[1] Emergency lockdowns have been initiated in countries across the globe, and the effect on health, wellbeing, business, and other aspects of daily life are felt throughout societies and by individuals. With no effective pharmacological interventions or vaccine available in the imminent future, reducing the rate of infection (ie, flattening the curve) is a priority, and prevention of infection is the best approach to achieve this aim.

SARS-CoV-2 spreads person-to-person through close contact and causes COVID-19. It has not been solved if

ID-GOV-21-0012-A-000042

Research in context

Evidence before this study

We searched 21 databases and resources from inception to May 3, 2020, with no restriction by language, for studies of any design evaluating physical distancing, face masks, and eye protection to prevent transmission of the viruses that cause COVID-19 and related diseases (eg, severe acute respiratory syndrome [SARS] and Middle East respiratory syndrome [MERS]) between infected individuals and people close to them (eg, household members, caregivers, and health-care workers). Previous related meta-analyses have focused on randomised trials and reported imprecise data for common respiratory viruses such as seasonal influenza, rather than the pandemic and epidemic betacoronaviruses causative of COVID-19 (severe acute respiratory syndrome coronavirus 2 [SARS-CoV-2]), SARS (SARS-CoV), or MERS (MERS-CoV). Other meta-analyses have focused on interventions in the health-care setting and have not included non-health-care (eg, community) settings. Our search did not retrieve any systematic review of information on physical distancing, face masks, or eye protection to prevent transmission of SARS-CoV-2, SARS-CoV, and MERS-CoV.

Added value of this study

We did a systematic review of 172 observational studies in health-care and non-health-care settings across 16 countries and six continents; 44 comparative studies were included in a meta-analysis, including 25 697 patients with COVID-19, SARS, or MERS. Our findings are, to the best of our knowledge, the first to rapidly synthesise all direct information on COVID-19 and, therefore, provide the best available evidence to inform optimum use of three common and simple interventions to help reduce the rate of infection and inform non-pharmaceutical interventions, including pandemic mitigation in non-health-care settings. Physical distancing of 1 m or more was associated with a much lower risk of infection, as was use of face masks (including N95 respirators or similar and surgical or similar masks [eg, 12–16-layer cotton or gauze masks]) and eye protection (eg, goggles or face shields). Added benefits are likely with even larger physical distances (eg, 2 m or more based on modelling) and might be present with N95 or similar respirators versus medical masks or similar. Across 24 studies in health-care and non-health-care settings of contextual factors to consider when formulating recommendations, most stakeholders found these personal protection strategies acceptable, feasible, and reassuring but noted harms and contextual challenges, including frequent discomfort and facial skin breakdown, high resource use linked with the potential to decrease equity, increased difficulty communicating clearly, and perceived reduced empathy of care providers by those they were caring for.

Implications of all the available evidence

In view of inconsistent guidelines by various organisations based on limited information, our findings provide some clarification and have implications for multiple stakeholders. The risk for infection is highly dependent on distance to the individual infected and the type of face mask and eye protection worn. From a policy and public health perspective, current policies of at least 1 m physical distancing seem to be strongly associated with a large protective effect, and distances of 2 m could be more effective. These data could also facilitate harmonisation of the definition of exposed (eg, within 2 m), which has implications for contact tracing. The quantitative estimates provided here should inform disease-modelling studies, which are important for planning pandemic response efforts. Policy makers around the world should strive to promptly and adequately address equity implications for groups with currently limited access to face masks and eye protection. For health-care workers and administrators, our findings suggest that N95 respirators might be more strongly associated with protection from viral transmission than surgical masks. Both N95 and surgical masks have a stronger association with protection compared with single-layer masks. Eye protection might also add substantial protection. For the general public, evidence shows that physical distancing of more than 1 m is highly effective and that face masks are associated with protection, even in non-health-care settings, with either disposable surgical masks or reusable 12–16-layer cotton ones, although much of this evidence was on mask use within households and among contacts of cases. Eye protection is typically underconsidered and can be effective in community settings. However, no intervention, even when properly used, was associated with complete protection from infection. Other basic measures (eg, hand hygiene) are still needed in addition to physical distancing and use of face masks and eye protection.

SARS-CoV-2 might spread through aerosols from respiratory droplets; so far, air sampling has found virus RNA in some studies[2–4] but not in others.[5–8] However, finding RNA virus is not necessarily indicative of replication-competent and infection-competent (viable) virus that could be transmissible. The distance from a patient that the virus is infective, and the optimum person-to-person physical distance, is uncertain. For the currently foreseeable future (ie, until a safe and effective vaccine or treatment becomes available), COVID-19 prevention will continue to rely on non-pharmaceutical interventions, including pandemic mitigation in community settings.[9] Thus, quantitative assessment of physical distancing is relevant to inform safe interaction and care of patients with SARS-CoV-2 in both health-care and non-health-care settings. The definition of close contact or potentially exposed helps to risk stratify, contact trace, and develop guidance documents, but these definitions differ around the globe.

To contain widespread infection and to reduce morbidity and mortality among health-care workers and others in contact with potentially infected people, jurisdictions have issued conflicting advice about physical or social distancing. Use of face masks with or

ID-GOV-21-0012-A-000043
www.thelancet.com Published online June 1, 2020 https://doi.org/10.1016/S0140-6736(20)31142-9

without eye protection to achieve additional protection is debated in the mainstream media and by public health authorities, in particular the use of face masks for the general population;[10] moreover, optimum use of face masks in health-care settings, which have been used for decades for infection prevention, is facing challenges amid personal protective equipment (PPE) shortages.[11]

Any recommendations about social or physical distancing, and the use of face masks, should be based on the best available evidence. Evidence has been reviewed for other respiratory viral infections, mainly seasonal influenza,[12,13] but no comprehensive review is available of information on SARS-CoV-2 or related betacoronaviruses that have caused epidemics, such as severe acute respiratory syndrome (SARS) or Middle East respiratory syndrome (MERS). We, therefore, systematically reviewed the effect of physical distance, face masks, and eye protection on transmission of SARS-CoV-2, SARS-CoV, and MERS-CoV.

Methods

Search strategy and selection criteria

To inform WHO guidance documents, on March 25, 2020, we did a rapid systematic review.[14] We created a large international collaborative and we used Cochrane methods[15] and the GRADE approach.[16] We prospectively submitted the systematic review protocol for registration on PROSPERO (CRD42020177047; appendix pp 23–29). We have followed PRISMA[17] and MOOSE[18] reporting guidelines (appendix pp 30–33).

From database inception to May 3, 2020, we searched for studies of any design and in any setting that included patients with WHO-defined confirmed or probable COVID-19, SARS, or MERS, and people in close contact with them, comparing distances between people and COVID-19 infected patients of 1 m or larger with smaller distances, with or without a face mask on the patient, or with or without a face mask, eye protection, or both on the exposed individual. The aim of our systematic review was for quantitative assessment to ascertain the physical distance associated with reduced risk of acquiring infection when caring for an individual infected with SARS-CoV-2, SARS-CoV, or MERS-CoV. Our definition of face masks included surgical masks and N95 respirators, among others; eye protection included visors, faceshields, and goggles, among others.

We searched (up to March 26, 2020) MEDLINE (using the Ovid platform), PubMed, Embase, CINAHL (using the Ovid platform), the Cochrane Library, COVID-19 Open Research Dataset Challenge, COVID-19 Research Database (WHO), Epistemonikos (for relevant systematic reviews addressing MERS and SARS, and its COVID-19 Living Overview of the Evidence platform), EPPI Centre living systematic map of the evidence, ClinicalTrials.gov, WHO International Clinical Trials Registry Platform, relevant documents on the websites of governmental and other relevant organisations, reference lists of included papers, and relevant systematic reviews.[19,20] We hand-searched (up to May 3, 2020) preprint servers (bioRxiv, medRxiv, and Social Science Research Network First Look) and coronavirus resource centres of *The Lancet*, *JAMA*, and *N Engl J Med* (appendix pp 3–5). We did not limit our search by language. We initially could not obtain three full texts for evaluation, but we obtained them through interlibrary loan or contacting a study author. We did not restrict our search to any quantitative cutoff for distance.

Data collection

We screened titles and abstracts, reviewed full texts, extracted data, and assessed risk of bias by two authors and independently, using standardised prepiloted forms (Covidence; Veritas Health Innovation, Melbourne, VIC, Australia), and we cross-checked screening results using artificial intelligence (Evidence Prime, Hamilton, ON, Canada). We resolved disagreements by consensus. We extracted data for study identifier, study design, setting, population characteristics, intervention and comparator characteristics, quantitative outcomes, source of funding

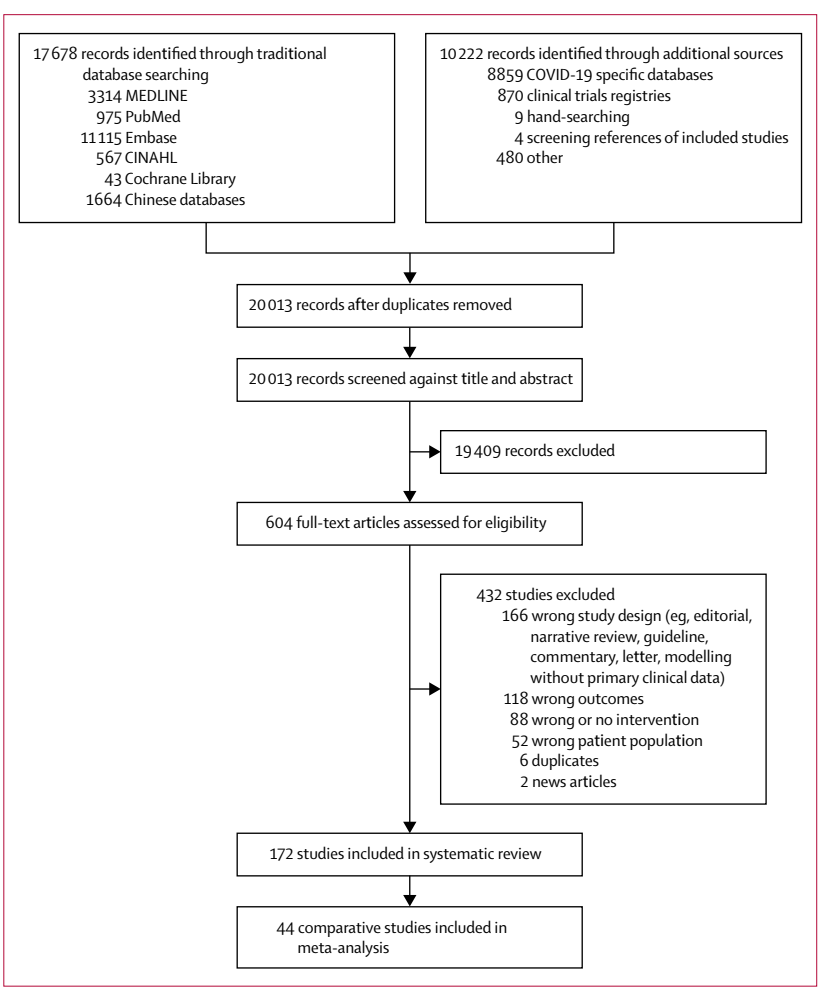


Figure 1: **Study selection**

	Population size (n)	Country	Setting	Disease caused by virus	Case definition (WHO)	Adjusted estimates	Risk of bias*
Alraddadi et al (2016)[34]	283	Saudi Arabia	Health care	MERS	Confirmed	Yes	********
Arwady et al (2016)[35]	79	Saudi Arabia	Non-health care (household and family contacts)	MERS	Confirmed	No	******
Bai et al (2020)[36]	118	China	Health care	COVID-19	Confirmed	No	*****
Burke et al (2020)[37]	338	USA	Health care and non-health care (including household and community)	COVID-19	Confirmed	No	****
Caputo et al (2006)[38]	33	Canada	Health care	SARS	Confirmed	No	*****
Chen et al (2009)[39]	758	China	Health care	SARS	Confirmed	Yes	*******
Cheng et al (2020)[40]	226	China	Non-health care (household and family contacts)	COVID-19	Confirmed	No	******
Ha et al (2004)[42]	117	Vietnam	Health care	SARS	Confirmed	No	**
Hall et al (2014)[43]	48	Saudi Arabia	Health care	MERS	Confirmed	No	***
Heinzerling et al (2020)[44]	37	USA	Health care	COVID-19	Confirmed	No	****
Ho et al (2004)[45]	372	Taiwan	Health care	SARS	Confirmed	No	********
Ki et al (2019)[47]	446	South Korea	Health care	MERS	Confirmed	No	******
Kim et al (2016)[48]	9	South Korea	Health care	MERS	Confirmed	No	*****
Kim et al (2016)[49]	1169	South Korea	Health care	MERS	Confirmed	No	******
Lau et al (2004)[50]	2270	China	Non-health care (households)	SARS	Probable	Yes	******
Liu et al (2009)[51]	477	China	Health care	SARS	Confirmed	Yes	*****
Liu et al (2020)[52]	20	China	Non-health care (close contacts)	COVID-19	Confirmed	No	*******
Loeb et al (2004)[53]	43	Canada	Health care	SARS	Confirmed	No	**
Ma et al (2004)[54]	426	China	Health care	SARS	Confirmed	Yes	*********
Nishiura et al (2005)[55]	115	Vietnam	Health care	SARS	Confirmed	Yes	********
Nishiyama et al (2008)[56]	146	Vietnam	Health care	SARS	Confirmed	Yes	******
Olsen et al (2003)[57]	304	China	Non-health care (airplane)	SARS	Confirmed	No	******
Park et al (2004)[58]	110	USA	Health care	SARS	Confirmed	No	**********
Park et al (2016)[59]	80	South Korea	Health care	MERS	Confirmed and probable	No	***
Peck et al (2004)[60]	26	USA	Health care	SARS	Confirmed	No	*********
Pei et al (2006)[61]	443	China	Health care	SARS	Confirmed	No	********
Rea et al (2007)[62]	8662	Canada	Non-health care (community contacts)	SARS	Probable	No	****
Reuss et al (2014)[63]	81	Germany	Health care	MERS	Confirmed	No	*****
Reynolds et al (2006)[64]	153	Vietnam	Health care	SARS	Confirmed	No	***
Ryu et al (2019)[65]	34	South Korea	Health care	MERS	Confirmed	No	******
Scales et al (2003)[66]	69	Canada	Health care	SARS	Probable	No	**
Seto et al (2003)[67]	254	China	Health care	SARS	Confirmed	Yes	********
Teleman et al (2004)[68]	86	Singapore	Health care	SARS	Confirmed	Yes	********
Tuan et al (2007)[69]	212	Vietnam	Non-health care (household and community contacts)	SARS	Confirmed	Yes	******
Van Kerkhove et al (2019)[46]	828	Saudi Arabia	Non-health care (dormitory)	MERS	Confirmed	Yes	********
Wang et al (2020)[41]	493	China	Health care	COVID-19	Confirmed	Yes	****

(Table 1 continues on next page)

	n	Country	Setting	Disease caused by virus	Case definition (WHO)	Adjusted estimates	Risk of bias*
(Continued from previous page)							
Wang et al (2020)[70]	5442	China	Health care	COVID-19	Confirmed	No	*****
Wiboonchutikul et al (2016)[71]	38	Thailand	Health care	MERS	Confirmed	No	*****
Wilder-Smith et al (2005)[72]	80	Singapore	Health care	SARS	Confirmed	No	********
Wong et al (2004)[73]	66	China	Health care	SARS	Confirmed	No	*****
Wu et al (2004)[74]	375	China	Non-health care (community)	SARS	Confirmed	Yes	********
Yin et al (2004)[75]	257	China	Health care	SARS	Confirmed	Yes	******
Yu et al (2005)[76]	74	China	Health care	SARS	Confirmed	No	*******
Yu et al (2007)[77]	124 wards	China	Health care	SARS	Confirmed	Yes	*******

Across studies, mean age was 30–60 years. SARS=severe acute respiratory syndrome. MERS=Middle East respiratory syndrome. *The Newcastle-Ottawa Scale was used for the risk of bias assessment, with more stars equalling lower risk.

Table 1: **Characteristics of included comparative studies**

and reported conflicts of interests, ethics approval, study limitations, and other important comments.

Outcomes

Outcomes of interest were risk of transmission (ie, WHO-defined confirmed or probable COVID-19, SARS, or MERS) to people in health-care or non-health-care settings by those infected; hospitalisation; intensive care unit admission; death; time to recovery; adverse effects of interventions; and contextual factors such as acceptability, feasibility, effect on equity, and resource considerations related to the interventions of interest. However, data were only available to analyse intervention effects for transmission and contextual factors. Consistent with WHO, studies generally defined confirmed cases with laboratory confirmation (with or without symptoms) and probable cases with clinical evidence of the respective infection (ie, suspected to be infected) but for whom confirmatory testing either had not yet been done for any reason or was inconclusive.

Data analysis

Our search did not identify any randomised trials of COVID-19, SARS, or MERS. We did a meta-analysis of associations by pooling risk ratios (RRs) or adjusted odds ratios (aORs) depending on availability of these data from observational studies, using DerSimonian and Laird random-effects models. We adjusted for variables including age, sex, and severity of source case; these variables were not the same across studies. Because between-study heterogeneity can be misleadingly large when quantified by I^2 during meta-analysis of observational studies,[21,22] we used GRADE guidance to assess between-study heterogeneity.[21] Throughout, we present RRs as unadjusted estimates and aORs as adjusted estimates.

We used the Newcastle-Ottawa scale to rate risk of bias for comparative non-randomised studies corresponding to every study's design (cohort or case-control).[23,24] We planned to use the Cochrane Risk of Bias tool 2.0 for randomised trials,[25] but our search did not identify any eligible randomised trials. We synthesised data in both narrative and tabular formats. We graded the certainty of evidence using the GRADE approach. We used the GRADEpro app to rate evidence and present it in GRADE evidence profiles and summary of findings tables[26,27] using standardised terms.[28,29]

For more on the **GRADEpro app** see https://www.gradepro.org

We analysed data for subgroup effects by virus type, intervention (different distances or face mask types), and setting (health care *vs* non-health care). Among the studies assessing physical distancing measures to prevent viral transmission, the intervention varied (eg, direct physical contact [0 m], 1 m, or 2 m). We, therefore, analysed the effect of distance on the size of the associations by random-effects univariate meta-regressions, using restricted maximum likelihood, and we present mean effects and 95% CIs. We calculated tests for interaction using a minimum of 10 000 Monte Carlo random permutations to avoid spurious findings.[30] We formally assessed the credibility of potential effect-modifiers using GRADE guidance.[21] We did two sensitivity analyses to test the robustness of our findings. First, we used Bayesian meta-analyses to reinterpret the included studies considering priors derived from the effect point estimate and variance from a meta-analysis of ten randomised trials evaluating face mask use versus no face mask use to prevent influenza-like illness in health-care workers.[31] Second, we used Bayesian meta-analyses to reinterpret the efficacy of N95 respirators versus medical masks on preventing influenza-like illness after seasonal viral (mostly influenza) infection.[13] For these sensitivity analyses, we used hybrid Metropolis-Hastings and Gibbs sampling, a 10 000 sample burn-in, 40 000 Markov chain Monte Carlo samples, and we tested non-informative and sceptical priors (eg, four time variance)[32,33] to inform

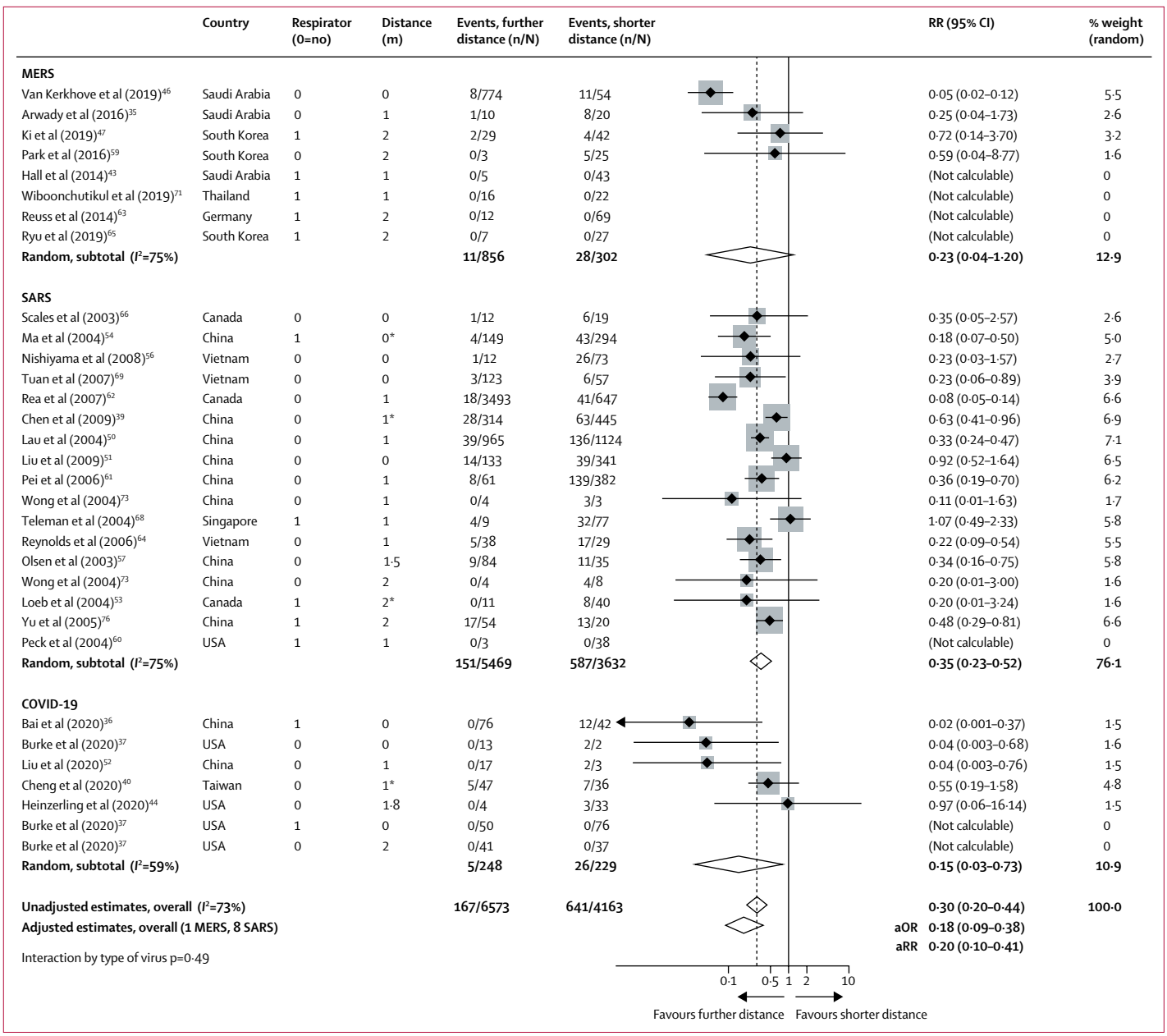


Figure 2: **Forest plot showing the association of COVID-19, SARS, or MERS exposure proximity with infection**
SARS=severe acute respiratory syndrome. MERS=Middle East respiratory syndrome. RR=relative risk. aOR=adjusted odds ratio. aRR=adjusted relative risk. *Estimated values; sensitivity analyses excluding these values did not meaningfully alter findings.

mean estimates of effect, 95% credibility intervals (CrIs), and posterior distributions. We used non-informative hyperpriors to estimate statistical heterogeneity. Model convergence was confirmed in all cases with good mixing in visual inspection of trace plots, autocorrelation plots, histograms, and kernel density estimates in all scenarios. Parameters were blocked, leading to acceptance of approximately 50% and efficiency greater than 1% in all cases (typically about 40%). We did analyses using Stata version 14.3.

Role of the funding source

The funder contributed to defining the scope of the review but otherwise had no role in study design and data collection. Data were interpreted and the report drafted and submitted without funder input, but according to contractual agreement, the funder provided review at the time of final publication. The corresponding author had full access to all data in the study and had final responsibility for the decision to submit for publication.

ID-GOV-21-0012-A-000047
www.thelancet.com Published online June 1, 2020 https://doi.org/10.1016/S0140-6736(20)31142-9

	Studies and participants	Relative effect (95% CI)	Anticipated absolute effect (95% CI), eg, chance of viral infection or transmission		Difference (95% CI)	Certainty*	What happens (standardised GRADE terminology)[29]
			Comparison group	Intervention group			
Physical distance ≥1 m *vs* <1 m	Nine adjusted studies (n=7782); 29 unadjusted studies (n=10 736)	aOR 0·18 (0·09 to 0·38); unadjusted RR 0·30 (95% CI 0·20 to 0·44)	Shorter distance, 12·8%	Further distance, 2·6% (1·3 to 5·3)	−10·2% (−11·5 to −7·5)	Moderate†	A physical distance of more than 1 m probably results in a large reduction in virus infection; for every 1 m further away in distancing, the relative effect might increase 2·02 times
Face mask *vs* no face mask	Ten adjusted studies (n=2647); 29 unadjusted studies (n=10 170)	aOR 0·15 (0·07 to 0·34); unadjusted RR 0·34 (95% CI 0·26 to 0·45)	No face mask, 17·4%	Face mask, 3·1% (1·5 to 6·7)	−14·3% (−15·9 to −10·7)	Low‡	Medical or surgical face masks might result in a large reduction in virus infection; N95 respirators might be associated with a larger reduction in risk compared with surgical or similar masks§
Eye protection (faceshield, goggles) *vs* no eye protection	13 unadjusted studies (n=3713)	Unadjusted RR 0·34 (0·22 to 0·52)¶	No eye protection, 16·0%	Eye protection, 5·5% (3·6 to 8·5)	−10·6% (−12·5 to −7·7)	Low‖	Eye protection might result in a large reduction in virus infection

Table based on GRADE approach.[26–29] Population comprised people possibly exposed to individuals infected with SARS-CoV-2, SARS-CoV, or MERS-CoV. Setting was any health-care or non-health-care setting. Outcomes were infection (laboratory-confirmed or probable) and contextual factors. Risk (95% CI) in intervention group is based on assumed risk in comparison group and relative effect (95% CI) of the intervention. All studies were non-randomised and evaluated using the Newcastle-Ottawa Scale; some studies had a higher risk of bias than did others but no important difference was noted in sensitivity analyses excluding studies at higher risk of bias; we did not further rate down for risk of bias. Although there was a high I^2 value (which can be exaggerated in non-randomised studies)[21] and no overlapping CIs, point estimates generally exceeded the thresholds for large effects and we did not rate down for inconsistency. We did not rate down for indirectness for the association between distance and infection because SARS-CoV-2, SARS-CoV, and MERS-CoV all belong to the same family and have each caused epidemics with sufficient similarity; there was also no convincing statistical evidence of effect-modification across viruses; some studies also used bundled interventions but the studies include only those that provide adjusted estimates. aOR=adjusted odds ratio. RR=relative risk. SARS-CoV-2=severe acute respiratory syndrome coronavirus 2. SARS-CoV=severe acute respiratory syndrome coronavirus. MERS-CoV=Middle East respiratory syndrome coronavirus. *GRADE category of evidence; high certainty (we are very confident that the true effect lies close to that of the estimate of the effect); moderate certainty (we are moderately confident in the effect estimate; the true effect is probably close to the estimate, but it is possibly substantially different); low certainty (our confidence in the effect estimate is limited; the true effect could be substantially different from the estimate of the effect); very low certainty (we have very little confidence in the effect estimate; the true effect is likely to be substantially different from the estimate of effect). †The effect is very large considering the thresholds set by GRADE, particularly at plausible levels of baseline risk, which also mitigated concerns about risk of bias; data also suggest a dose–response gradient, with associations increasing from smaller distances to 2 m and beyond, by meta-regression; we did not rate up for this domain alone but it further supports the decision to rate up in combination with the large effects. ‡The effect was very large, and the certainty of evidence could be rated up, but we made a conservative decision not to because of some inconsistency and risk of bias; hence, although the effect is qualitatively highly certain, the precise quantitative effect is low certainty. §In a subgroup analysis comparing N95 respirators with surgical or similar masks (eg, 12–16-layer cotton), the association was more pronounced in the N95 group (aOR 0·04, 95% CI 0·004–0·30) compared with other masks (0·33, 0·17–0·61; $p_{interaction}$=0·090); there was also support for effect-modification by formal analysis of subgroup credibility. ¶Two studies[54,75] provided adjusted estimates with n=295 in the eye protection group and n=406 in the group not wearing eye protection; results were similar to the unadjusted estimate (aOR 0·22, 95% CI 0·12–0·39). ||The effect is large considering the thresholds set by GRADE assuming that ORs translate into similar magnitudes of RR estimates; this mitigates concerns about risk of bias, but we conservatively decided not to rate up for large or very large effects.

Table 2: **GRADE summary of findings**

Results

We identified 172 studies for our systematic review from 16 countries across six continents (figure 1; appendix pp 6–14, 41–47). Studies were all observational in nature; no randomised trials were identified of any interventions that directly addressed the included study populations. Of the 172 studies, 66 focused on how far a virus can travel by comparing the association of different distances on virus transmission to people (appendix pp 42–44). Of these 66 studies, five were mechanistic, assessing viral RNA, virions, or both cultured from the environment of an infected patient (appendix p 45).

44 studies were comparative[34–77] and fulfilled criteria for our meta-analysis (n=25 697; figure 1; table 1). We used these studies rather than case series and qualitative studies (appendix pp 41–47) to inform estimates of effect. 30 studies[34,37,41–45,47–51,53–56,58–61,64–70,72,74,75] focused on the association between use of various types of face masks and respirators by health-care workers, patients, or both with virus transmission. 13 studies[34,37–39,47,49,51,54,58,60,61,65,75] addressed the association of eye protection with virus transmission.

Some direct evidence was available for COVID-19 (64 studies, of which seven were comparative in design),[36,37,40,41,44,52,70] but most studies reported on SARS (n=55) or MERS (n=25; appendix pp 6–12). Of the 44 comparative studies, 40 included WHO-defined confirmed cases, one included both confirmed and probable cases, and the remaining three studies included probable cases. There was no effect-modification by case-definition (distance $p_{interaction}$=0·41; mask $p_{interaction}$=0·46; all cases for eye protection were confirmed). Most studies reported on bundled interventions, including different components of PPE and distancing, which was usually addressed by statistical adjustment. The included studies all occurred during recurrent or novel outbreak settings of COVID-19, SARS, or MERS.

Risk of bias was generally low-to-moderate after considering the observational designs (table 1), but both within studies and across studies the overall findings were similar between adjusted and unadjusted estimates. We did not detect strong evidence of publication bias in the body of evidence for any intervention (appendix pp 15–18). As we did not use case series data to inform estimates of effect of each intervention, we did not systematically rate risk of bias of these data. Therefore, we report further only those studies with comparative data.

ID-GOV-21-0012-A-000048

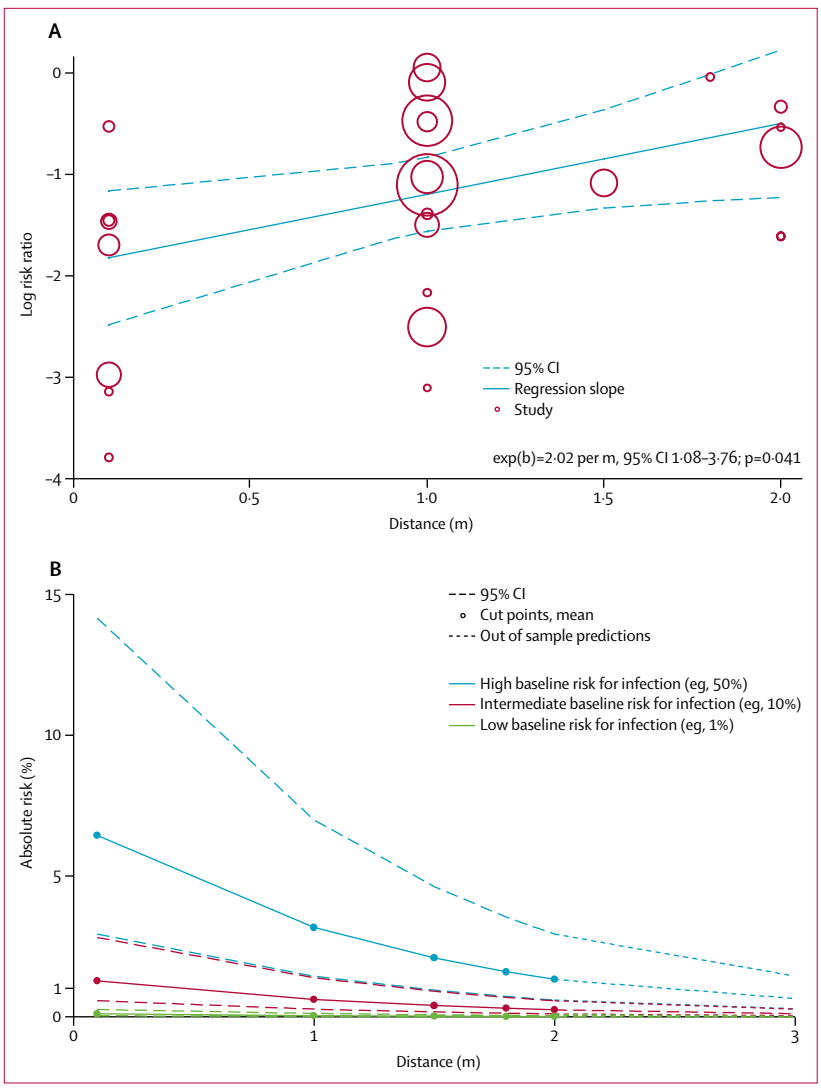


Figure 3: **Change in relative risk with increasing distance and absolute risk with increasing distance**
Meta-regression of change in relative risk with increasing distance from an infected individual (A). Absolute risk of transmission from an individual infected with SARS-CoV-2, SARS-CoV, or MERS-CoV with varying baseline risk and increasing distance (B). SARS-CoV-2=severe acute respiratory syndrome coronavirus 2. SARS-CoV=severe acute respiratory syndrome coronavirus. MERS-CoV=Middle East respiratory syndrome coronavirus.

Across 29 unadjusted and nine adjusted studies,[35–37,39,40,43,44,46,47,50–54,56,57,59–66,68,69,71,73,76] a strong association was found of proximity of the exposed individual with the risk of infection (unadjusted n=10 736, RR 0·30, 95% CI 0·20 to 0·44; adjusted n=7782, aOR 0·18, 95% CI 0·09 to 0·38; absolute risk [AR] 12·8% with shorter distance *vs* 2·6% with further distance, risk difference [RD] –10·2%, 95% CI –11·5 to –7·5; moderate certainty; figure 2; table 2; appendix p 16). Although there were six studies on COVID-19, the association was seen irrespective of causative virus ($p_{interaction}$=0·49), health-care setting versus non-health-care setting ($p_{interaction}$=0·14), and by type of face mask ($p_{interaction}$=0·95; appendix pp 17, 19). However, different studies used different distances for the intervention. By meta-regression, the strength of association was larger with increasing distance (2·02 change in RR per m, 95% CI 1·08 to 3·76; $p_{interaction}$=0·041; moderate credibility subgroup effect; figure 3A; table 2). AR values with increasing distance given different degrees of baseline risk are shown in figure 3B, with potential values at 3 m also shown.

Across 29 unadjusted studies and ten adjusted studies,[34,37,41–45,47–51,53–56,58–61,64–70,72,74,75] the use of both N95 or similar respirators or face masks (eg, disposable surgical masks or similar reusable 12–16-layer cotton masks) by those exposed to infected individuals was associated with a large reduction in risk of infection (unadjusted n=10 170, RR 0·34, 95% CI 0·26 to 0·45; adjusted studies n=2647, aOR 0·15, 95% CI 0·07 to 0·34; AR 3·1% with face mask *vs* 17·4% with no face mask, RD –14·3%, 95% CI –15·9 to –10·7; low certainty; figure 4; table 2; appendix pp 16, 18) with stronger associations in health-care settings (RR 0·30, 95% CI 0·22 to 0·41) compared with non-health-care settings (RR 0·56, 95% CI 0·40 to 0·79; $p_{interaction}$=0·049; low-to-moderate credibility for subgroup effect; figure 4; appendix p 19). When differential N95 or similar respirator use, which was more frequent in health-care settings than in non-health-care settings, was adjusted for the possibility that face masks were less effective in non-health-care settings, the subgroup effect was slightly less credible ($p_{interaction}$=0·11, adjusted for differential respirator use; figure 4). Indeed, the association with protection from infection was more pronounced with N95 or similar respirators (aOR 0·04, 95% CI 0·004 to 0·30) compared with other masks (aOR 0·33, 95% CI 0·17 to 0·61; $p_{interaction}$=0·090; moderate credibility subgroup effect; figure 5). The interaction was also seen when additionally adjusting for three studies that clearly reported aerosol-generating procedures ($p_{interaction}$=0·048; figure 5). Supportive evidence for this interaction was also seen in within-study comparisons (eg, N95 had a stronger protective association compared with surgical masks or 12–16-layer cotton masks); both N95 and surgical masks also had a stronger association with protection versus single-layer masks.[38,39,51,53,54,61,66,67,75]

We did a sensitivity analysis to test the robustness of our findings and to integrate all available information on face mask treatment effects for protection from COVID-19. We reconsidered our findings using random-effects Bayesian meta-analysis. Although non-informative priors showed similar results to frequentist approaches (aOR 0·16, 95% CrI 0·04–0·40), even using informative priors from the most recent meta-analysis on the effectiveness of masks versus no masks to prevent influenza-like illness (RR 0·93, 95% CI 0·83–1·05)[31] yielded a significant association with protection from COVID-19 (aOR 0·40, 95% CrI 0·16–0·97; posterior probability for RR <1, 98%). Minimally informing (25% influence with or without four-fold smaller mean effect size) the most recent and rigorous meta-analysis of the effectiveness of N95

ID-GOV-21-0012-A-000049
www.thelancet.com Published online June 1, 2020 https://doi.org/10.1016/S0140-6736(20)31142-9

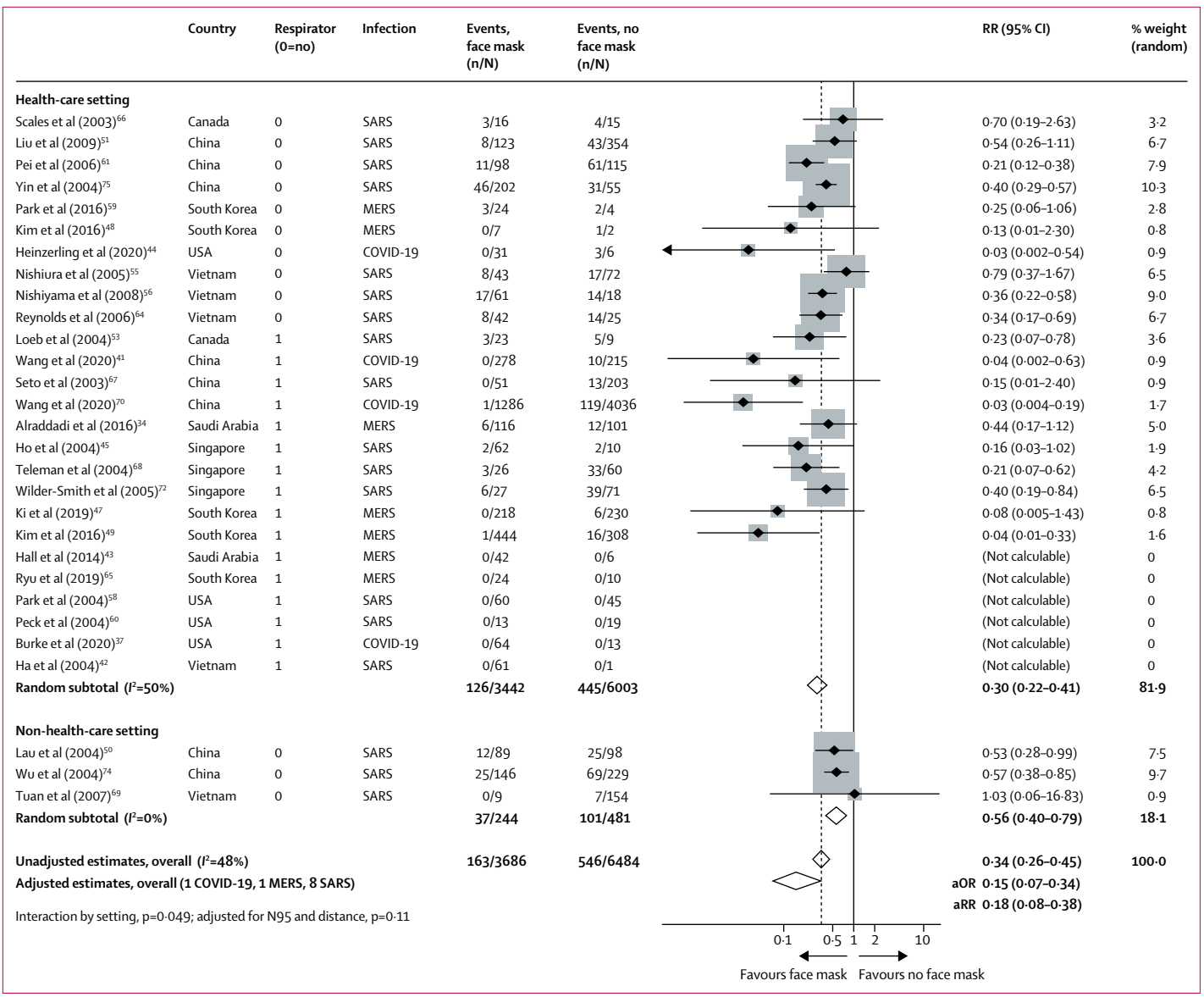


Figure 4: **Forest plot showing unadjusted estimates for the association of face mask use with viral infection causing COVID-19, SARS, or MERS**
SARS=severe acute respiratory syndrome. MERS=Middle East respiratory syndrome. RR=relative risk. aOR=adjusted odds ratio. aRR=adjusted relative risk.

respirators versus medical masks in randomised trials (OR 0·76, 95% CI 0·54–1·06)[13] with the effect-modification seen in this meta-analysis on COVID-19 (ratio of aORs 0·14, 95% CI 0·02–1·05) continued to support a stronger association of protection from COVID-19, SARS, or MERS with N95 or similar respirators versus other face masks (posterior probability for RR <1, 100% and 95%, respectively).

In 13 unadjusted studies and two adjusted studies,[34,37-39,47,49,51,54,58,60,61,65,75] eye protection was associated with lower risk of infection (unadjusted n=3713, RR 0·34, 95% CI 0·22 to 0·52; AR 5·5% with eye protection *vs* 16·0% with no eye protection, RD –10·6%, 95% CI –12·5 to –7·7; adjusted n=701, aOR 0·22, 95% CI 0·12 to 0·39; low certainty; figure 6; table 2; appendix pp 16–17).

Across 24 studies in health-care and non-health-care settings during the current pandemic of COVID-19, previous epidemics of SARS and MERS, or in general use, looking at contextual factors to consider in recommendations, most stakeholders found physical distancing and use of face masks and eye protection acceptable, feasible, and reassuring (appendix pp 20–22). However, challenges included frequent discomfort, high resource use linked with potentially decreased equity, less clear communication, and perceived reduced empathy of care providers by those they were caring for.

ID-GOV-21-0012-A-000050

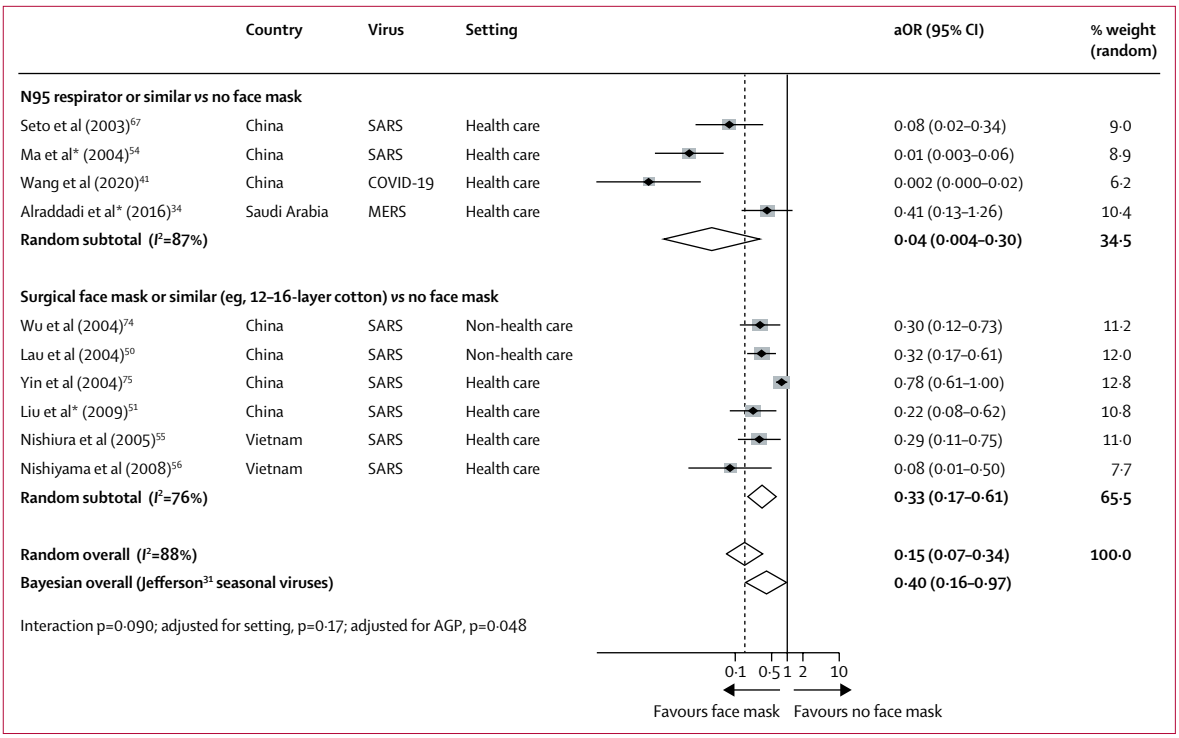


Figure 5: **Forest plot showing adjusted estimates for the association of face mask use with viral infection causing COVID-19, SARS, or MERS**
SARS=severe acute respiratory syndrome. MERS=Middle East respiratory syndrome. RR=relative risk. aOR=adjusted odds ratio. AGP=aerosol-generating procedures. *Studies clearly reporting AGP.

Discussion

The findings of this systematic review of 172 studies (44 comparative studies; n=25 697 patients) on COVID-19, SARS, and MERS provide the best available evidence that current policies of at least 1 m physical distancing are associated with a large reduction in infection, and distances of 2 m might be more effective. These data also suggest that wearing face masks protects people (both health-care workers and the general public) against infection by these coronaviruses, and that eye protection could confer additional benefit. However, none of these interventions afforded complete protection from infection, and their optimum role might need risk assessment and several contextual considerations. No randomised trials were identified for these interventions in COVID-19, SARS, or MERS.

Previous reviews are limited in that they either have not provided any evidence from COVID-19 or did not use direct evidence from other related emerging epidemic betacoronaviruses (eg, SARS and MERS) to inform the effects of interventions to curtail the current COVID-19 pandemic.[13,19,31,78] Previous data from randomised trials are mainly for common respiratory viruses such as seasonal influenza, with a systematic review concluding low certainty of evidence for extrapolating these findings to COVID-19.[13] Further, previous syntheses of available randomised controlled trials have not accounted for cluster effects in analyses, leading to substantial imprecision in treatment effect estimates. In between-study and within-study comparisons, we noted a larger effect of N95 or similar respirators compared with other masks. This finding is inconsistent with conclusions of a review of four randomised trials,[13] in which low certainty of evidence for no larger effect was suggested. However, in that review, the CIs were wide so a meaningful protective effect could not be excluded. We harmonised these findings with Bayesian approaches, using indirect data from randomised trials to inform posterior estimates. Despite this step, our findings continued to support the ideas not only that masks in general are associated with a large reduction in risk of infection from SARS-CoV-2, SARS-CoV, and MERS-CoV but also that N95 or similar respirators might be associated with a larger degree of protection from viral infection than disposable medical masks or reusable multilayer (12–16-layer) cotton masks. Nevertheless, in view of the limitations of these data, we did not rate the certainty of effect as high.[21] Our findings accord with those of a cluster randomised trial showing a potential benefit of continuous N95 respirator use over medical masks against seasonal viral infections.[79] Further high-quality research, including randomised trials of the optimum physical distance and the effectiveness of different types of masks in the general population and for health-care workers' protection, is urgently needed. Two trials are registered to better inform the optimum use of face masks for COVID-19 (NCT04296643 [n=576] and

ID-GOV-21-0012-A-000051
www.thelancet.com Published online June 1, 2020 https://doi.org/10.1016/S0140-6736(20)31142-9

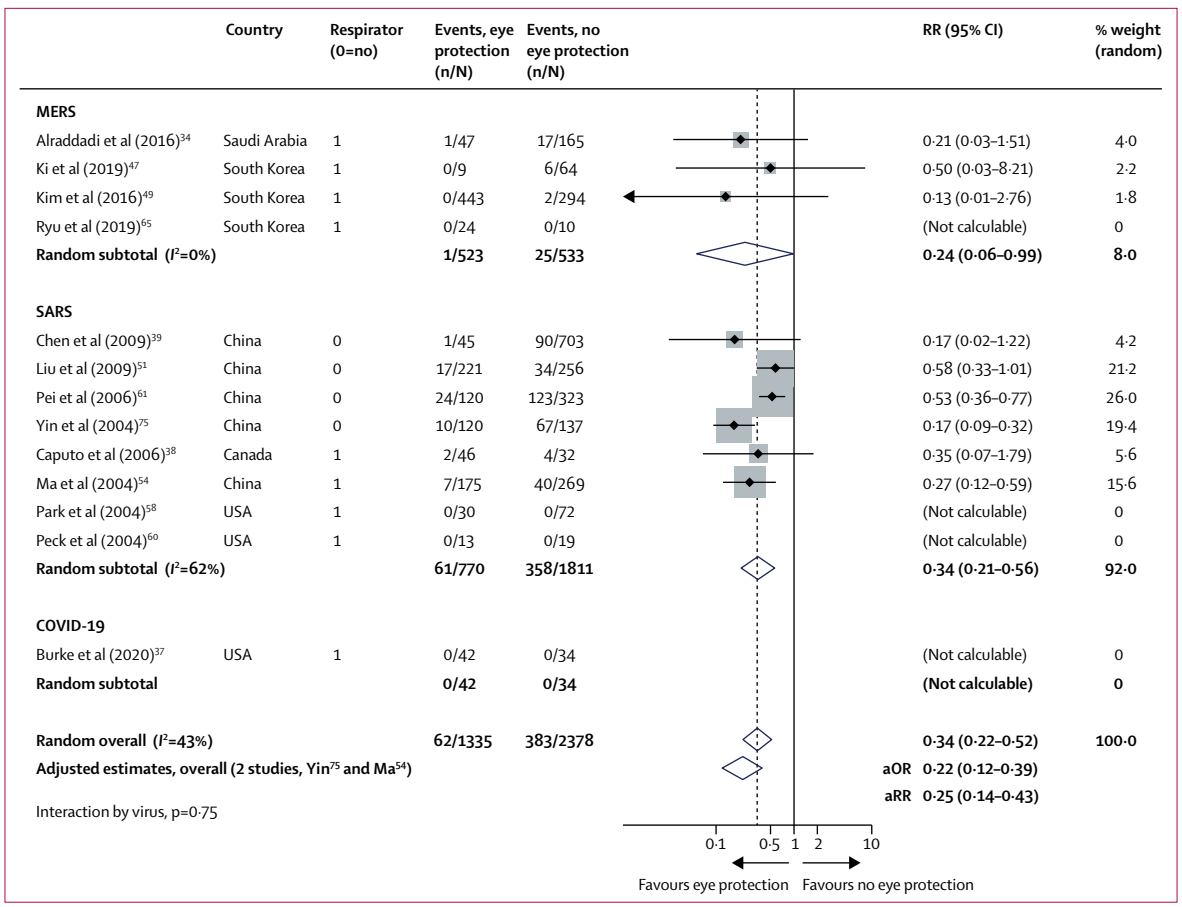


Figure 6: **Forest plot showing the association of eye protection with risk of COVID-19, SARS, or MERS transmission**
Forest plot shows unadjusted estimates. SARS=severe acute respiratory syndrome. MERS=Middle East respiratory syndrome. RR=relative risk. aOR=adjusted odds ratio. aRR=adjusted relative risk.

NCT04337541 [n=6000]). Until such data are available, our findings represent the current best estimates to inform face mask use to reduce infection from COVID-19. We recognise that there are strong, perhaps opposing, sentiments about policy making during outbreaks. In one viewpoint, the 2007 SARS Commission report stated:

> "...recognize, as an aspect of health worker safety, the precautionary principle that reasonable action to reduce risk, such as the use of a fitted N95 respirator, need not await scientific certainty".[80]

> "...if we do not learn from SARS and we do not make the government fix the problems that remain, we will pay a terrible price in the next pandemic".[81]

A counter viewpoint is that the scientific uncertainty and contextual considerations require a more nuanced approach. Although challenging, policy makers must carefully consider these two viewpoints along with our findings.

We found evidence of moderate certainty that current policies of at least 1 m physical distancing are probably associated with a large reduction in infection, and that distances of 2 m might be more effective, as implemented in some countries. We also provide estimates for 3 m. The main benefit of physical distancing measures is to prevent onward transmission and, thereby, reduce the adverse outcomes of SARS-CoV-2 infection. Hence, the results of our current review support the implementation of a policy of physical distancing of at least 1 m and, if feasible, 2 m or more. Our findings also provide robust estimates to inform models and contact tracing used to plan and strategise for pandemic response efforts at multiple levels.

The use of face masks was protective for both health-care workers and people in the community exposed to infection, with both the frequentist and Bayesian analyses lending support to face mask use irrespective of setting. Our unadjusted analyses might, at first impression, suggest use of face masks in the community setting to be less effective than in the health-care setting, but after accounting for differential N95 respirator use between health-care and non-health-care settings, we did not detect any striking differences in effectiveness of

face mask use between settings. The credibility of effect-modification across settings was, therefore, low. Wearing face masks was also acceptable and feasible. Policy makers at all levels should, therefore, strive to address equity implications for groups with currently limited access to face masks and eye protection. One concern is that face mask use en masse could divert supplies from people at highest risk for infection.[10] Health-care workers are increasingly being asked to ration and reuse PPE,[82,83] leading to calls for government-directed repurposing of manufacturing capacity to overcome mask shortages[84] and finding solutions for mask use by the general public.[84] In this respect, some of the masks studied in our review were reusable 12–16-layer cotton or gauze masks.[51,54,61,75] At the moment, although there is consensus that SARS-CoV-2 mainly spreads through large droplets and contact, debate continues about the role of aerosol,[2–8,85,86] but our meta-analysis provides evidence (albeit of low certainty) that respirators might have a stronger protective effect than surgical masks. Biological plausibility would be supported by data for aerosolised SARS-CoV-2[5–8] and preclinical data showing seasonal coronavirus RNA detection in fine aerosols during tidal breathing,[87] albeit, RNA detection does not necessarily imply replication and infection-competent virus. Nevertheless, our findings suggest it plausible that even in the absence of aerosolisation, respirators might be simply more effective than masks at preventing infection. At present, there is no data to support viable virus in the air outside of aerosol generating procedures from available hospital studies. Other factors such as super-spreading events, the subtype of health-care setting (eg, emergency room, intensive care unit, medical wards, dialysis centre), if aerosolising procedures are done, and environmental factors such as ventilation, might all affect the degree of protection afforded by personal protection strategies, but we did not identify robust data to inform these aspects.

Strengths of our review include adherence to full systematic review methods, which included artificial intelligence-supported dual screening of titles and abstracts, full-text evaluation, assessment of risk of bias, and no limitation by language. We included patients infected with SARS-CoV-2, SARS-CoV, or MERS-CoV and searched relevant data up to May 3, 2020. We followed the GRADE approach[16] to rate the certainty of evidence. Finally, we identified and appraise a large body of published work from China, from which much evidence emerged before the pandemic spread to other global regions.

The primary limitation of our study is that all studies were non-randomised, not always fully adjusted, and might suffer from recall and measurement bias (eg, direct contact in some studies might not be measuring near distance). However, unadjusted, adjusted, frequentist, and Bayesian meta-analyses all supported the main findings, and large or very large effects were recorded. Nevertheless, we are cautious not to be overly certain in the precise quantitative estimates of effects, although the qualitative effect and direction is probably of high certainty. Many studies did not provide information on precise distances, and direct contact was equated to 0 m distance; none of the eligible studies quantitatively evaluated whether distances of more than 2 m were more effective, although our meta-regression provides potential predictions for estimates of risk. Few studies assessed the effect of interventions in non-health-care settings, and they primarily evaluated mask use in households or contacts of cases, although beneficial associations were seen across settings. Furthermore, most evidence was from studies that reported on SARS and MERS (n=6674 patients with COVID-19, of 25 697 total), but data from these previous epidemics provide the most direct information for COVID-19 currently. We did not specifically assess the effect of duration of exposure on risk for transmission, although whether or not this variable was judged a risk factor considerably varied across studies, from any duration to a minimum of 1 h. Because of inconsistent reporting, information is limited about whether aerosol-generating procedures were in place in studies using respirators, and whether masks worn by infected patients might alter the effectiveness of each intervention, although the stronger association with N95 or similar respirators over other masks persisted when adjusting for studies reporting aerosol-generating medical procedures. These factors might account for some of the residual statistical heterogeneity seen for some outcomes, albeit I^2 is commonly inflated in meta-analyses of observational data,[21,22] and nevertheless the effects seen were large and probably clinically important in all adjusted studies.

Our comprehensive systematic review provides the best available information on three simple and common interventions to combat the immediate threat of COVID-19, while new evidence on pharmacological treatments, vaccines, and other personal protective strategies is being generated. Physical distancing of at least 1 m is strongly associated with protection, but distances of up to 2 m might be more effective. Although direct evidence is limited, the optimum use of face masks, in particular N95 or similar respirators in health-care settings and 12–16-layer cotton or surgical masks in the community, could depend on contextual factors; action is needed at all levels to address the paucity of better evidence. Eye protection might provide additional benefits. Globally collaborative and well conducted studies, including randomised trials, of different personal protective strategies are needed regardless of the challenges, but this systematic appraisal of currently best available evidence could be considered to inform interim guidance.

Contributors

DKC, EAA, SD, KS, SY, and HJS designed the study. SY, SD, KS, and HJS coordinated the study. SY and LH designed and ran the literature search. All authors acquired data, screened records, extracted data, and assessed risk of bias. DKC did statistical analyses. DKC and HJS wrote the report. All authors provided critical conceptual input, analysed and interpreted data, and critically revised the report.

COVID-19 Systematic Urgent Review Group Effort (SURGE) study authors
Argentina—German Hospital of Buenos Aires (Ariel Izcovich); Canada—Cochrane Consumer Executive (Maureen Smith); McMaster University (Mark Loeb, Anisa Hajizadeh, Carlos A Cuello-Garcia, Gian Paolo Morgano, Leila Harrison, Tejan Baldeh, Karla Solo, Tamara Lotfi, Antonio Bognanni, Rosa Stalteri, Thomas Piggott, Yuan Zhang, Stephanie Duda, Derek K Chu, Holger J Schünemann); Southlake Regional Health Centre (Jeffrey Chan); University of British Columbia (David James Harris); Chile—Pontificia Universidad Católica de Chile (Ignacio Neumann); China—Beijing University of Chinese Medicine, Dongzhimen Hospital (Guang Chen); Guangzhou University of Chinese Medicine, The Fourth Clinical Medical College (Chen Chen); China Academy of Chinese Medical Sciences (Hong Zhao); Germany—Finn Schünemann; Italy—Azienda USL–IRCCS di Reggio Emilia (Paolo Giorgi Rossi); Universita Vita-Salute San Raffaele, Milan, Italy (Giovanna Elsa Ute Muti Schünemann); Lebanon—American University of Beirut (Layal Hneiny, Amena El-Harakeh, Fatimah Chamseddine, Joanne Khabsa, Nesrine Rizk, Rayane El-Khoury, Zahra Saad, Sally Yaacoub, Elie A Akl); Rafik Hariri University Hospital (Pierre AbiHanna); Poland—Evidence Prime, Krakow (Anna Bak, Ewa Borowiack); UK—The London School of Hygiene & Tropical Medicine (Marge Reinap); University of Hull (Assem Khamis).

Declaration of interests
ML is an investigator of an ongoing clinical trial on medical masks versus N95 respirators for COVID-19 (NCT04296643). All other authors declare no competing interests.

Acknowledgments
This systematic review was commissioned and in part paid for by WHO. The authors alone are responsible for the views expressed in this article and they do not necessarily represent the decisions, policy, or views of WHO. We thank Susan L Norris, April Baller, and Benedetta Allegranzi (WHO) for input in the protocol or the final article; Xuan Yu (Evidence Based Medicine Center of Lanzhou University, China), Eliza Poon, and Yuqing (Madison) Zhang for assistance with Chinese literature support; Neera Bhatnagar and Aida Farha (information specialists) for peer-reviewing the search strategy; Artur Nowak (Evidence Prime, Hamilton, ON, Canada) for help with searching and screening using artificial intelligence; and Christine Keng for additional support. DKC is a CAAIF-CSACI-AllerGen Emerging Clinician-Scientist Research Fellow, supported by the Canadian Allergy, Asthma and Immunology Foundation (CAAIF), the Canadian Society of Allergy and Clinical Immunology (CSACI), and AllerGen NCE (the Allergy, Genes and Environment Network).

Editorial note: the *Lancet* Group takes a neutral position with respect to territorial claims in published maps and institutional affiliations.

References
1 Worldometer. COVID-19 coronavirus pandemic. 2020. https://www.worldometers.info/coronavirus/ (accessed May 28, 2020).
2 Guo ZD, Wang ZY, Zhang SF, et al. Aerosol and surface distribution of severe acute respiratory syndrome coronavirus 2 in hospital wards, Wuhan, China, 2020. *Emerg Infect Dis* 2020; published online April 10. DOI:10.3201/eid2607.200885.
3 Chia PY, Coleman KK, Tan YK, et al. Detection of air and surface contamination by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in hospital rooms of infected patients. *medRxiv* 2020; published online April 9. DOI:10.1101/2020.03.29.20046557 (preprint).
4 Santarpia JL, Rivera DN, Herrera V, et al. Transmission potential of SARS-CoV-2 in viral shedding observed at the University of Nebraska Medical Center. *medRxiv* 2020; published online March 26. DOI:10.1101/2020.03.23.20039446 (preprint).
5 Cheng V, Wong S-C, Chen J, et al. Escalating infection control response to the rapidly evolving epidemiology of the coronavirus disease 2019 (COVID-19) due to SARS-CoV-2 in Hong Kong. *Infect Control Hosp Epidemiol* 2020; **41:** 493–98.
6 Wong SCY, Kwong RT-S, Wu TC, et al. Risk of nosocomial transmission of coronavirus disease 2019: an experience in a general ward setting in Hong Kong. *J Hosp Infect* 2020; **105:** 119–27.
7 Faridi S, Niazi S, Sadeghi K, et al. A field indoor air measurement of SARS-CoV-2 in the patient rooms of the largest hospital in Iran. *Sci Total Environ* 2020; **725:** 138401.
8 Ong SWX, Tan YK, Chia PY, et al. Air, surface environmental, and personal protective equipment contamination by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) from a symptomatic patient. *JAMA* 2020; **323:** 1610–12.
9 Qualls N, Levitt A, Kanade N, et al. Community mitigation guidelines to prevent pandemic influenza: United States, 2017. *MMWR Recomm Rep* 2017; **66:** 1–34.
10 Feng S, Shen C, Xia N, Song W, Fan M, Cowling BJ. Rational use of face masks in the COVID-19 pandemic. *Lancet Respir Med* 2020; **8:** 434–36.
11 MacIntyre R, Chughtai A, Tham CD, Seale H. COVID-19: should cloth masks be used by healthcare workers as a last resort? April 9, 2020. https://blogs.bmj.com/bmj/2020/04/09/covid-19-should-cloth-masks-be-used-by-healthcare-workers-as-a-last-resort/ (accessed May 12, 2020).
12 Loeb M, Dafoe N, Mahony J, et al. Surgical mask *vs* N95 respirator for preventing influenza among health care workers: a randomized trial. *JAMA* 2009; **302:** 1865–71.
13 Bartoszko JJ, Farooqi MAM, Alhazzani W, Loeb M. Medical masks vs N95 respirators for preventing COVID-19 in healthcare workers: a systematic review and meta-analysis of randomized trials. *Influenza Other Respir Viruses* 2020; published online April 4. DOI:10.1111/irv.12745.
14 Schünemann HJ, Moja L. Reviews: rapid! Rapid! Rapid! . . . and systematic. *Syst Rev* 2015; **4:** 4.
15 Cochrane Training. Cochrane handbook for systematic reviews of interventions, version 6. 2019. https://training.cochrane.org/handbook/current (accessed May 12, 2020).
16 Guyatt GH, Oxman AD, Vist GE, et al. GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. *BMJ* 2008; **336:** 924–26.
17 Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *J Clin Epidemiol* 2009; **62:** 1006–12.
18 Stroup DF, Berlin JA, Morton SC, et al. Meta-analysis of observational studies in epidemiology: a proposal for reporting. *JAMA* 2000; **283:** 2008–12.
19 Jefferson T, Del Mar CB, Dooley L, et al. Physical interventions to interrupt or reduce the spread of respiratory viruses. *Cochrane Database Syst Rev* 2011; **7:** CD006207.
20 Offeddu V, Yung CF, Low MSF, Tam CC. Effectiveness of masks and respirators against respiratory infections in healthcare workers: a systematic review and meta-analysis. *Clin Infect Dis* 2017; **65:** 1934–42.
21 Guyatt GH, Oxman AD, Kunz R, et al. GRADE guidelines, 7: rating the quality of evidence—inconsistency. *J Clin Epidemiol* 2011; **64:** 1294–302.
22 Iorio A, Spencer FA, Falavigna M, et al. Use of GRADE for assessment of evidence about prognosis: rating confidence in estimates of event rates in broad categories of patients. *BMJ* 2015; **350:** h870.
23 Moskalewicz A, Oremus M. No clear choice between Newcastle-Ottawa Scale and Appraisal Tool for Cross-Sectional Studies to assess methodological quality in cross-sectional studies of health-related quality of life and breast cancer. *J Clin Epidemiol* 2020; **120:** 94–103.
24 Wells GA, Shea B, O'Connell D, et al. The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses. 2019. http://www.ohri.ca/programs/clinical_epidemiology/oxford.asp (accessed May 12, 2020).
25 Sterne JAC, Savović J, Page MJ, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. *BMJ* 2019; **366:** l4898.
26 Guyatt G, Oxman AD, Akl EA, et al. GRADE guidelines, 1: introduction—GRADE evidence profiles and summary of findings tables. *J Clin Epidemiol* 2011; **64:** 383–94.
27 Guyatt GH, Thorlund K, Oxman AD, et al. GRADE guidelines, 13: preparing summary of findings tables and evidence profiles—continuous outcomes. *J Clin Epidemiol* 2013; **66:** 173–83.
28 Santesso N, Carrasco-Labra A, Langendam M, et al. Improving GRADE evidence tables part 3: detailed guidance for explanatory footnotes supports creating and understanding GRADE certainty in the evidence judgments. *J Clin Epidemiol* 2016; **74:** 28–39.
29 Santesso N, Glenton C, Dahm P, et al. GRADE guidelines, 26: informative statements to communicate the findings of systematic reviews of interventions. *J Clin Epidemiol* 2020; **119:** 126–35.

30 Higgins JP, Thompson SG. Controlling the risk of spurious findings from meta-regression. *Stat Med* 2004; **23:** 1663–82.

31 Jefferson T, Jones M, Al Ansari LA, et al. Physical interventions to interrupt or reduce the spread of respiratory viruses, part 1: face masks, eye protection and person distancing—systematic review and meta-analysis. *medRxiv* 2020; published online April 7. DOI:10.1101/2020.03.30.20047217 (preprint).

32 Sutton AJ, Abrams KR. Bayesian methods in meta-analysis and evidence synthesis. *Stat Methods Med Res* 2001; **10:** 277–303.

33 Goligher EC, Tomlinson G, Hajage D, et al. Extracorporeal membrane oxygenation for severe acute respiratory distress syndrome and posterior probability of mortality benefit in a post hoc Bayesian analysis of a randomized clinical trial. *JAMA* 2018; **320:** 2251–59.

34 Alraddadi BM, Al-Salmi HS, Jacobs-Slifka K, et al. Risk factors for Middle East respiratory syndrome coronavirus infection among healthcare personnel. *Emerg Infect Dis* 2016; **22:** 1915–20.

35 Arwady MA, Alraddadi B, Basler C, et al. Middle East respiratory syndrome coronavirus transmission in extended family, Saudi Arabia, 2014. *Emerg Infect Dis* 2016; **22:** 1395–402.

36 Bai Y, Wang X, Huang Q, et al. SARS-CoV-2 infection in health care workers: a retrospective analysis and a model study. *medRxiv* 2020; published online April 1. DOI:10.1101/2020.03.29.20047159 (preprint).

37 Burke RM, Balter S, Barnes E, et al. Enhanced contact investigations for nine early travel-related cases of SARS-CoV-2 in the United States. *medRxiv* 2020; published online May 3. DOI:10.1101/2020.04.27.20081901 (preprint).

38 Caputo KM, Byrick R, Chapman MG, Orser BJ, Orser BA. Intubation of SARS patients: infection and perspectives of healthcare workers. *Can J Anaesth* 2006; **53:** 122–29.

39 Chen WQ, Ling WH, Lu CY, et al. Which preventive measures might protect health care workers from SARS? *BMC Public Health* 2009; **9:** 81.

40 Cheng H-Y, Jian S-W, Liu D-P, Ng T-C, Huang W-T, Lin H-H. High transmissibility of COVID-19 near symptom onset. *medRxiv* 2020; published online March 19. DOI:10.1101/2020.03.18.20034561 (preprint).

41 Wang X, Pan Z, Cheng Z. Association between 2019-nCoV transmission and N95 respirator use. *J Hosp Infect* 2020; **105:** 104–05.

42 Ha LD, Bloom SA, Hien NQ, et al. Lack of SARS transmission among public hospital workers, Vietnam. *Emerg Infect Dis* 2004; **10:** 265–68.

43 Hall AJ, Tokars JI, Badreddine SA, et al. Health care worker contact with MERS patient, Saudi Arabia. *Emerg Infect Dis* 2014; **20:** 2148–51.

44 Heinzerling A, Stuckey MJ, Scheuer T, et al. Transmission of COVID-19 to health care personnel during exposures to a hospitalized patient: Solano County, California, February 2020. *MMWR Morb Mortal Wkly Rep* 2020; **69:** 472–76.

45 Ho KY, Singh KS, Habib AG, et al. Mild illness associated with severe acute respiratory syndrome coronavirus infection: lessons from a prospective seroepidemiologic study of health-care workers in a teaching hospital in Singapore. *J Infect Dis* 2004; **189:** 642–47.

46 Van Kerkhove MD, Alaswad S, Assiri A, et al. Transmissibility of MERS-CoV infection in closed setting, Riyadh, Saudi Arabia, 2015. *Emerg Infect Dis J* 2019; **25:** 1802–09.

47 Ki HK, Han SK, Son JS, Park SO. Risk of transmission via medical employees and importance of routine infection-prevention policy in a nosocomial outbreak of Middle East respiratory syndrome (MERS): a descriptive analysis from a tertiary care hospital in South Korea. *BMC Pulm Med* 2019; **19:** 190.

48 Kim T, Jung J, Kim SM, et al. Transmission among healthcare worker contacts with a Middle East respiratory syndrome patient in a single Korean centre. *Clin Microbiol Infect* 2016; **22:** e11–13.

49 Kim CJ, Choi WS, Jung Y, et al. Surveillance of the Middle East respiratory syndrome (MERS) coronavirus (CoV) infection in healthcare workers after contact with confirmed MERS patients: incidence and risk factors of MERS-CoV seropositivity. *Clin Microbiol Infect* 2016; **22:** 880–86.

50 Lau JTF, Lau M, Kim JH, Tsui HY, Tsang T, Wong TW. Probable secondary infections in households of SARS patients in Hong Kong. *Emerg Infect Dis* 2004; **10:** 235–43.

51 Liu W, Tang F, Fang LQ, et al. Risk factors for SARS infection among hospital healthcare workers in Beijing: a case control study. *Trop Med Int Health* 2009; **14** (suppl 1)**:** 52–59.

52 Liu ZQ, Ye Y, Zhang H, Guohong X, Yang J, Wang JL. Analysis of the spatio-temporal characteristics and transmission path of COVID-19 cluster cases in Zhuhai. *Trop Geogr* 2020; published online March 12. DOI:10.13284/j.cnki.rddl.003228.

53 Loeb M, McGeer A, Henry B, et al. SARS among critical care nurses, Toronto. *Emerg Infect Dis* 2004; **10:** 251–55.

54 Ma HJ, Wang HW, Fang LQ, et al. A case-control study on the risk factors of severe acute respiratory syndromes among health care workers. *Zhonghua Liu Xing Bing Xue Za Zhi* 2004; **25:** 741–44 (in Chinese).

55 Nishiura H, Kuratsuji T, Quy T, et al. Rapid awareness and transmission of severe acute respiratory syndrome in Hanoi French Hospital, Vietnam. *Am J Trop Med Hyg* 2005; **73:** 17–25.

56 Nishiyama A, Wakasugi N, Kirikae T, et al. Risk factors for SARS infection within hospitals in Hanoi, Vietnam. *Jpn J Infect Dis* 2008; **61:** 388–90.

57 Olsen SJ, Chang HL, Cheung TY, et al. Transmission of the severe acute respiratory syndrome on aircraft. *N Engl J Med* 2003; **349:** 2416–22.

58 Park BJ, Peck AJ, Kuehnert MJ, et al. Lack of SARS transmission among healthcare workers, United States. *Emerg Infect Dis* 2004; **10:** 244–48.

59 Park JY, Kim BJ, Chung KH, Hwang YI. Factors associated with transmission of Middle East respiratory syndrome among Korean healthcare workers: infection control via extended healthcare contact management in a secondary outbreak hospital. *Respirology* 2016; **21** (suppl 3)**:** 89 (abstr APSR6-0642).

60 Peck AJ, Newbern EC, Feikin DR, et al. Lack of SARS transmission and U.S. SARS case-patient. *Emerg Infect Dis* 2004; **10:** 217–24.

61 Pei LY, Gao ZC, Yang Z, et al. Investigation of the influencing factors on severe acute respiratory syndrome among health care workers. *Beijing Da Xue Xue Bao Yi Xue Ban* 2006; **38:** 271–75.

62 Rea E, Laflèche J, Stalker S, et al. Duration and distance of exposure are important predictors of transmission among community contacts of Ontario SARS cases. *Epidemiol Infect* 2007; **135:** 914–21.

63 Reuss A, Litterst A, Drosten C, et al. Contact investigation for imported case of Middle East respiratory syndrome, Germany. *Emerg Infect Dis* 2014; **20:** 620–25.

64 Reynolds MG, Anh BH, Thu VH, et al. Factors associated with nosocomial SARS-CoV transmission among healthcare workers in Hanoi, Vietnam, 2003. *BMC Public Health* 2006; **6:** 207.

65 Ryu B, Cho SI, Oh MD, et al. Seroprevalence of Middle East respiratory syndrome coronavirus (MERS-CoV) in public health workers responding to a MERS outbreak in Seoul, Republic of Korea, in 2015. *Western Pac Surveill Response J* 2019; **10:** 46–48.

66 Scales DC, Green K, Chan AK, et al. Illness in intensive care staff after brief exposure to severe acute respiratory syndrome. *Emerg Infect Dis* 2003; **9:** 1205–10.

67 Seto WH, Tsang D, Yung RWH, et al. Effectiveness of precautions against droplets and contact in prevention of nosocomial transmission of severe acute respiratory syndrome (SARS). *Lancet* 2003; **361:** 1519–20.

68 Teleman MD, Boudville IC, Heng BH, Zhu D, Leo YS. Factors associated with transmission of severe acute respiratory syndrome among health-care workers in Singapore. *Epidemiol Infect* 2004; **132:** 797–803.

69 Tuan PA, Horby P, Dinh PN, et al. SARS transmission in Vietnam outside of the health-care setting. *Epidemiol Infect* 2007; **135:** 392–401.

70 Wang Q, Huang X, Bai Y, et al. Epidemiological characteristics of COVID-19 in medical staff members of neurosurgery departments in Hubei province: a multicentre descriptive study. *medRxiv* 2020; published online April 24. DOI:10.1101/2020.04.20.20064899 (preprint).

71 Wiboonchutikul S, Manosuthi W, Likanonsakul S, et al. Lack of transmission among healthcare workers in contact with a case of Middle East respiratory syndrome coronavirus infection in Thailand. *Antimicrob Resist Infect Control* 2016; **5:** 21.

72 Wilder-Smith A, Teleman MD, Heng BH, Earnest A, Ling AE, Leo YS. Asymptomatic SARS coronavirus infection among healthcare workers, Singapore. *Emerg Infect Dis* 2005; **11:** 1142–45.

73 Wong TW, Lee CK, Tam W, et al. Cluster of SARS among medical students exposed to single patient, Hong Kong. *Emerg Infect Dis* 2004; **10:** 269–76.

74 Wu J, Xu F, Zhou W, et al. Risk factors for SARS among persons without known contact with SARS patients, Beijing, China. *Emerg Infect Dis* 2004; **10:** 210–16.

75 Yin WW, Gao LD, Lin WS, et al. Effectiveness of personal protective measures in prevention of nosocomial transmission of severe acute respiratory syndrome. *Zhonghua Liu Xing Bing Xue Za Zhi* 2004; **25:** 18–22.

76 Yu ITS, Wong TW, Chiu YL, Lee N, Li Y. Temporal-spatial analysis of severe acute respiratory syndrome among hospital inpatients. *Clin Infect Dis* 2005; **40:** 1237–43.

77 Yu IT, Xie ZH, Tsoi KK, et al. Why did outbreaks of severe acute respiratory syndrome occur in some hospital wards but not in others? *Clin Infect Dis* 2007; **44:** 1017–25.

78 Verbeek JH, Rajamaki B, Ijaz S, et al. Personal protective equipment for preventing highly infectious diseases due to exposure to contaminated body fluids in healthcare staff. *Cochrane Database Syst Rev* 2019; **7:** CD011621.

79 MacIntyre CR, Wang Q, Seale H, et al. A randomized clinical trial of three options for N95 respirators and medical masks in health workers. *Am J Respir Crit Care Med* 2013; **187:** 960–66.

80 Campbell A. Chapter eight: it's not about the mask: SARS Commission final report, volume 3. December, 2006. http://www.archives.gov.on.ca/en/e_records/sars/report/v3-pdf/Vol3Chp8.pdf (accessed May 12, 2020).

81 Webster P. Ontario issues final SARS Commission report. *Lancet* 2007; **369:** 264.

82 Rimmer A. COVID-19: experts question guidance to reuse PPE. *BMJ* 2020; **369:** m1577.

83 Mackenzie D. Reuse of N95 masks. *Engineering* 2020; published online April 13. DOI:10.1016/j.eng.2020.04.003.

84 Greenhalgh T, Schmid MB, Czypionka T, Bassler D, Gruer L. Face masks for the public during the covid-19 crisis. *BMJ* 2020; **369:** m1435.

85 Bahl P, Doolan C, de Silva C, Chughtai AA, Bourouiba L, MacIntyre CR. Airborne or droplet precautions for health workers treating coronavirus disease 2019? *J Infect Dis* 2020; published online April 16. DOI:10.1093/infdis/jiaa189.

86 Schünemann HJ, Khabsa J, Solo K, et al. Ventilation techniques and risk for transmission of coronavirus disease, including COVID-19: a living systematic review of multiple streams of evidence. *Ann Intern Med* 2020; published online May 22. DOI:10.7326/M20-2306.

87 Leung NHL, Chu DKW, Shiu EYC, et al. Respiratory virus shedding in exhaled breath and efficacy of face masks. *Nat Med* 2020; **26:** 676–80.

Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Journal of Infection xxx (xxxx) xxx

Contents lists available at ScienceDirect

Journal of Infection

journal homepage: www.elsevier.com/locate/jinf

The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2

Vincent Chi-Chung Cheng[a,b], Shuk-Ching Wong[b], Vivien Wai-Man Chuang[c], Simon Yung-Chun So[a], Jonathan Hon-Kwan Chen[a], Siddharth Sridhar[d], Kelvin Kai-Wang To[d], Jasper Fuk-Woo Chan[d], Ivan Fan-Ngai Hung[e], Pak-Leung Ho[d], Kwok-Yung Yuen[d,*]

[a] Department of Microbiology, Queen Mary Hospital, Hong Kong Special Administrative Region, China
[b] Infection Control Team, Queen Mary Hospital, Hong Kong West Cluster, Hong Kong Special Administrative Region, China
[c] Quality & Safety Division (Infection, Emergency, and Contingency), Hospital Authority, Hong Kong Special Administrative Region, China
[d] Department of Microbiology, Li Ka Shing Faculty of Medicine, The University of Hong Kong, Hong Kong Special Administrative Region, China
[e] Department of Medicine, Li Ka Shing Faculty of Medicine, The University of Hong Kong, Hong Kong Special Administrative Region, China

ARTICLE INFO

Article history:
Accepted 17 April 2020
Available online xxx

Keywords:
Face mask
Community
Coronavirus
COVID-19
SARS-COV-2
Epidemic

SUMMARY

Background: Face mask usage by the healthy population in the community to reduce risk of transmission of respiratory viruses remains controversial. We assessed the effect of community-wide mask usage to control coronavirus disease 2019 (COVID-19) in Hong Kong Special Administrative Region (HKSAR).

Methods: Patients presenting with respiratory symptoms at outpatient clinics or hospital wards were screened for COVID-19 per protocol. Epidemiological analysis was performed for confirmed cases, especially persons acquiring COVID-19 during mask-off and mask-on settings. The incidence of COVID-19 per million population in HKSAR with community-wide masking was compared to that of non-mask-wearing countries which are comparable with HKSAR in terms of population density, healthcare system, BCG vaccination and social distancing measures but not community-wide masking. Compliance of face mask usage in the HKSAR community was monitored.

Findings: Within first 100 days (31 December 2019 to 8 April 2020), 961 COVID-19 patients were diagnosed in HKSAR. The COVID-19 incidence in HKSAR (129.0 per million population) was significantly lower ($p<0.001$) than that of Spain (2983.2), Italy (2250.8), Germany (1241.5), France (1151.6), U.S. (1102.8), U.K. (831.5), Singapore (259.8), and South Korea (200.5). The compliance of face mask usage by HKSAR general public was 96.6% (range: 95.7% to 97.2%). We observed 11 COVID-19 clusters in recreational 'mask-off' settings compared to only 3 in workplace 'mask-on' settings ($p=0.036$ by Chi square test of goodness-of-fit).

Conclusion: Community-wide mask wearing may contribute to the control of COVID-19 by reducing the amount of emission of infected saliva and respiratory droplets from individuals with subclinical or mild COVID-19.

Introduction

Coronavirus disease 2019 (COVID-19) due to severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which is closely related to bat SARS related coronaviruses,[1] is the second pandemic of the 21st century following the influenza A H1N1 pandemic of 2009. With the rapidly galloping epidemic due to globalization and international travel, World Health Organization (WHO) declared COVID-19 to be a pandemic on 11 March 2020,[2] which is 72 days after the first official announcement of clusters of patients with community-acquired pneumonia in Wuhan, Hubei Province of China on 31 December 2019 (day 1).[3] As of 8 April 2020 (day 100), over 1.35 million people have been infected worldwide with nearly 80,000 deaths.[4] In response, proactive infection control measures have been implemented in hospital settings.[5,6] In addition, non-pharmaceutical public health interventions including border control or closure, quarantine and testing of all incoming travelers or returnees, massive reverse-transcription polymerase chain reaction (RT-PCR) testing for case detection, rapid contact tracing and quarantine, frequent hand hygiene, and later social distancing measures

* Corresponding author.
E-mail address: kyyuen@hku.hk (K.-Y. Yuen).

https://doi.org/10.1016/j.jinf.2020.04.024
0163-4453/

including school closure, home office, cancelation of all mass gatherings, later stay-at-home order, and cessation of all socioeconomic activities except essential services, were also adopted to various degrees and at different time points in different geographical areas to reduce the risk of community transmission. Many of these measures had been used for the control of community transmission of severe acute respiratory syndrome (SARS) in 2003 and pandemic influenza A H1N1 in 2009 in Hong Kong Special Administrative Region of China (HKSAR) and other parts of the world.[7,8] However, the efficacy of community-wide masking of the population during these past epidemics or the present COVID-19 pandemic has not been clearly investigated. Unlike 2003 SARS which was generally manifested with high fever and progressive pneumonia with a mortality of about 10%, COVID-19 can be associated with very mild symptoms and a mortality of less than 4%. Thus subclinical or asymptomatic SARS-CoV-2 shedders may play an important role in perpetuating the pandemic.[9,10] We hypothesized that community-wide masking in HKSAR may break the chain of transmission of SARS-CoV-2 by reducing the infectiousness of the subclinical virus shedders while also offering some protection to the susceptible population.

In HKSAR, community-wide masking was practiced by the general population at an early stage of the local COVID-19 epidemic. Here, we described the comparative epidemiology of COVID-19 during the first 100 days. We also analyzed the incidence of COVID-19 in geographical areas with or without community-wide masking for most individuals, and also the number of COVID-19 clusters of COVID-19 in relation to workplace (mask-on setting) or non-workplace recreational settings (mask-off setting) of HKSAR.

Methods

Community control measures against COVID-19 in HKSAR

HKSAR is a cosmopolitan city of 7.45 million people in Southern China. Occupying only 1104 square-kilometers, it is the third most densely populated area in the world with around 6700 people per square-kilometer. Soon after the official announcement of a cluster of patients with community-acquired pneumonia in Wuhan by the National Health Commission of the People's Republic of China, on 31 December 2019 (day 1), the center for Health Protection (CHP) of the Department of Health, the HKSAR government alerted members of the public to maintain good personal and environmental hygiene, with specific emphasis on hand hygiene, refraining from work or attending class at school, avoiding crowded places, seek medical advice promptly and wear a surgical mask if they develop respiratory symptoms.[3] Step-wise introduction of other community interventions later to control the spread of COVID-19 was described. As an objective parameter of community-wide preparedness, compliance of face mask usage by the general public monitored by staff working in Infection Control Unit, and Department of Microbiology, Queen Mary Hospital for three consecutive days from 6 April to 8 April 2020 (day 98 to day 100). Each staff member would count the number of persons not wearing a mask among the first 50 persons encountered in the street during their morning commute. The residential district of the staff was recorded.

Epidemiology of COVID-19 in HKSAR

A multi-pronged screening strategy to identify patients infected with SARS-CoV-2 was implemented.[5,6] The epidemiology of newly confirmed cases was announced in the daily press conference jointly held by CHP and Hospital Authority. Major clusters arising from mask-on (workplace) and mask-off (recreational) settings were analyzed to evaluate the efficacy of wearing face masks.

Comparing the epidemiology of COVID-19 in HKSAR and other parts of the world

The epidemiology of COVID-19 of HKSAR was compared to that of the representative countries in North America, Europe, and Asia using publicly accessible information from the website of WHO to understand the overall effect of our control measures used in HKSAR. Countries with well-established healthcare system, where face mask usage was not universally adopted in the community, and having over 100 confirmed cases at day 72 when WHO declared a pandemic were selected for comparison.

Laboratory diagnosis of SARS-CoV-2

Clinical specimens including nasopharyngeal aspirates, nasopharyngeal swabs, throat swab, saliva, sputum, endotracheal aspirates, or bronchoalveolar lavage were subjected to nucleic acid extraction by the eMAG extraction system (bioMérieux, Marcy-l'Étoile France) as we previously described.[5,6] The presence of SARS-CoV-2 RNA in specimens was first determined by the Light-Mix Modular SebeccoV E-gene commercial kit (TIB Molbiol, Berlin, Germany) at all public hospitals under the Hospital Authority and the Public Health Laboratory Service of the Department of Health, and further confirmed by in-house real-time RT-PCR assay targeting the SARS-CoV-2 RNA-dependent RNA polymerase/helicase gene as described.[11]

Statistical analysis

Incidence rates were compared using the exact Poisson test using R software. Proportions were compared using the chi-squared test. A p value of <0.05 was considered statistically significant.

Results

Community response to COVID-19 in HKSAR

Due to the prior experience of the SARS outbreak in 2003, the general public of HKSAR was on high alert after the official announcement of a cluster of pneumonia cases of unknown etiology in Wuhan on 31 December 2019 (day 1), because a total of 1755 infected persons with 299 (17.0%) deaths over 133 days (11 February 2003 to 23 June 2003) was recorded during this past SARS epidemic. When the causative agent of COVID-19 was identified on 9 January 2020 (day 10), and named as SARS-CoV-2 on 12 February 2020 (day 44), this emerging pathogen was perceived to be as detrimental as 2003 SARS-CoV by the HKSAR general public. Even though initially HKSAR government only advocated people with respiratory symptoms to wear a surgical mask according to the recommendations of WHO and Centers for Disease Control and Prevention (CDC) of the United States, the general public volunteered to wear face mask quite compliantly from the pre-pandemic to pandemic phase of COVID-19.

Sixty-seven staff members (9 from Infection Control Unit, and 58 from Department of Microbiology), residing in all 18 administrative districts in HKSAR, recorded the number of persons not wearing face mask among the first 50 people they encountered during their morning commute to Queen Mary Hospital (located in Southern district) between 7:00am to 9:00am over three consecutive days from 6 April to 8 April 2020 (day 98 to day 100). A total of 10,050 persons were observed. Only 337 (3.4%) persons did not wear face mask. The daily compliance of face mask usage was 97.2%, 97.1%, and 95.7% over three consecutive days in all 18 administrative districts in HKSAR.

Besides proactive infection control measures implemented by public hospitals under the governance of Hospital Authority,[5,6]

Please cite this article as: V.C.-C. Cheng, S.-C. Wong and V.W.-M. Chuang et al., The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2, Journal of Infection, https://doi.org/10.1016/j.jinf.2020.04.024
ID-GOV-21-0012-A-000059

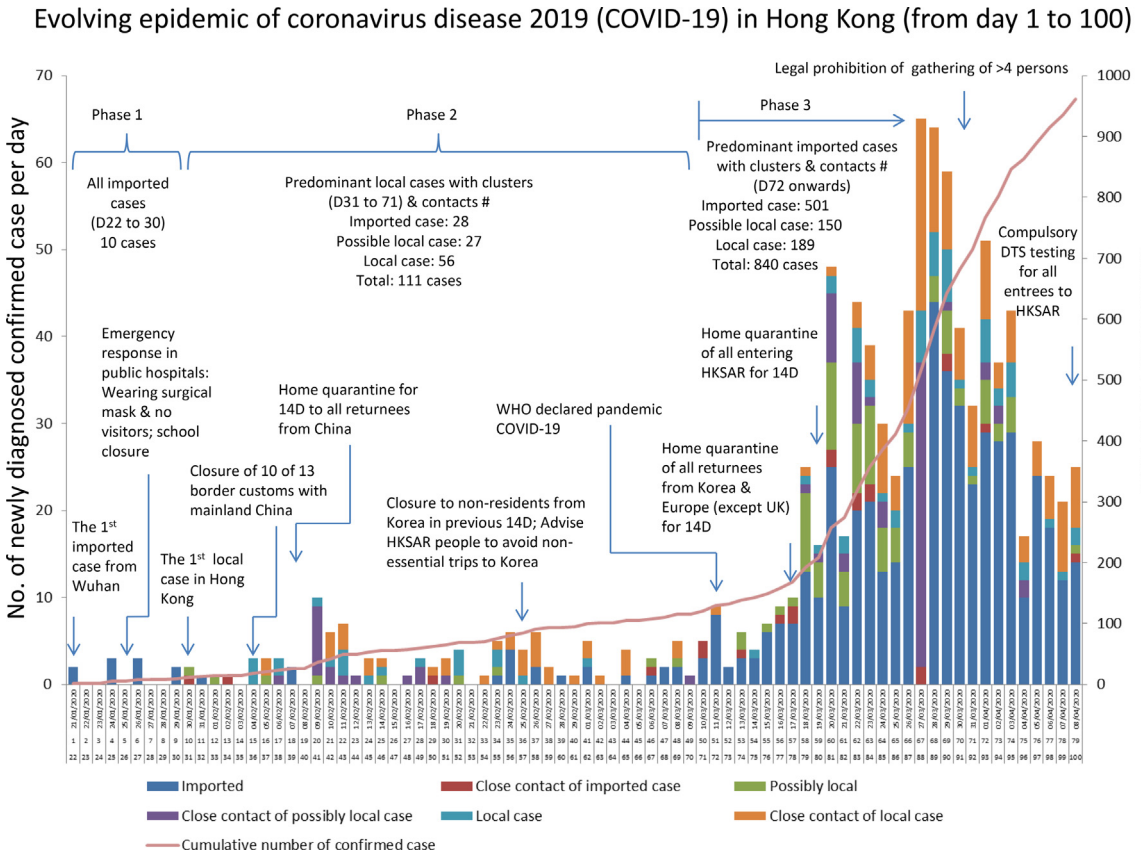


Fig. 1. Evolving epidemic of coronavirus disease 2019 (COVID-19) in Hong Kong (from day 1 to 100).
Note. #including their close contacts
COVID-19, coronavirus disease 2019; DTS, deep throat saliva; WHO, World Health Organization.

step-wise introduction of epidemiological measures by the HKSAR government were enforced. They included border controls to reduce imported SARS-CoV-2 cases from mainland China on 4 February 2020 (day 36). This was followed by imposing home quarantine order for 14 days to all entrees from mainland China on 8 February 2020 (day 40). Subsequently, the quarantine order was progressively imposed to all entrees into HKSAR on and after 19 March 2020 (day 80) (Fig. 1). All entrees were compulsorily tested for SARS-CoV-2 by collecting their posterior oropharyngeal saliva with effect from 8 April 2020 (day 100). As in other localities, isolation of confirmed case, contact tracing and quarantine, closure of affected or high risk premises, and social distancing measures such as home-office and school closure were instituted.

Epidemiology of COVID-19 in HKSAR

Up to day 100 of the epidemic, a total of 961 cases of COVID-19 were confirmed in HKSAR. Transmission of COVID-19 was divisible into four phases: phase 0 (from day 1 to 21) with no confirmed cases of COVID-19 in HKSAR; phase 1 (from day 22 to 30) with 10 imported cases; phase 2 (from day 31 to 71) with 111 cases (predominantly local cases) and; phase 3 (from day 72, WHO declared COVID-19 pandemic, onwards) with 840 cases (predominantly imported cases with local clusters of cases) (Fig. 1). Among the 961 confirmed cases, there were 11 clusters of 113 persons that were directly engaged in mask-off activities such as dining and drinking in restaurant or bar, singing at karaoke, and exercise in fitness clubs. There were only three clusters involving 11 persons engaged in mask-on settings at the workplace. Using the chi-square test of goodness-of-fit with Williams' continuity correction, there were significantly more COVID-19 clusters involving mask-off settings than might be expected assuming that the null hypothesis of equal number of clusters involving mask-on and mask-off settings was true ($p = 0.036$).

Comparing the epidemic progression of COVID-19 in HKSAR with other parts of the world

The incidence and cumulative number of COVID-19 cases in HKSAR and the representative countries or areas since the first laboratory-confirmed case of SARS-CoV-2 are illustrated in Fig. 2a& 2b. The incidence of COVID-19 in HKSAR was significantly less than that of the selected countries (with well-established healthcare system and having over 100 confirmed cases at day 72 when WHO declared a pandemic) in Asia, Europe, and North America, where face mask usage was not universally adopted in the community (Table 1). Singapore's land area and population density are comparable to HKSAR.[4] On day 100 (8 April 2020), the incidence of COVID-19 per million population in Singapore was significantly higher than that in HKSAR (259.8 per million population vs 129.0 per million population, $p < 0.001$) (Table 2). In South Korea, the number of molecular diagnostic tests per million population was comparable to HKSAR. The proportion of local cases in South Korea related to mask-off settings was significantly higher than that in HKSAR [5150/10,384 (49.6%) vs 113 / 961 (11.8%), $p < 0.001$] because of super-spreading events at a church which was also a mask-off setting (Table 2).

Discussion

Evidence for using face masks to prevent transmission of respiratory viruses in the community remains limited to a few stud-

Please cite this article as: V.C.-C. Cheng, S.-C. Wong and V.W.-M. Chuang et al., The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2, Journal of Infection, https://doi.org/10.1016/j.jinf.2020.04.024

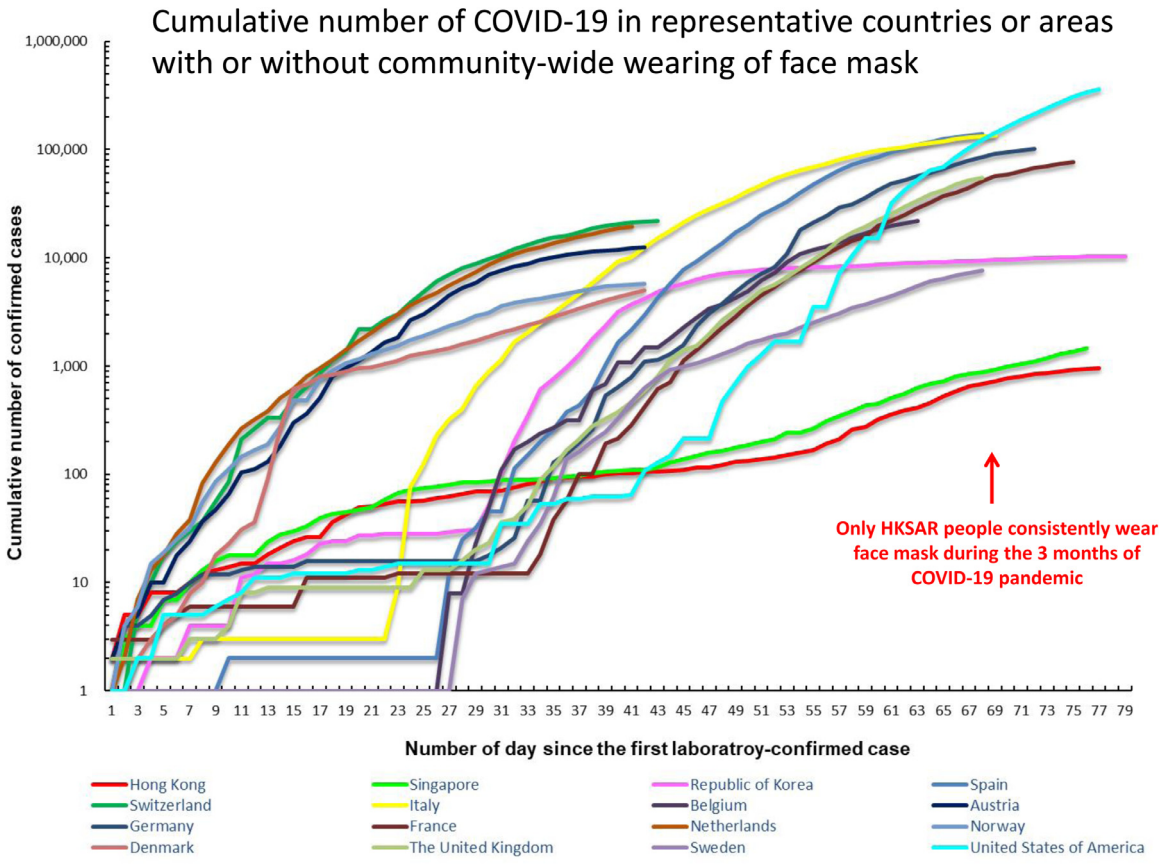


Fig. 2a. Cumulative number of COVID-19 in representative countries or areas with or without community-wide wearing of face mask
Note. The x-axis denotes the number of days since the first laboratory-confirmed case in the representative countries or areas.
The date of first laboratory-confirmed case in Hong Kong (21 January 2020), Singapore (24 January 2020), South Korea (21 January 2020), Spain (1 February 2020), Switzerland (26 February 2020), Italy (31 January 2020), Belgium (06 February 2020), Austria (27 February 2020), Germany (28 January 2020), France (25 January 2020), Netherlands (28 February 2020), Norway (27 February 2020), Denmark (27 February 2020), The United Kingdom (1 February 2020), Sweden (01 February 2020) and United States of America (23 January 2020).

ies conducted in the household setting.[12,13] Although there is no expert consensus on this issue, universal masking is voluntarily adopted by people in our HKSAR community soon after the first imported case of COVID-19 was reported. This public action was linked to the painful experience of the 2003 SARS outbreak (1755 cases with 299 deaths in 6.73 million population) when HKSAR people adopted universal masking in addition to other non-pharmaceutical interventions such as hand hygiene, social distancing and school closure.[7] These community hygienic measures during the SARS outbreak resulted in a significant reduction of positive specimens of all circulating respiratory viruses including influenza viruses in 2003 compared with preceding periods.[14] In a case-control study conducted in Beijing during 2003 SARS, consistent wearing of a face mask outdoors was associated with a 70% risk reduction, compared to those not wearing a face mask.[15]

HKSAR is the only area practicing universal masking despite the recommendation of WHO and CDC that mask should be reserved for those with symptoms and in healthcare settings. We therefore compared the number of COVID-19 clusters in mask-on settings at workplace with that of the mask-off settings such as dining and drinking in restaurant or bar, singing at karaoke, and exercising in gymnasium, where there was a large gathering of people sharing food, drinks, and instruments. In effect, these mask-off settings allowed the sharing of their saliva and respiratory droplets, which may contain a viral load of 100 million per ml, directly or indirectly.[16,17] In HKSAR hospitals, wearing face masks is mandatory during the pandemic. It is also the practice among many community service providers and those who are working indoors. Since the supply of face mask was tight in the community as well as in the healthcare setting, it is the practice of our general public not to use more than one face mask per person per day. We observed that the overall compliance of face mask usage was 97% in all administrative districts in the morning. Thus we have the reason to believe that their compliance to face mask usage would remain high throughout the day at the workplace. It is therefore not surprising that the number of COVID-19 clusters was significantly higher in the mask-off recreational settings in HKSAR.

Universal masking in the community may mitigate the extent of transmission of COVID-19 and may be a necessary adjunctive public health measure in a densely populated city like HKSAR, with an average of 170,000 people entering HKSAR from Mainland and overseas per day.[18] Our incidence of COVID-19 was also lower than that of other areas with local transmission, vindicating this approach. In particular, our incidence of COVID-19 was significantly lower than that of Singapore, a city comparable with HKSAR in terms of area, population density, healthcare infrastructure, BCG vaccination,[19] as well as adopting social distancing strategies and SARS-CoV-2 testing infrastructure.[20] Besides a lower ambient temperature and a higher risk of importation of COVID-19 cases from the mainland which are factors promoting COVID-19 transmission in HKSAR, the most important difference between the two cities is the community-wide usage of face masks in HKSAR but not in Singapore. Moreover, 50% of local transmission of COVID-19 in South Korea was attributed to religious activities where face mask usage

Please cite this article as: V.C.-C. Cheng, S.-C. Wong and V.W.-M. Chuang et al., The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2, Journal of Infection, https://doi.org/10.1016/j.jinf.2020.04.024

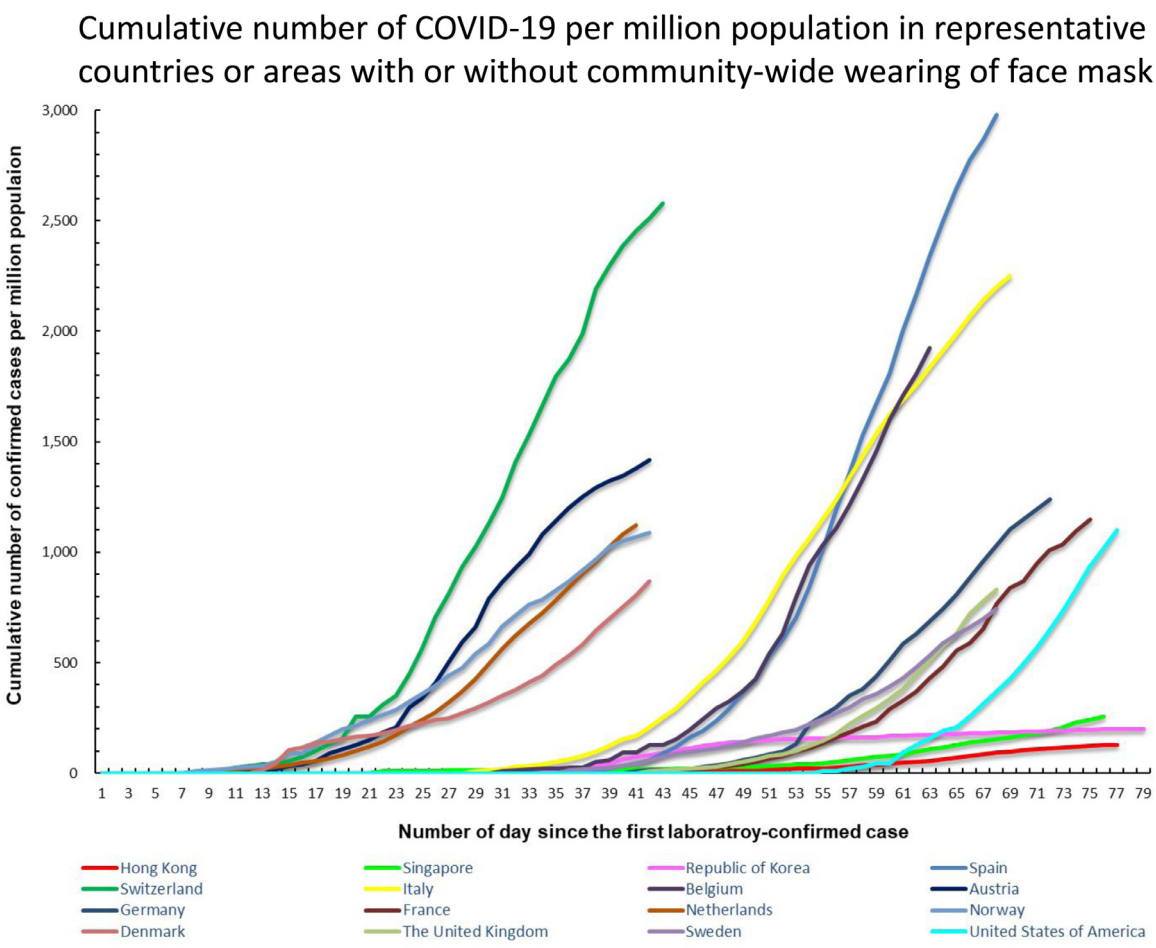


Fig. 2b. Cumulative number of COVID-19 per million population in representative countries or areas with or without community-wide wearing of face mask
Note. The x-axis denotes the number of day since the first laboratory-confirmed case in the representative countries or areas.
The date of first laboratory-confirmed case in Hong Kong (21 January 2020), Singapore (24 January 2020), South Korea (21 January 2020), Spain (1 February 2020), Switzerland (26 February 2020), Italy (31 January 2020), Belgium (06 February 2020), Austria (27 February 2020), Germany (28 January 2020), France (25 January 2020), Netherlands (28 February 2020), Norway (27 February 2020), Denmark (27 February 2020), The United Kingdom (1 February 2020), Sweden (01 February 2020) and United States of America (23 January 2020).

was discouraged. Mask-off activities clearly have potential implications for COVID-19 transmission in the community.

However, the use of face mask in the community remains controversial.[21,22] WHO issued an interim guideline regarding the use of masks in the context of COVID-19 on 6 April 2020, stating no evidence that wearing a mask by healthy persons in the wider community setting can prevent acquisition of COVID-19.[23] European Centre for Disease Prevention and Control issued a technical report on 8 April 2020 that the use of face masks in the community could be considered, especially when visiting busy, closed spaces, despite not knowing how much the use of masks in the community can contribute to a decrease in transmission in addition to the other counter measures.[24] On 3 April 2020, CDC recommended the use of cloth face coverings, especially in areas of significant community-based transmission.[25] The shift of paradigm from not recommending to promoting the use of face masks was based on the rationale of pre-symptomatic shedding of SARS-Cov-2 and presence of asymptomatic patients with high viral load in the community.[9,26] The use of face mask may serve as source control by preventing dispersal of droplets during talking, sneezing, and coughing,[27] and also reduce the risk of environmental contamination by SARS-CoV-2. Despite some supporters of WHO recommendation speaking against universal masking in our local medical community, most opinion leaders in the clinical microbiology and infectious disease specialties of HKSAR openly championed this measure for the control of community transmission of COVID-19.[28] Masking is a continuous form of protection to stop the spreading of saliva and respiratory droplets to others or from others, and to the environment or from the environment to the susceptible by hands through touching of nose, mouth and eye. Touching nose and mouth is a subconscious behavior.[29] Hand hygiene is always the cornerstone to prevent transmission of COVID-19 but it is a one-off discontinuous process where hand contamination may occur easily between each alcoholic handrubbing or hand washing. Although we have successfully implemented directly observed hand hygiene (DOHH) by regular delivery of alcohol-based hand rub to conscious hospitalized patients and persons in residential care homes for the elderly before meal and medication rounds,[30–32] it may be difficult to practice DOHH in the community. Studies have also shown that wearing a mask with frequent hand hygiene significantly reduced transmission of seasonal influenza virus in the community setting. But once the effect of the use of surgical mask was removed, the effect of hand hygiene became insignificant.[33] With the understanding that the supply of face masks should primarily be reserved for usage in healthcare settings, we believe that it is still advisable to encourage people to wear face masks in the public based on the precautionary principles.[34] Moreover, wearing a cloth mask with less filtration efficiency may still be better than no mask at all in communities of high transmission.

Please cite this article as: V.C.-C. Cheng, S.-C. Wong and V.W.-M. Chuang et al., The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2, Journal of Infection, https://doi.org/10.1016/j.jinf.2020.04.024

Table 1
Incidence of coronavirus disease 2019 (COVID-19) infection in Hong Kong Special Administrative Region (HKSAR) as compared with that of selected countries as of 8 April 2020 (at day 100 after official announcement of pneumonia outbreak in Wuhan, Hubei Province, China)[a].

Countries or city	Population (million)[b]	Cumulative number of confirmed case[c]	Number (percentage) of death	Incidence per million population[d]	P value (incidence compared with HKSAR)	Population density: population per km^2 (rank in the world)[e]
Hong Kong SAR[f]	7.45	961	4 (0.4%)	129.0	Not applicable	6782 (3rd)
Western Pacific Region						
Singapore	5.70	1,481	6 (0.4%)	259.8	$P<0.001$	7894 (2nd)
South Korea	51.78	10,384	200 (1.9%)	200.5	$P<0.001$	517 (13th)
European Region						
Spain	47.10	140,510	13,798 (9.8%)	2,983.2	$P<0.001$	93 (89th)
Switzerland	8.59	22,164	641 (2.9%)	2,580.2	$P<0.001$	208 (48th)
Italy	60.24	135,586	17,129 (12.6%)	2,250.8	$P<0.001$	200 (51st)
Belgium	11.52	22,194	2,035 (9.2%)	1,926.6	$P<0.001$	376 (22nd)
Austria	8.90	12,640	243 (1.9%)	1,420.2	$P<0.001$	106 (76th)
Germany	83.15	103,228	1,861 (1.8%)	1,241.5	$P<0.001$	233 (41st)
France	67.06	77,226	10,313 (13.4%)	1,151.6	$P<0.001$	123 (68th)
Netherlands	17.44	19,580	2,101 (10.7%)	1,122.7	$P<0.001$	420 (16th)
Norway	5.37	5,863	69 (1.7%)	1,091.8	$P<0.001$	17 (171st)
Denmark	5.82	5,071	203 (4.0%)	871.3	$P<0.001$	135 (64th)
The United Kingdom	66.44	55,246	6,159 (11.1%)	831.5	$P<0.001$	274 (32nd)
Sweden	10.33	7,693	591 (7.7%)	744.7	$P<0.001$	23 (159th)
Region of Americas						
United States of America	329.45	363,321	10,845 (3.0%)	1,102.8	$P<0.001$	34 (145th)

[a] Developed countries with well-established healthcare system and reached more than 100 confirmed cases at day 72 (WHO declare pandemic COVID-19) were selected for comparison.
[b] The population of country or city were retrieved from the website of World Health Organization.
[c] Infection retrieved from situation report - 79 of World Health Organization issued on 8 April 2020 (day 100 after the official announcement of clusters of community-acquired pneumonia in Wuhan, Hubei Province, China.
[d] The sequence of countries was listed as descending order in accordance with the incidence of COVID-19 per million population.
[e] Information retrieved from Wikipedia - List of countries and dependencies by population density. https://en.wikipedia.org/wiki/List_of_countries_and_dependencies_by_population_density (Accessed 12 April 2020).
[f] The number of confirmed case was based on the official announcement daily by HKSAR, China.

Table 2
Comparison of the epidemiology and community responses against coronavirus disease 2019 (COVID-19) in Hong Kong SAR, Singapore, and South Korea.

Epidemiology parameter as of 8 April 2020	Hong Kong SAR	Singapore	South Korea
Total number of confirmed case	961	1,481	10,384
Number of imported cases	517 (53.8%)	567 (38.3%)[a]	NM
Number of RT-PCR performed per million population	~15,000	~12,800[b]	~9,900[c]
Number of local cases related to mask-off setting (i.e. religious activities, dining and drinking in restaurant or bar, singing at karaoke, and exercise in gymnasium)	113 (11.8%)	NM	5150 (49.6%)[c,d]
Number of local cases related to family (other than mask-off setting described above)	41 (4.3%)	NM	NM
Number of local cases related to mask-on setting (i.e. workplace)	11 (1.4%)	NM	NM
Date of border restrictions	25 March 2020[e]	23 March 2020, 2359[f]	1 April 2020[g]
Average of ambient temperature range in the first 100 days of COVID-19 transmission	18 °C to 22 °C[h]	24 °C to 31 °C[i]	1 °C to 9 °C[j]
Routine childhood BCG immunization program[k]	Yes	Yes	Yes

Note. NM, not mentioned.
[a] Daily report on COVID-19. Minister of Health, Singapore. https://www.moh.gov.sg/docs/librariesprovider5/local-situation-report/situation-report-1-apr-2020.pdf. Accessed 12 April 2020.
[b] Information obtained from Minister of Health, Singapore. https://www.moh.gov.sg/covid-19. Accessed 12 April 2020.
[c] Information obtained from Coronavirus Disease-19, Republic of Korea. http://ncov.mohw.go.kr/en/. Accessed 12 April 2020.
[d] These patients were all related to a cohort of participants involving in religious activities - wearing face masks was discouraged. These were the believer of Olive Tree, a Christian new religious movement, originally known as Jesus Christ Congregation Revival Association of Korea, founded in Republic of Korea by Park Tae Son. https://en.wikipedia.org/wiki/Olive_Tree_(religious_movement). Accessed 12 April 2020.
[e] Deny entry of non-Hong Kong resident.
[f] All short-term visitors (from anywhere in the world) will not be allowed to enter or transit through Singapore.
[g] All passengers are subject to mandatory self-quarantine for 14 days, except for airline crew. https://en.wikipedia.org/wiki/Travel_restrictions_related_to_the_2019%E2%80%9320_coronavirus_pandemic. Accessed 12 April 2020.
[h] https://www.hko.gov.hk/en/wxinfo/pastwx/mws/mws.htm. Accessed 12 April 2020.
[i] https://www.climatestotravel.com/climate/singapore. Accessed 12 April 2020.
[j] https://www.climatestotravel.com/climate/south-korea. Accessed 12 April 2020.
[k] There is postulation of countries with BCG vaccination program tends to have lower incidence and death due to COVID-19[19].

SARS-CoV-2 is a highly transmissible respiratory virus which causes upper and lower respiratory tract infection leading to a high viral load in respiratory secretions and saliva as shown in clinical studies and transmission studies by close contact in animal models.[35] Moreover, SARS-CoV-2 can suppress the host innate immune response in terms of interferon and cytokine response which in turn leads to a higher level of viral replication than that by the 2003 SARS-CoV in an *ex vivo* lung tissue explant model.[10] These *ex vivo* findings supported the suggestion that an important proportion of COVID-19 patients may be pre-symptomatic or mildly symptomatic virus shedders. These groups of patients are unlikely to be tested or isolated and may contribute to the perpetuation of

Please cite this article as: V.C.-C. Cheng, S.-C. Wong and V.W.-M. Chuang et al., The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2, Journal of Infection, https://doi.org/10.1016/j.jinf.2020.04.024

the pandemic. Therefore community-wide mask usage irrespective of symptoms may reduce the infectivity of these silent COVID-19 cases to the susceptible individuals.

There are several limitations in our study. First, we did not analyze the mask-off settings in the family because the modes of transmission among close household contacts can be more diverse. If the 15 family clusters were also counted within the mask-off settings, the difference would be even more significant ($p<0.001$). Second, the type of mask used in the community cannot be controlled. The compliance of wearing face mask in terms of not touching the external surface of mask or face, and hand hygiene before or after touching the mask cannot be assessed. Third, we cannot count the mask compliance directly for every community settings. Nevertheless, in the absence of effective antiviral and vaccines, the pandemic spread COVID-19 to many countries provide an unique opportunity to study the effectiveness of this non-pharmaceutical control measures. As of 27 February 2020 (day 38 since the first reported case in South Korea), South Korea government has started to distribute face masks to the public amid the outbreak of the COVID-19,[36] which was associated with a flattening of the epidemic curve. As of 14 April 2020 (day 82 since the first reported case in Singapore), Singapore government has started to enforce a penalty of 300 Singapore dollar for anyone going out from home without a mask.[37] Further studies on this important non-pharmaceutical control measure are warranted. In order to live with emerging infectious diseases and seasonal influenza epidemics, every individual should have personalized reusable mask, gown, and gloves made of self-disinfecting fabrics, and even reusable anti-fog face shield within their own set of Epidemic Combat Kit for their personal protection.

Financial support

This work was supported in part by the Consultancy Service for Enhancing Laboratory Surveillance of Emerging Infectious Diseases of the Department of Health, Hong Kong Special Administrative Region; and the Collaborative Innovation Center for Diagnosis and Treatment of Infectious Diseases, the Ministry of Education of China.

Declaration of Competing Interest

All authors report no conflicts of interest relevant to this article.

Acknowledgement

We thank colleagues of Hospital Authority and Department of Health for facilitating this study.

References

1. Chan JF, Kok KH, Zhu Z, Chu H, To KK, Yuan S, et al. Genomic characterization of the 2019 novel human-pathogenic coronavirus isolated from a patient with atypical pneumonia after visiting Wuhan. *Emerg Microbes Infect* 2020;**9**:221–36.
2. WHO Director-General's opening remarks at the media briefing on COVID-19 - 11 March 2020. 2020. https://www.who.int/dg/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19-11-march-2020 Accessed 10 April 2020.
3. The Centre for health protection closely monitors cluster of pneumonia cases on Mainland. Press release of the department of health, Hong Kong Special Administrative Region. 2019. https://www.info.gov.hk/gia/general/201912/31/P2019123100667.htm Accessed 10 April 2020.
4. Coronavirus disease 2019 (COVID-19). Situation Report – 79. World Health Organization. 2020. https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200408-sitrep-79-covid-19.pdf?sfvrsn=4796b143_6 Accessed 10 April 2020.
5. Cheng VCC, Wong SC, To KKW, Ho PL, Yuen KY. Preparedness and proactive infection control measures against the emerging novel coronavirus in China. *J Hosp Infect* 2020;**104**:254–5.
6. Cheng VCC, Wong SC, Chen JHK, Yip CCY, Chuang VWM, Tsang OTY, et al. Escalating infection control response to the rapidly evolving epidemiology of the coronavirus disease 2019 (COVID-19) due to SARS-CoV-2 in Hong Kong. *Infect Control Hosp Epidemiol* 2020:1–6.
7. Cheng VC, Lau SK, Woo PC, Yuen KY. Severe acute respiratory syndrome coronavirus as an agent of emerging and reemerging infection. *Clin Microbiol Rev* 2007;**20**:660–94.
8. Cheng VC, To KK, Tse H, Hung IF, Yuen KY. Two years after pandemic influenza A/2009/H1N1: what have we learned? *Clin Microbiol Rev* 2012;**25**:223–63.
9. Chan JF, Yuan S, Kok KH, To KK, Chu H, Yang J, et al. A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission: a study of a family cluster. *Lancet* 2020;**395**:514–23.
10. Chu H, Chan JF, Wang Y, Yuen TT, Chai Y, Hou Y, et al. Comparative replication and immune activation profiles of SARS-CoV-2 and SARS-CoV in human lungs: an ex vivo study with implications for the pathogenesis of COVID-19. *Clin Infect Dis* 2020.
11. Chan JF, Yip CC, To KK, Tang TH, Wong SC, Leung KH, et al. Improved molecular diagnosis of COVID-19 by the novel, highly sensitive and specific COVID-19-RdRp/Hel real-time reverse transcription-polymerase chain reaction assay validated in vitro and with clinical specimens. *J Clin Microbiol* 2020.
12. MacIntyre CR, Cauchemez S, Dwyer DE, Seale H, Cheung P, Browne G, et al. Face mask use and control of respiratory virus transmission in households. *Emerg Infect Dis* 2009;**15**:233–41.
13. Cowling BJ, Chan KH, Fang VJ, Cheng CK, Fung RO, Wai W, et al. Facemasks and hand hygiene to prevent influenza transmission in households: a cluster randomized trial. *Ann Intern Med* 2009;**151**:437–46.
14. Lo JY, Tsang TH, Leung YH, Yeung EY, Wu T, Lim WW. Respiratory infections during SARS outbreak, Hong Kong, 2003. *Emerg Infect Dis* 2005;**11**:1738–41.
15. Wu J, Xu F, Zhou W, Feikin DR, Lin CY, He X, et al. Risk factors for SARS among persons without known contact with SARS patients, Beijing, China. *Emerg Infect Dis* 2004;**10**:210–16.
16. To KK, Tsang OT, Chik-Yan Yip C, Chan KH, Wu TC, Chan JMC, et al. Consistent detection of 2019 novel coronavirus in saliva. *Clin Infect Dis* 2020.
17. To KK, Tsang OT, Leung WS, Tam AR, Wu TC, Lung DC, 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* 2020.
18. Hong Kong in figures. Census and Statistics Department. Hong Kong Special Administrative Region. 2020. https://www.statistics.gov.hk/pub/B10100062020AN20B0100.pdf. Accessed 24 April 2020.
19. Gursel M, Gursel I. Is global BCG vaccination coverage relevant to the progression of SARS-CoV-2 pandemic? *Med Hypothesis* 2020.
20. Updates on COVID-19 (Coronavirus disease 2019) local situation. Ministry of Health, Singapore. 2020. https://www.moh.gov.sg/covid-19 Accessed 12 April 2020.
21. Chan KH, Yuen KY. COVID-19 epidemic: disentangling the re-emerging controversy about medical facemasks from an epidemiological perspective. *Int J Epidemiol* 2020.
22. Feng S, Shen C, Xia N, Song W, Fan M, Cowling BJ. Rational use of face masks in the COVID-19 pandemic. *Lancet Respir Med* 2020.
23. World Health Organization. Advice on the use of masks in the context of COVID-19. Interim guidance (6 April 2020). https://apps.who.int/iris/bitstream/handle/10665/331693/WHO-2019-nCov-IPC_Masks-2020.3-eng.pdf?sequence=1&isAllowed=y Accessed 10 April 2020.
24. Using face masks in the community - Reducing COVID-19 transmission from potentially asymptomatic or pre-symptomatic people through the use of face masks. 2020. https://www.ecdc.europa.eu/en/publications-data/using-face-masks-community-reducing-covid-19-transmission Accessed 10 April 2020.
25. Centers for Disease Control and Prevention. Coronavirus disease 2019 (COVID-19). Recommendation regarding the use of cloth face coverings, especially in areas of significant community-based transmission. 2020. https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/cloth-face-cover.html Accessed 10 April 2020
26. Zou L, Ruan F, Huang M, Liang L, Huang H, Hong Z, et al. SARS-CoV-2 viral load in upper respiratory specimens of infected patients. *N Engl J Med* 2020;**382**:1177–9.
27. Hui DS, Chow BK, Chu L, Ng SS, Lee N, Gin T, et al. Exhaled air dispersion during coughing with and without wearing a surgical or N95 mask. *PLoS ONE* 2012;**7**:e50845.
28. Chan ALY, Leung CC, Lam TH, Cheng KK. To wear or not to wear: WHO's confusing guidance on masks in the covid-19 pandemic. *BMJ opinion* 2020. https://blogs.bmj.com/bmj/2020/03/11/whos-confusing-guidance-masks-covid-19-epidemic/. Accessed 24 April 2020
29. Hendley JO, Wenzel RP, Gwaltney JM Jr. Transmission of rhinovirus colds by self-inoculation. *N Engl J Med* 1973;**288**:1361–4.
30. Cheng VC, Tai JW, Li WS, Chau PH, So SY, Wong LM, et al. Implementation of directly observed patient hand hygiene for hospitalized patients by hand hygiene ambassadors in Hong Kong. *Am J Infect Control* 2016;**44**:621–4.
31. Cheng VCC, Wong SC, Wong SCY, Yuen KY. Directly observed hand hygiene - from healthcare workers to patients. *J Hosp Infect* 2019;**101**:380–2.
32. Cheng VCC, Chen H, Wong SC, Chen JHK, Ng WC, So SYC, et al. Role of hand hygiene ambassador and implementation of directly observed hand hygiene among residents in residential care homes for the elderly in Hong Kong. *Infect Control Hosp Epidemiol* 2018;**39**:571–7.

Please cite this article as: V.C.-C. Cheng, S.-C. Wong and V.W.-M. Chuang et al., The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2, Journal of Infection, https://doi.org/10.1016/j.jinf.2020.04.024

33. Wong VW, Cowling BJ, Aiello AE. Hand hygiene and risk of influenza virus infections in the community: a systematic review and meta-analysis. *Epidemiol Infect* 2014;**142**:922–32.
34. Greenhalgh T, Schmid MB, Czypionka T, Bassler D, Gruer L. Face masks for the public during the covid-19 crisis. *BMJ* 2020;**369**:m1435.
35. Chan JF, Zhang AJ, Yuan S, Poon VK, Chan CC, Lee AC, et al. Simulation of the clinical and pathological manifestations of coronavirus disease 2019 (COVID-19) in golden Syrian hamster model: implications for disease pathogenesis and transmissibility. *Clin Infect Dis* 2020.
36. South Korea takes new measures to have enough face masks domestically amid coronavirus. abc News. 2020. https://abcnews.go.com/International/south-korea-takes-measures-face-masks-domestically-amid/story?id=69254114 Accessed 16 April 2020.
37. Mandatory for all in Singapore to wear mask when out, except for kids under 2 and those doing strenuous exercise. Straits Times. 2020. https://www.straitstimes.com/singapore/coronavirus-mandatory-for-all-to-wear-a-mask-when-out-with-exceptions-for-kids-under-2-and Accessed 16 April 2020.

Please cite this article as: V.C.-C. Cheng, S.-C. Wong and V.W.-M. Chuang et al., The role of community-wide wearing of face mask for control of coronavirus disease 2019 (COVID-19) epidemic due to SARS-CoV-2, Journal of Infection, https://doi.org/10.1016/j.jinf.2020.04.024

Universal Masking is Urgent in the COVID-19 Pandemic: SEIR and Agent Based Models, Empirical Validation, Policy Recommendations

De Kai PhD MBA
HKUST (University of Science & Technology), Hong Kong
International Computer Science Institute, Berkeley, CA, USA
dekai@cs.ust.hk dekai@icsi.berkeley.edu
@dekai123 http://dek.ai

Guy-Philippe Goldstein MBA
Ecole de Guerre Economique, Paris, France
guyphilippeg@gmail.com
@guypgoldstein

Alexey Morgunov
University of Cambridge, UK
Manifold Research, Cambridge, UK
asm63@cam.ac.uk alexey@manifoldresearch.com
@AlexeyMorgunov

Vishal Nangalia PhD MBChB FRCA
University College London, UK
ELU AI Ltd, London, UK
Royal Free Hospital, London, UK
vishal.nangalia@gmail.com
@v_alien

Anna Rotkirch PhD
Population Research Institute, The Family Federation of Finland
anna.rotkirch@vaestoliitto.fi
@AnnaRotkirch https://blogs.helsiki.fi/rotkirch

21 April 2020

Abstract

We present two models for the COVID-19 pandemic predicting the impact of universal face mask wearing upon the spread of the SARS-CoV-2 virusone employing a stochastic dynamic network based compartmental SEIR (susceptible-exposed-infectious-recovered) approach, and the other employing individual ABM (agent-based modelling) Monte Carlo simulationindicating (1) significant impact under (near) universal masking when at least 80% of a population is wearing masks, versus minimal impact when only 50% or less of the population is wearing masks, and (2) significant impact when universal masking is adopted early, by Day 50 of a regional outbreak, versus minimal impact when universal masking is adopted late. These effects hold even at the lower filtering rates of homemade masks. To validate these theoretical models, we compare their predictions against a new empirical data set we have collected that includes whether regions have universal masking cultures or policies, their daily case growth rates, and their percentage reduction from peak daily case growth rates. Results show a near perfect correlation between early universal masking and successful suppression of daily case growth rates and/or reduction from peak daily case growth rates, as predicted by our theoretical simulations.

Taken in tandem, our theoretical models and empirical results argue for urgent implementation of universal masking in regions that have not yet adopted it as policy or

*This collective work grew out of a Kinnernet discussion group about COVID-19 initiated by Guy-Philippe Goldstein. All authors contributed to the overall design and writing. Additionally, Goldstein formulated overall study goals and analysed policy data, Morgunov ran the SEIR simulation and collected policy data, De Kai created the online interactive ABM simulation, Nangalia contributed with medical expertise and to the model design, and Rotkirch and De Kai first drafted the report.

as a broad cultural norm. As governments plan how to exit societal lockdowns, universal masking is emerging as one of the key NPIs (non-pharmaceutical interventions) for containing or slowing the spread of the pandemic. Combined with other NPIs including social distancing and mass contact tracing, a "mouth-and-nose lockdown" is far more sustainable than a "full body lockdown", from economic, social, and mental health standpoints. To provide both policy makers and the public with a more concrete feel for how masks impact the dynamics of virus spread, we are making an interactive visualization of the ABM simulation available online at http://dek.ai/masks4all. We recommend immediate mask wearing recommendations, official guidelines for correct use, and awareness campaigns to shift masking mindsets away from pure self-protection, towards aspirational goals of responsibly protecting one's community.

1 Introduction

With almost all of the world's countries having imposed measures of social distancing and restrictions on movement in March 2020 to combat the COVID-19 pandemic, governments now seek a sustainable pathway back towards eased social restrictions and a functioning economy. Mass testing for infection and serological tests for immunity, combined with mass contact tracing, quarantine of infected individuals, and social distancing, are recommended by the WHO and have become widely acknowledged means of controlling spread of the SARS-CoV-2 virus until a vaccine is available.

Against this backdrop, a growing number of voices suggest that universal face mask wearing, as practiced effectively in most East Asian regions, is an additional, essential component in the mitigation toolkit for a sustainable exit from harsh lockdowns. The masks-for-all argument claims that "test, trace, isolate" should be expanded to "test, trace, isolate, mask". This paper presents cross-disciplinary, multi-perspective arguments for the urgency of universal masking, via both new theoretical models and new empirical data analyses. Specifically, we aim to illustrate how different degrees of mass face wearing affects infection rates, and why the timing of introduction of universal masking is crucial.

In the first of two new theoretical models, we introduce an SEIR (susceptible-exposed-infectious-recovered) model of the effects of mass face mask wearing over time compared to effects of social distancing and lockdown. In the second of two new theoretical models, we introduce a new interactive individual ABM (agent-based modelling) Monte Carlo simulation showing how masking significantly lowers rates of transmission. Both models predict significant reduction in the daily growth of infections on average under universal masking (80-90% of the population) if instituted by day 50 of an outbreak, but not if only 50% of the population wear masks or if institution of universal masking is delayed.

We then compare the two new simulations presented here against a new empirical data set we have collected that includes whether regions have universal masking cultures or policies, their daily case growth rates, and their percentage reduction from peak daily case growth rates. Since little precise quantitative data is available on cultures where masking is prevalent, we explain in some depth the historical and sociological factors that support our classification of masking cultures. Results show a near perfect correlation between early universal masking and successful suppression of daily case growth rates and/or reduction from peak daily case growth rates, as predicted by our theoretical simulations.

To preview the key policy recommendations that our two new SEIR and ABM predictive models and empirical validation all lead to:

1. Masking should be mandatory or strongly recommended for the general public when in public transport and public spaces, for the duration of the pandemic.

2. Masking should be mandatory for individuals in essential functions (health care workers, social and family workers, the police and the military, the service sector, construction workers, etc.) and medical masks and gloves or equally safe protection should be provided to them by employers. Cloth masks should be used if medical masks are unavailable.

3. Countries should aim to eventually secure mass production and availability of appropriate medical masks (without exploratory valves) for the entire population during the pandemic.

ID-GOV-21-0012-A-000067

4. Until supplies are sufficient, members of the general public should wear nonmedical fabric face masks when going out in public and medical masks should be reserved for essential functions.

5. The authorities should issue masking guidelines to residents and companies regarding the correct and optimal ways to make, wear and disinfect masks.

6. The introduction of mandatory masking will benefit from being rolled out together with campaigns, citizen initiatives, the media, NGOs, and influencers in order to avoid a public backlash in societies not culturally accustomed to masking. Public awareness is needed that "masking protects your communitynot just you".

2 Background

Masks indisputably protect individuals against airborne transmission of respiratory diseases. A recent Cochrane meta-analysis found that masking, handwashing, and using gowns and/or gloves can reduce the spread of respiratory viruses, although evidence for any individual one of these measures is still of low certainty (Burch and Bunt, 2020). Currently, the lowest recorded daily growth rates in COVID-19 infections appear to be found in countries with a culture of mass face mask wearing, most of whom have also made mask wearing in public mandatory during the epidemic, and most of whom are not currently locked downan observation that we study systematically in section 5.

Outside of East Asia, support for universal masking is emerging elsewhere across the globe. The Czech Republic was the first non-Asian country to embrace and impose mandatory universal masking on March 11, 2020. The Czech policy swiftly inspired various initiatives from citizens, journalists and scientistse.g., De Kai (2020), Howard and Fast.ai team (2020), Manjoo (2020), Abaluck *et al.* (2020), Feng *et al.* (2020), Fineberg (2020), Tufekci (2020)and created global movements such as #masks4all and #wearafuckingmask. Their arguments build on the ability of the COVID-19 virus to spread from pre- and asymptomatic individuals who may not know that they are infected, and to linger in airborne droplets.

Leading political and medical experts who early were advocated masking included Chinese CDC director-general Prof. George Fu Gao (Servick, 2020), former FDA commissioner Scott Gottlieb and Prof. Caitlin Rivers of Johns Hopkins (Gottlieb and Rivers, 2020), and the American Enterprise Institute's roadmap (Gottlieb *et al.*, 2020).

In early April 2020 a rapidly increasing number of governments from countries without a previous culture of mask wearing require or recommend universal masking including the Czech Republic, Austria and Slovakia. Additionally, public health bodies in the USA, Germany, France (Acadmie nationale de mdecine, 2020) and New Zealand have moved toward universal masking recommendations (Morgunov *et al.*, 2020), as shown below in Figure 6.

The World Health Organization (2019) previously issued guidelines discouraging the use of masks in the public. However in early April 2020 the World Health Organization (2020) modified the guidelines, allowing self-made masks but rightly stressing the need to reserve medical masks for healthcare workers (Nebehay and Shalal, 2020), and to combine masking with the other main NPI needed to combat the pandemic. The policy shifts of the WHO and other CDCs reflect advances in our scientific understanding of this pandemic, and help legitimise the altruistic "mask resistance" of civil society in this global effort against COVID-19.

3 SEIR modelling of universal masking impact

In the first of our two new theoretical models, we employed stochastic dynamic network based compartmental SEIR modeling to forecast the relative impact of masking compared to the two main other societal non-pharmaceutical interventions, lockdown, and social distancing.

The SEIR simulations were fit to the current timeline in many Western countries, with a lockdown imposed March the 24th (day 1) and planned to be lifted on May 31st. Universal masking is introduced in April. The simulation continues for 500 days from day 0, or around 17 months.

The experimental results strongly support the need for

universal masking as an alternative to continued lockdown scenarios. For this strategy to be most effective, the vast majority of the population must adopt mask wearing immediately, as most regions outside East Asia are rapidly approaching Day 50.

In a SEIR model, the population is divided into compartments which represent different states with respect to disease progression of an individual: susceptible (S), exposed (E), infectious (I) and recovered (R). A susceptible individual may become exposed if they interact with an infectious individual at rate β (rate of transmission per S- I contact per time). From E , the individual progresses to being infectious (I) and eventually recovered (R) with rates σ (rate of progression) and γ (rate of recovery), respectively. Additionally, individuals in I are removed from the population (i.e., die of the disease) at rate μ_I (rate of mortality).

We used a SEIR model implemented[1] on a stochastic dynamical network that more closely mimics interactions between individuals in society, instead of assuming uniform mixing as is the case with deterministic SEIR models. Furthermore, such approach allows setting different model parameters for each individual, which we use to model masking. In a network model, a graph of society is built with nodes representing individuals and edgestheir interactions. Each node has a state S, E, I, R, or F (the latter added to represent dead individuals). Adjacent nodes form close contact networks of an individual, while contacts made with an individual from anywhere in the network represent global contacts in the population. Varying the parameters affecting the two levels of interaction, as well as setting network properties such as the mean number of adjacent nodes ("close contacts") allows us to model the degree of social distancing and lockdown measures.

Formally, each node i is associated with a state X_i which is updated based on the following probability transition rates:

$$\Pr(X_i = S \to E) = [p\frac{\beta I}{N} + (1-p)\frac{\beta \sum_{j \in C_G(i)} \delta_{X_j=i}}{|C_G(i)|}]\delta_{X_i=S} \quad (1)$$

$$\Pr(X_i = E \to I) = \sigma \delta_{X_i=E} \quad (2)$$

$$\Pr(X_i = I \to R) = \gamma \delta_{X_i=I} \quad (3)$$

$$\Pr(X_i = I \to F) = \mu_I \delta_{X_i=I} \quad (4)$$

where $\delta_{X_i=A} = 1$ if the state of X_i is A , or 0 if not, and where $C_G(i)$ denotes the set of close contacts of node i .

3.1 Experimental model

We implemented SEIR dynamics on a stochastic dynamic network with a heterogeneous population. We assumed an initial infected population of 1% and modelled the assumed effects of social distancing, lockdown, and universal masking over time on the rates of infection in the population.

All SEIR models were built using the SEIRS+ modelling tool[2], version 0.0.14. The baseline model parameters are fit to the empirical characteristics of COVID-19 spread, as documented in the SEIRS+ distributed COVID-19 notebooks. Specifically, we set $\beta = 0.155$, $\sigma = 1/5.2$ and $\gamma = 1/12.39$. This parameterisation describes a SEIR model with best estimates for COVID-19 dynamics.

The initial infected population (init_i) was set to 1%, and all others to 0%. The size of the total population was set to 67,000 (a representative typical case, that is a factor of 1,000 from the population of the UK).

Social distancing. In the model, social distancing was defined as the degree distribution of the contact network of an individual. Default interaction networks were used, constructed as Barabasi-Albert graphs with $m = 9$ and processes using the package function custom_exponential_graph with different scale parameters. Normal graph (scale=100) with mean degree 13.2, distancing graph (scale=10) with mean degree 4.1 and lockdown graph (scale=5) with mean degree 2.2.

Lockdown stringency. Lockdown stringency was modelled considering no stringent lockdown (i.e. only

[1] https://github.com/ryansmcgee/seirsplus

[2] https://github.com/ryansmcgee/seirsplus

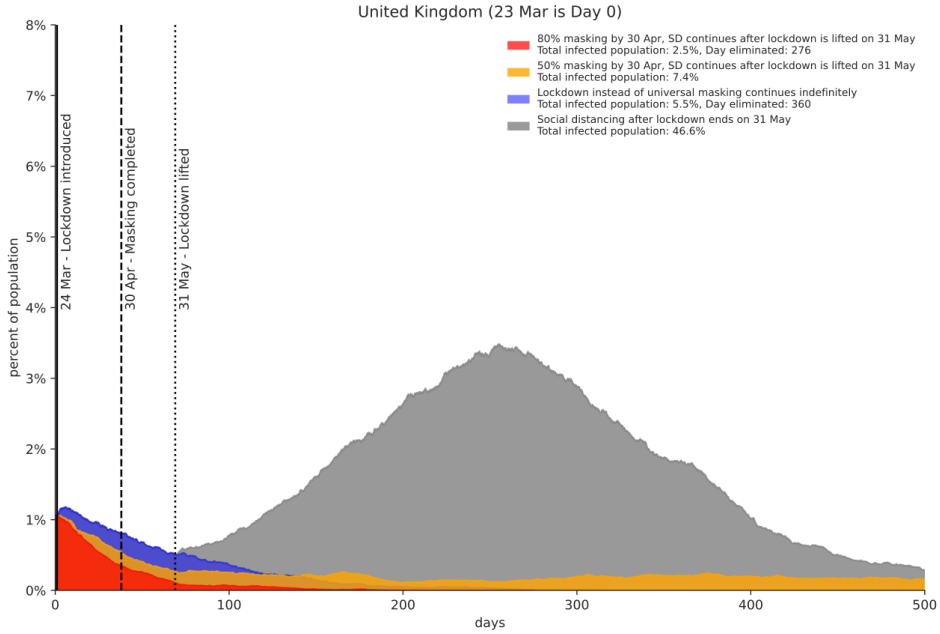


Figure 1: Simulation results for a representative scenario: universal masking at 80% adoption (red) flattens the curve significantly more than maintaining a strict lockdown (blue). Masking at only 50% adoption (orange) is not sufficient to prevent continued spread. Replacing the strict lockdown with social distancing on May 31 without masking results in unchecked spread.

social distancing) or stringent lockdown using the locality parameter p, which was set to 0.02 during lockdown and 0.2 during social distancing phases. This dictates the probability of individuals coming into contact with those outside of their immediate network. Assuming that individuals have around 13 contacts in normal everyday life, social distancing will reduce this to 4 and lockdown to only 2.

Mask wearing. A gradual increase in *mask wearing* was modelled using a linear increase in the proportion of individuals randomly allocated with a reduced rate of transmission. The factor by which β was reduced was conservatively set to 2. The period of time over which the mask wearing went from 0 to maximum % was set to 10 days. 50% and 80% maximum values were considered.

Date fitting. The progression in the number of deaths was used to fit the model to an approximate calendar date representing Day 0. For the representative typical case of the UK, this corresponded to Mar 23.

3.2 Experimental results

Figure 1 shows the simulation results for a representative scenario: universal masking at 80% adoption (red) flattens the curve significantly more than maintaining a strict lockdown (blue). Masking at only 50% adoption (orange) is not sufficient to prevent continued spread. Replacing the strict lockdown with social distancing on May 31 without masking results in unchecked spread.

Our model suggests a substantial impact of universal

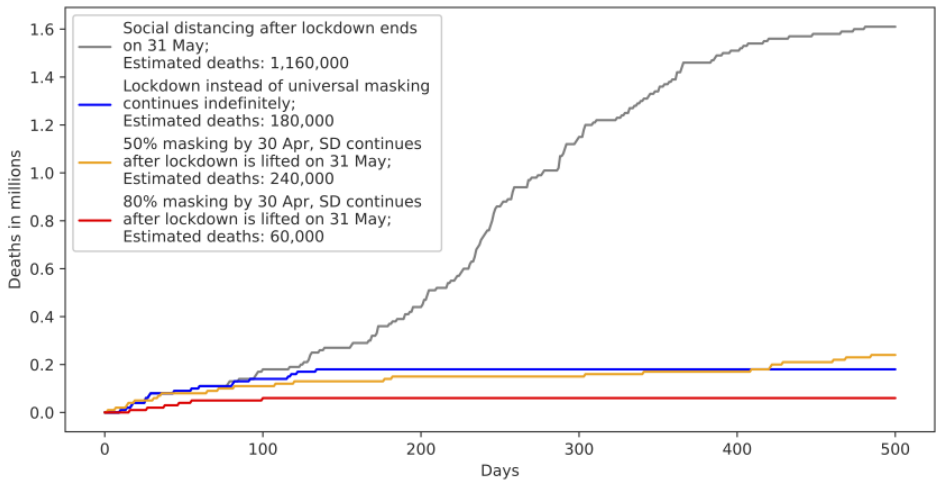


Figure 2: Simulation results for a representative scenario: universal masking at 80% adoption (red) results in 60,000 deaths, compared to maintaining a strict lockdown (blue) which results in 180,000 deaths. Masking at only a 50% adoption rate (orange) is not sufficient to prevent continued spread and eventually results in 240,000 deaths. Replacing the strict lockdown with social distancing on May 31 without masking results in unchecked spread.

masking. Without masking, but even with continued social distancing in place once the lockdown is lifted, the infection rate will increase and almost half of the population will become affected. This scenario, rendered in grey in Figure 1, would potentially lead to over a million deaths in a population the size of the UK. A continued lockdown, illustrated in blue colour, does eventually result in bringing the disease under control after around 6 months. However, the economic and social costs of a "full body lockdown" will be enormous, which strongly supports finding an alternative solution.

In the model, social distancing and masking at both 50% and 80% of the populationbut no lockdown beyond the end of Mayresult in substantial reduction of infection, with 80% masking eventually eliminating the disease. Figure 2 shows the simulation results for a representative scenario: universal masking at 80% adoption (red) results in 60,000 deaths, compared to maintaining a strict lockdown (blue) which results in 180,000 deaths. Masking at only a 50% adoption rate (orange) is not sufficient to prevent continued spread and eventually results in 240,000 deaths. Replacing the strict lockdown with social distancing on May 31 without masking results in unchecked spread.

4 Agent based modelling of universal masking impact

In the second of our two new theoretical models, we employed stochastic individual agent based modelling (ABM) as an alternative Monte Carlo simulation technique for understanding the impact of universal masking. Agent based models have roots in various disciplines. A stochastic agent program can be defined as a agent function $f : \mathbf{p} \rightarrow \Pr(a)$ which maps possible *percept* vectors to a probabilistic distribution over possible *actions* (or to states that influence subsequent actions). In AI, Russell and Norvig (2009) summarise five classes of intelligent agents: simple reflex agents, model-based reflex agents, goal-based agents, utility-based agents, and learning agents; note, however, that agents may also be sus-

ceptible to *imperceptible* environmental factors such as viruses. Holland and Miller (1991) discuss artificial adaptive agents for modeling complex systems in economics. Bonabeau (2002) surveys agent based models for simulating human systems.

As in other disciplines, ABM approaches in epidemiology (see, e.g., Hunter *et al.* (2017). Tracy *et al.* (2018), or Hunter *et al.* (2018)) have several advantages compared to compartmental models which group undifferentiated individuals into large aggregates (like in the above SEIR simulation). First, because the behavior and characteristics of each agent is independent, they can simulate complex dynamic systems with less oversimplification of rich variation among individuals. Second, because agents can be simulated in physical two- or three-dimensional spaces, they can better simulate the geometry of contact between individuals, which is highly relevant in epidemiology. Third, the randomization on each run makes the statistical *variance* more apparent than in the SIR family of models, whose smooth curves often misleadingly convey more certainty than warranted. Fourth, ABMs lend themselves well to visualization, as seen in Figure 5, which helps convey the non-linear behavior of complex dynamic systemsan especially relevant advantage when the exponential effect of masking can be counterintuitive in many cultures due to pre-existing cultural biases (Leung, 2020) and unconscious cognitive biases (De Kai, 2020).

4.1 Mask characteristics

The ABM approach allows us to put masks on individual agents and to assign properties to those masks, to shed light on the question of how face maskseven nonmedical cloth maskscarry the promise to be so surprisingly effective. The objective is to examine how even a small barrier to individual infection transmission can multiply into a substantial effect on the level of communities and populations.

Face masks work in two ways: They can protect an infected person from spreading the virus (transmission), and they can limit how much the non-infected individual is exposed to the virus (absorption). Traditionally, masks are worn to protect the wearer from being infected by an ill person when in close and prolonged contact. In such classic situations, for instance in hospitals and elderly homes, only medical masks combined with other protective equipment provide protection. Comparing different mask materials, medical masks have been found to be up to three times more effective in blocking transmission compared to homemade masks (Davies *et al.*, 2013). Surgical masks most efficaciously reduce the emission of influenza virus particles into the environment in respiratory droplets. Still, although masks vary greatly in their ability to protect, using any type of face mask (without an exploratory valve) can help decrease viral transmission (Sande *et al.*, 2008).

However, the effect of universal masking does not require full protection from disease to be effective in lowering infection rates of COVID-19. Masks may be especially crucial for containing the COVID-19 pandemic, since many infections appear to come from people with no signs of illness. For instance, around 48% of COVID-19 transmissions were pre-symptomatic in Singapore and 62% in Tianjin, China (Ganyani *et al.*, 2020). This suggests that masking needs to be universal and not restricted to individuals who think they may be infected.

Furthermore, the SARS-CoV-2 virus is known to spread through airborne particles (Leung *et al.*, 2020) and quite possibly via aerosolised droplets as well according to Service (2020), van Doremalen *et al.* (2020), Santarpia *et al.* (2020), and Liu *et al.* (2020). It may linger in the air for and travel several meters, which is why social distancing rules require at least 2 meters between individuals to be effective.

4.2 Experimental model

As a contrastive baseline we employed a compartmental SEIR model with the same parameters as given for our SEIR experiments of section 3.

For the new agent based model, we implemented an environment consisting of a square wraparound two-dimensional space, within which a population of individual agents reside in four states: susceptible (S), exposed (E), infectious (I) and recovered (R). The wraparound space means that agents who move outside a border reenter the square from the opposite side. As in our SEIR models, the initial infected population (init_i) was set to 1%, and all others to 0%. The size of the total population was set to 200, but the wraparound feature of the two-dimensional space in effect represents arbitrarily larger

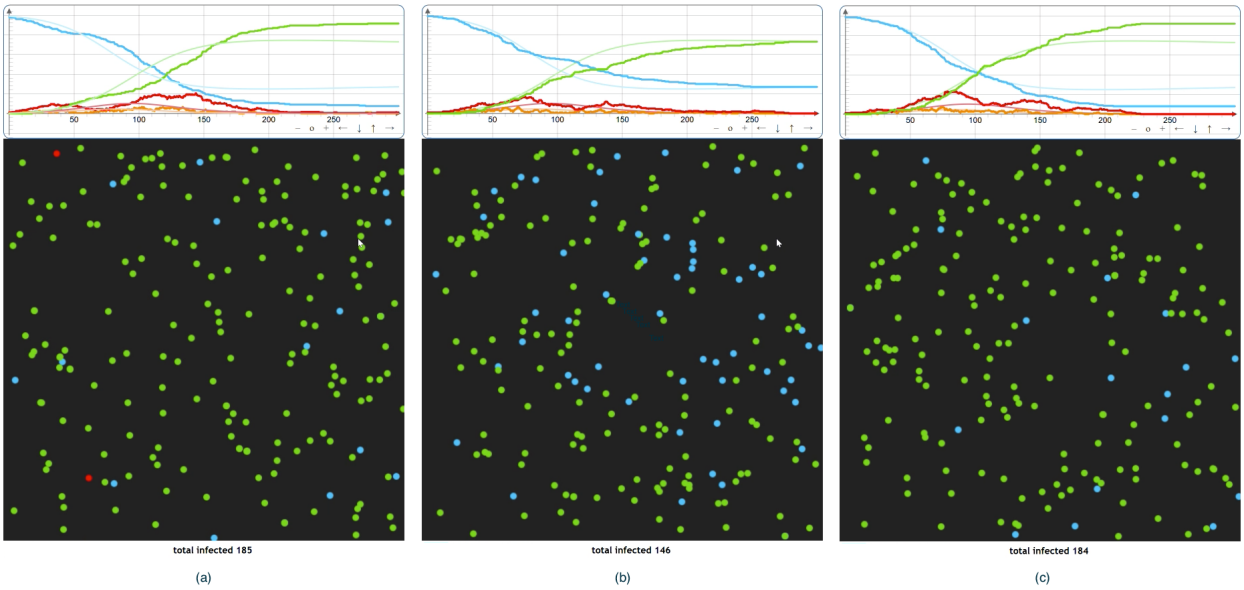


Figure 3: Three successive randomised runs of the agent based model for 300 days, with no mask wearing. Blue is susceptible, orange is exposed, red is infected, and green is recovered. The contrastive SEIR baseline model's predicted curves are shown in thinner, fainter lines. The ABM runs produce curves with a fine granularity of randomisation, centering on average around the ODE based SEIR curves.

spaces that are approximated by replicated square tiles, thus giving more accurate dynamics without boundary effects from small spaces.

To best fit the same empirical characteristics of COVID-19 spread as our SEIR models, we again set $\sigma = 1/5.2$ and $\gamma = 1/12.39$. Note that β is inapplicable in the ABM since infection transmission between individuals arises from physical proximity, which is more realistic than randomly infecting other individuals anywhere with some probability β with no regard to their physical location. In the baseline Monte Carlo simulation, agents decide on a random destination location within a parameterised radius of their current point, then proceed at a parameterised speed to move there, and then repeat the process iteratively. We adjusted such ABM-specific parameters, as well as physical exposure distance, to optimise fit to the baseline SEIR model curves, assuming none of the population to be wearing masks. Again, this was done so as to best approximate known COVID-19 dynamics.

ABM runs were for 300 days from the onset of the outbreak since empirically, the emergent SEIR curves stabilise before the 300th day.

To model the impact of masking, the following masking parameters can be varied:

Mask wearing. Gradual increases (or decreases) in *mask wearing* can be modelled using parameterised rates of masking M(or unmasking U) in the proportion of unmasked (or masked) individuals. The parameters m_{min} and m_{max} also allow modelling the minimum and maximum absolute numbers of masked agents. These masking parameters can be dynamically adjusted any time during any ABM run, to simulate varying policy decisions and cultural mindset shifts.

Mask characteristics. Varying degrees of mask effectiveness are modelled by the *mask transmission rate* T and *mask absorption rate* A, which denote the proportion of viruses that are stopped by the mask during exhaling (transmission) versus inhaling (absorption), respectively. We set $T = 0.7$ and $A = 0.7$ to model the use of inexpensive, widely available, and even nonmedical or homemade

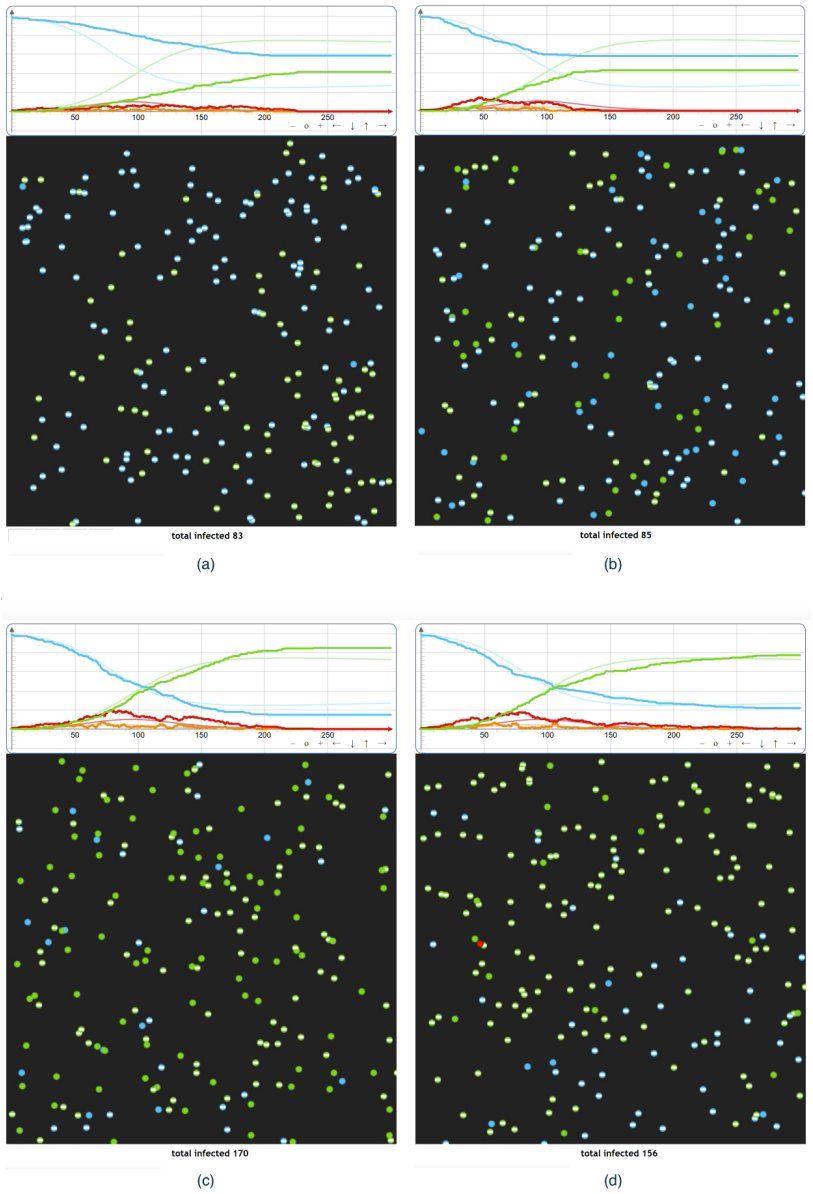


Figure 4: Four ABM runs under varying masking scenarios. (a) 100% of the population wearing masks from the onset of the outbreak, with excellent suppression of infection spread. (b) 0% of the population initially wearing masks, but instituting near universal masking of 90% of the population at day 50, still with significant suppression of infection spread. (c) 0% of the population initially wearing masks, and instituting some masking of 50% of the population at day 50, with not much impact on infection spread. (d) 0% of the population initially wearing masks, but instituting near universal masking of 90% of the population at day 75 with not much impact on infection spread.

masks with only 70% effectiveness for universal masking, and not higher quality N95, N99, N100, FFP1, FFP2, or FFP3 masks which in many regions need to be reserved for medical staff.

4.3 Experimental results

ABM simulation shows that universal masking can significantly reduce virus spread if adopted sufficiently early, even if the masks are nonmedical or homemade.

Figure 3 shows three successive runs for the baseline $m = 0$ case with zero mask adoption. Each dot (which is in motion during simulation runs) represents an individual agent, who may become exposed to the virus through proximity to other agents who are infectious. Blue dots are healthy susceptible agents, orange dots are exposed agents, red dots are infected agents, and green dots are recovered agents. A dot with a white rectangle on it represents an agent who is wearing a mask.

The three baseline ABM runs show how chance plays a significant role in the dynamics of virus spread. Since each simulation run is randomised, to decrease variance requires observation over multiple runs. On average, the baseline case with zero mask adoption adheres to the simpler SEIR model's predicted curves.

Figure 4 compares typical runs for four scenarios that simulate how COVID-19 spreads among individual agents under different masking scenarios, with the contrastive baseline SEIR model curves shown in thin lines as a reference: (a) $m_0 = 100\%$ meaning that the entire population adopts mask at the onset of the outbreak on day 0; (b) $m_0 = 0\%, m_{50} = 90\%$ meaning that none of the population is wearing masks at the onset but that nearly universal masking is instituted on day 50; and (c) $m_0 = 0\%$,$m_{50} = 50\%$ meaning that none of the population is wearing masks at the onset but that half of the population adopts masks on day 50, and (d) $m_0 = 0\%, m_{75} = 90\%$ meaning that none of the population is wearing masks at the onset but that nearly universal masking is instituted on day 75.

In scenario (a), a dramatic decrease in the number of infections is evident as a result of universal masking at the onset of the outbreak. Unfortunately, most regions outside East Asia missed the time window for scenario (a).

In scenario (b), even though the population is not initially wearing masks, if universal masking is instituted by day 50, good chances of dramatic suppression of infection rates can still be achieved. Fortunately, this option is within reach of most regions at the time of writing.

In scenario (c), again the population is not initially wearing masks. On day 50, half the population dons masks, but unlike scenario (b) which succeeds with 90% universal masking, unfortunately 50% is an insufficient level of mask adoption to suppress infection rates to a significant degree.

In scenario (d), the population again is not initially wearing masks, but unlike scenario (b) the 90% universal masking is not instituted until day 75, instead of day 50. Waiting too long unfortunately greatly decreases the degree to which infection rates can be suppressed.

To help policy makers and the general public gain a more concrete feel for how masks impact the dynamics of virus spread, we have made available online[3] an interactive visualisation tool for the ABM simulation model, as shown in Figure 5. The default view allows direct adjustment in real time of the percentage of masked individual agents through a slider control. Optional advanced controls allow playing with various scenarios: whether masking is used, the adoption rate of masking, virus transmission and absorption rates through masks of varying quality, as well as other modelling parameters such as the initial numbers of susceptible, exposed, infected, or recovered agents, and the contrastive baseline SEIR model parameters.

5 Evaluation of model predictions against empirical data on universal masking impact

For validation of the foregoing SEIR and ABM predictive models it is necessary to compare against what little historical macro scale empirical data is available, since precise numbers are not yet known for masking rates, mask transmission and absorption rates, and infectious but asymptomatic cases.

[3] http://dek.ai/masks4all

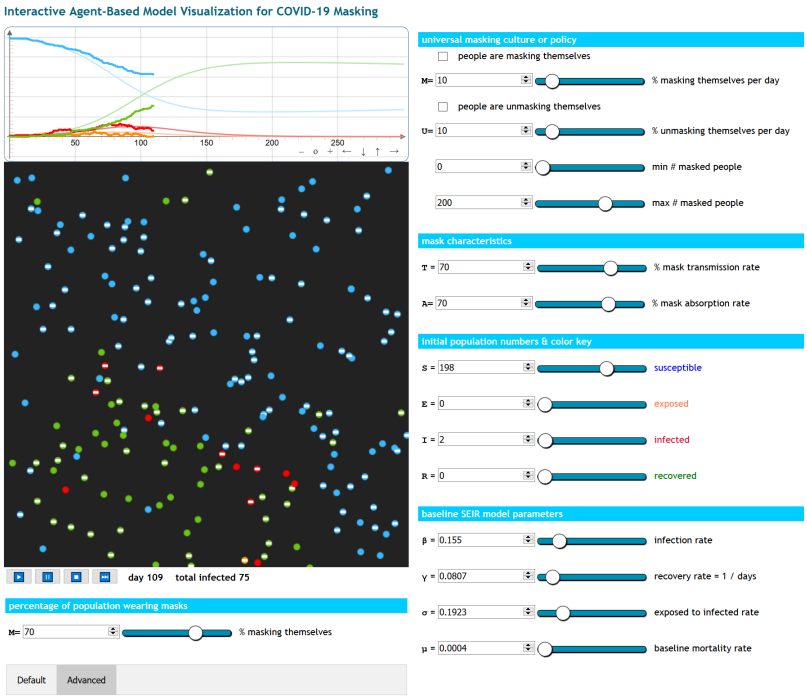


Figure 5: Interactive visualisation tool for the ABM simulation model to help policy makers and the general public gain a more concrete feel for how masks impact the dynamics of virus spread, available online at http://dek.ai/masks4all.

5.1 Validation data set

We collected a new data set describing the degree of success in managing COVID-19 by countries or regions segmented by the prevalence or enforcement of universal masking. The data set covers (a) a selection of 38 countries or provinces in Asia, Europe and North America that have similar, high levels of economic development (based on World Bank GDP purchasing power parity per capita), (b) detected COVID-19 cases from Jan 23 to April 10, 2020, and (c) characteristics of universal masking culture and/or universal masking orders or recommendations by governments.

5.2 Feature extraction

From our data set's 38 selected countries, we computed (a) the daily growth of confirmed cases, as well as (b) reduction from peak of new cases. Sorted in increasing order of the daily growth, Figure 6 presents these figures alongside features extracted from our data set denoting each country or region's (c) masking culture, (d) universal masking policy, and (c) lockdown policy. Additional clarification on definitions of a couple of these features follow.

Masking culture is defined as an established practice by a significant section of the general population to wear face masks prior to the start of the Covid-19 pandemic. A cursory review of the scientific literature and the general press has identified Japan, Thailand, Vietnam (Burgess and Horii, 2012), China's urban centers (Kuo, 2014), Hong Kong (Cowling *et al.*, 2020), Taiwan, Singapore and South Korea (Yang (2014), Jennings (2020)) as countries with such a consistent practice, at least in the decade predating the Covid-19 pandemic. Nevertheless, the notion of "culture" should not imply that the practice of face mask wearing has been extensive and consistent throughout time. For example, though this practice

Country or region	Daily growth	Reduction from peak	Masking culture?	Universal masking (date made mandatory or recommended)	Strict lockdown (mass home quarantine)
Macau	2.4%	96.0%	yes	Feb 19	
Beijing	3.6%	98.5%	yes	Feb 8	partial
Shanghai	3.7%	83.6%	yes	Feb 8	partial
Guangdong	5.0%	95.8%	yes	Feb 8	partial
Hong Kong	5.5%	69.8%	yes	Jan 15	
Taiwan	5.6%	85.0%	yes	Jan 27	
Singapore	6.8%	23.5%	yes	Jan 30 (sick) Apr 5 (all)	partial
Japan	9.1%	24.5%	yes	Mar 4	partial
Estonia	10.0%	69.4%			
Slovakia	11.3%	29.9%		Mar 24	
S Korea	11.6%	94.4%	yes	Feb 27	
Slovenia	12.0%	46.0%		Mar 19	
Malaysia	13.1%	38.2%			Mar 18
Australia	13.9%	77.7%			Mar 23
Finland	14.2%	27.3%			Mar 27
Hungary	14.3%	26.5%			Mar 28
Norway	14.5%	61.0%			Mar 12
Lithuania	15.5%	46.0%			Mar 16
Sweden	15.9%	17.2%			
Denmark	16.2%	20.3%			Mar 11
CZ	16.6%	36.8%		Mar 18	Mar 16
Israel	17.0%	54.9%			
Austria	17.0%	70.3%		Mar 31	Mar 16
Lux	17.0%	63.2%			
IT	17.2%	40.4%			Mar 9
NZ	17.2%	44.3%			Mar 26
CH	17.3%	45.8%			
ND	18.4%	16.6%			Mar 16
Pol	18.5%	17.5%			Mar 13
Belgium	18.5%	20.1%			Mar 18
Ire	18.6%	23.9%			Mar 12
Canada	18.7%	37.1%			
Germany	19.6%	36.0%			(only Bavaria)
France	20.2%	56.6%			Mar 17
Portugal	20.4%	27.1%			Mar 19
UK	20.4%	22.4%			Mar 24
US	21.6%	5.5%			Mar 19-24 (CA, NV, CT, IL, KS, MA, MI, NY, OR, WI)
Spain	21.9%	38.8%			Mar 14

Figure 6: Epidemic daily growth and reduction from peak daily growth, together with masking culture, universal masking policy, and lockdown policy, from January 23 to April 10, 2020 for selected list of countries or provinces with high GDP PPP per capita in Asia, Europe and North America. Universal masking was employed in every region that handled COVID-19 well. Sources: John Hopkins, Wikipedia, VOA News, Quartz, Straits Times, South China Morning Post, ABCNews, Time.com, Channel New Asia, Moh.gov.sg, Reuters, Financial Times, Yna.co.kr, Nippon.com, Euronews, Spectator.sme.sk

may have fit with preexisting Taoist and health precepts of Chinese traditional medicine, its actual emergence may be relatively recent, starting with the industrialization of Japan at the start of the XXth century and both the flu pandemics of the XXth century as well as the rise of particle pollution (Yang, 2014). The rest of the above-listed east Asian countries has followed the same course in the second half of the XXth century, including China as it was confronting a severe particle pollution crisis in the first part of the 2010s (Kuo (2014), Li (2014), Hansstein and Echegaray (2018)). Beyond price, availability and government recommendation, the actual practice of masking in the Asian general population may be mediated by factors such as social norms or peer-pressure, perception of one's competence, past behaviors or perception of the danger (Hansstein and Echegaray, 2018). As an example of the latter, in Hong Kong, masking was practiced by 79% of the general population during the 2003 SARS outbreak, but by only a maximum of 10% of the general population during the Influenza A pandemic in 2009 (Cowling *et al.*, 2020).

Universal masking policy. Additionally, to the extent that government recommendations or mandatory orders may shape perceptions and assist in masks availability, it may amplify the masking practice in the general population. It can thus be assumed that the maximum potency of universal masking in the context of epidemics may be reached when a government issues a mandatory or highly recommended order to the general population, issued at an early date, supported by the availability of face masks and amplified by a pre-existing "masking culture". In that case, we make the reasonable assumption that such national situations may be used to validate our SEIR and ABM predictive models at maximum values (80-90%) for the percentage of the general population wearing masks.

We also computed two additional meta-features to classify *successful* management of the epidemic outbreak. These meta-features help to highlight both (a) success in suppressing growth from the start (e.g., Hong Kong or Taiwan) or (b) success in managing the epidemic by reducing the number of new cases after a peak (e.g., South Korea).

Successful suppression of daily growth is defined as being below 12.5% daily growth (equivalent to number of cases doubling at the slower pace of 6 days or more) once the number of detected cases first reached 30. These daily

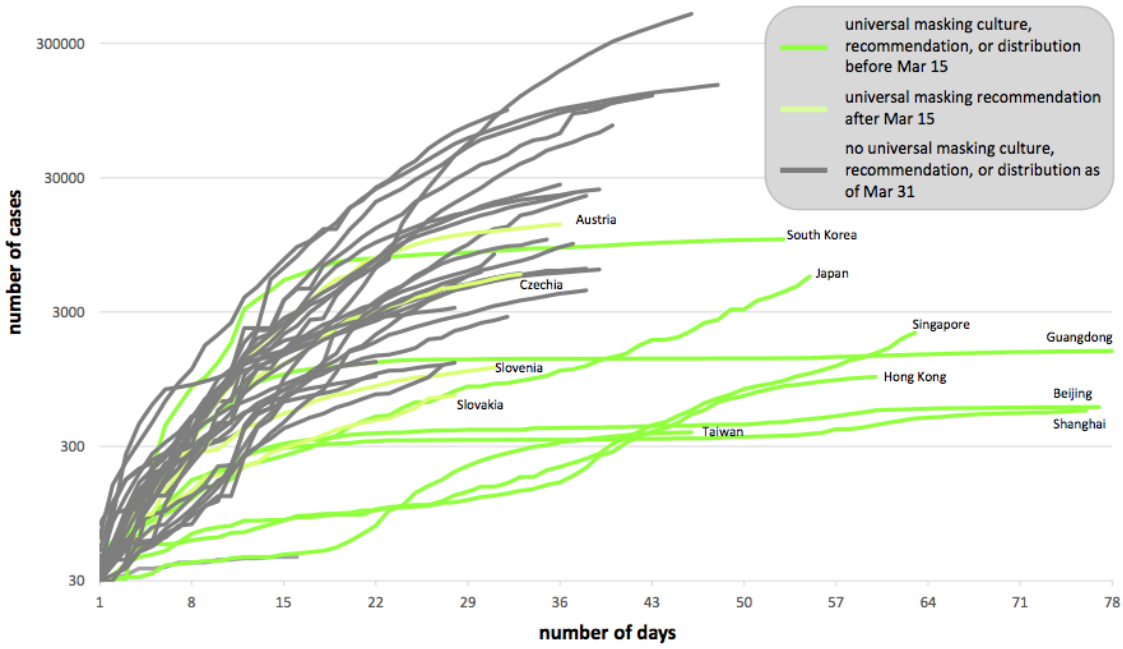


Figure 7: Daily growth curves showing the impact of universal masking on epidemic control: epidemic trajectory after 30 detected cases in universal masking selected countries and provinces (green) vs. others (grey). Masking is nearly perfectly correlated with lower daily growth or strong reduction from peak growth of COVID-19. Sources: John Hopkins, Wikipedia, VOA News, Quartz, Straits Times, South China Morning Post, ABCNews, Time.com, Channel New Asia, Moh.gov.sg, Reuters, Financial Times, Yna.co.kr, Nippon.com, Euronews, Spectator.sme.sk

growth rates are highlighted in green in Figure 6.

Successful reduction from peak is defined as a recent, significant (>60%) reduction of new cases calculated as the average of the last five days before April 10, 2020 compared to the average of the three highest number of daily new cases up to April 10, 2020 starting from the date when the number of detected cases first reached 30. Again, these reductions from peak are highlighted in green in Figure 6.

5.3 Validation results

Results bear out the predictions made by our SEIR and agent-based models as described in sections 3 and 4.

In Figure 6, the green (successful supression of daily growth and/or reduction from peak) areas show that as of April 10, 2020, an overwhelming majority of countries or regions that have best managed COVID-19 outbreaks were countries or regions with either (1) established universal masking cultures or (2) mandatory orders or government recommendations supported by significant and early mask production destined for the general population. These countries or regions include Taiwan, South Korea, Singapore, Japan, autonomous special administrative regions such as Hong Kong or Macau, and Chinese provinces such as Beijing, Shanghai, or Guangdong. In effect, masking in public has been required in Taiwan, metropolitan areas in China such as Shanghai and Beijing (as well as Guangzhou, Shenzhen, Tianjin, Hangzhou, and Chengdu), Japan, South Korea, and other countries (Morgunov *et al.*, 2020). On the other hand, the red (strict lockdown without universal masking) areas show that most of the countries which have adopted mass testing, tracking and quarantining, but lack a universal masking culture and clear recommendations and availability for universal masking, have not achieved an equiv-

alent level of COVID-19 epidemic control as of April 10, 2020. This nearly perfect correlation between early universal masking and successful management of COVID-19 outbreaks bears out our SEIR and ABM predictions.

In Figure 7, daily growth curves were extracted from our data set in order to reveal the impact of universal masking on epidemic control on a time axis. Results show that universal masking is nearly perfectly correlated with lower daily growth rates of COVID-19 cases over time, again validating the predictions from our SEIR and agent based models.

In Figure 8, daily growth was plotted against versus percentage reduction from peak daily daily growth. Green points, representing countries or regions with early universal masking, disproportionately fall within the two lower quadrants which represent successful management of COVID-19 outbreaks. Red points, representing countries with strict lockdowns but not universal masking, nearly all fall in the two upper quadrants which represent less successful management of COVID-19 outbreaks. Light green points, representing countries or regions with late universal masking, tend to fall in the middle regions. Again, the strong correlation of universal masking with successful control of COVID-19 case growth bears out our SEIR and agent based models' predictions.

Validation of the need for *universal* masking. These validations highlight the gradual nature of the protection against COVID-19 achieved with a higher fraction of the population practicing masking, as observed in the SEIR and ABM simulations when comparing situations with 80-90% universal masking versus only 50% masking or none. In countries or provinces with masking culture and universal masking orders or recommendations before March 15, 2020, the average daily growth was 5.9% and the reduction from peak was 74.6%. In the countries without masking culture and universal masking orders or recommendations after March 15, 2020, the average daily growth was 14.2% and the reduction from peak was 45.8%. Finally, for the rest of the other countries, the average daily growth was 17.2% and the reduction from peak was 37.4%, the lowest results of the sample. The latter group includes countries that have gone into "strict lockdown" (or mass home quarantine) for 20 out of 27 countries (74%). This is much higher than for the intermediate group of countries without masking culture and "late" universal masking orders (2 out 4, or 50% of the sample), or the first group of countries and provinces with masking culture and "early" universal masking orders. In that first group, no countries or provinces had to endure "strict lockdown".

Validation of the need for *early* universal masking. Yet even within this first group, the strength of *early* universal masking recommendations from the government may impact the proportion of the general population actually wearing masks and thus the level of epidemic control, as per our models' SEIR and ABM predictions. For example, Singapore initially encouraged people to wear masks only when feeling unwell. Then, on April, 5, the government changed policy and decided to distribute reusable face masks to all households (Cheong, 2020). On the other end, Hong Kong decided by January 24, 2020 to advise the general population to wear surgical masks in crowded places and public transports (Hong Kong Department of Health, 2020). As can be observed from Figure 6, as of April 10, 2020, the characteristics for epidemic control in terms of daily growth and peak from reduction are better for Hong Kong than for Singapore. These variations may be related to levels of adherence to masking by the general population. Though there are no available data as of April 10, 2020 as per adherence to universal masking in Singapore, telephone surveys in Hong Kong done in February 11-14, 2020 and then in March 10-13, 2020, both after Department of Health public advice, have shown declared masking adherence at the very high levels of 97.5% and 98.8% respectively when going out (Cowling *et al.*, 2020). Assuming the adherence level to masking was lower in Singapore since the general population order came much later, this would support our SEIR and ABM predictions of the need for *early* institution of universal masking.

Although these correlations may also be sensitive to other unobserved factors, the theoretical SEIR and ABM predictions as empirically validated in the various ways described here call for urgent policy and public action even as further enquiry is pursued into the effects of masking. Our results also confirm and amplify other previous findings. A recent macro-level regression analysis by economists at Yale University, taking into account masking cultures and times of country COVID-19 policy responses, estimated that growth of COVID-19 rates only half that of mask wearing countriesthe growth rate of confirmed cases is 18% in countries with no pre-existing

Figure 8: Visual representation of epidemic daily growth versus percentage reduction from peak daily daily growth in quadrants showing the impact of universal masking on epidemic control: and reduction from peak, from January 23 to April 10, 2020 for selected list of countries or provinces with high GDP PPP per capita in Asia, Europe and North America. Masking is nearly perfectly correlated with lower daily growth or strong reduction from peak growth of COVID-19. Sources: John Hopkins, Wikipedia, VOA News, Quartz, Straits Times, South China Morning Post, ABCNews, Time.com, Channel New Asia, Moh.gov.sg, Reuters, Financial Times, Yna.co.kr, Nippon.com, Euronews, Spectator.sme.sk

mask norms and 10% in countries with such norms, while the growth rate of deaths is 21% in countries with no mask norms and 11% in countries with such norms. The authors note that such a 10% reduction in transmission probabilities could correspond to a per capita gain of $3,000-6,000 per each additional cloth mask, and that the economic benefits of each medical mask for healthcare personnel could be substantially larger (Abaluck *et al.*, 2020).

6 Conclusion: Universal masking needs broad support and clear guidelines

Our SEIR and ABM models suggests a substantial impact of timely universal masking. Without masking, but even with continued social distancing in place once the lockdown is lifted, the infection rate will increase and almost half of the population will become affected. This scenario would potentially lead to over a million deaths in a population the size of the UK. Social distancing and

masking at both 50% and 80-90% of the populationbut no lockdown beyond the end of Mayresult in substantial reduction of infection, with 80-90% masking eventually eliminating the disease.

Moreover, for a significant chance of mitigating infection growth rates, universal masking must be adopted earlyby day 50 from the onset of COVID-19 outbreaks.

Without masking, lifting lockdown after nine weeks while keeping social distancing measures will risk a major second wave of the epidemic in 4-5 months' time. However, if four out of five citizens start wearing cloth masks in public before the lockdown is lifted, the number of new COVID-19 cases could decline enough to exit lockdown and still avoid a second wave of the epidemic. If only every second person starts wearing a mask, infection rates would also decline substantially, but likely not by enough to prevent the second wave.

Combined with the correlational empirical evidence, our results highlight the need for mass masking as an alternative to a continued lockdown scenario. For this strategy to be most effective, the vast majority of the population needs to adopt mask wearing immediately. When a well-timed "mouth-and-nose lockdown" accompanies the current "full body lockdown", both the human and economic costs of the COVID-19 pandemic can be significantly lowered.

Our theoretical and empirical results are in line with previous studies suggesting that a high rate of masking may be needed in a population to provide efficient protection from influenza (Yan *et al.*, 2019) and that masking can be an effective intervention strategy in reducing the spread of a pandemic (Tracht *et al.*, 2010).

Furthermore, universal masking can reduce stigmatization of ethnic groups, risk groups, or the sick and contribute to public solidarity (Feng *et al.*, 2020).

We urge governments and international bodies who have not yet done so to consider masking as one of the key tools in population policy after the COVID-19 lockdowns and until the virus is under control. The analysis presented here supports recent studies (Abaluck *et al.*, 2020), suggesting that the effectiveness of universal masking is comparable to that of social distancing or a societal lockdown with closed workplaces, schools, and public spaces and limited geographical mobility. The results from our simulation help explain the dynamics behind the perplexing advantage in the Asian experience of tackling COVID-19 compared to the situation elsewhere.

Our analyses lead to the following key policy recommendations:

1. Masking should be mandatory or strongly recommended for the general public when in public transport and public spaces, for the duration of the pandemic.

2. Masking should be mandatory for individuals in essential functions (health care workers, social and family workers, the police and the military, the service sector, construction workers, etc) and medical masks and gloves or equally safe protection should be provided to them by employers. Cloth masks should be used if medical masks are unavailable.

3. Countries should aim to eventually secure mass production and availability of appropriate medical masks (without exploratory valves) for the entire population during the pandemic.

4. Until supplies are sufficient, members of the general public should wear nonmedical fabric face masks when going out in public and medical masks should be reserved for essential functions.

5. The authorities should issue masking guidelines to residents and companies regarding the correct and optimal ways to make, wear and disinfect masks.

6. The introduction of mandatory masking will benefit from being rolled out together with campaigns, citizen initiatives, the media, NGOs, and influencers in order to avoid a public backlash in societies not culturally accustomed to masking. Public awareness is needed that "masking protects your communitynot just you".

The effectiveness of universal masking in a given population is likely to depend on (a) the type of masks used, (b) the acceptance of masking in the population, (c) the level of contagion of the virus, and (d) what other interventions have been applied. From this perspective, the Central European experience will be highly informative, since it represents the first major shift to universal masking in a formerly non-masking culture. The effects of this pioneering intervention on infection rates and fatalities will

appear only in the forthcoming weeks, although Slovakia and Slovenia are currently showing early indications of progress (see Figure 7). In any case, they illustrate that a country with no prior history of mask wearing in public may rapidly change course, and quickly adopt masks as a non-stigmatisedeven street smartway to express caring and solidarity in the community.

The medical and social risks of increased infections need to be countered by proper advice in the public domain. Some studies do indicate negative effects of naive improper cloth mass use, for instance higher risks of infection due to moisture retention, reuse of poorly washed cloth masks, and poor filtration in comparison to medical masks (MacIntyre *et al.*, 2015). To address concerns that lay individuals may use both medical and/or cloth and paper masks incorrectly, masking techniques and norms need to be taught with targeted information to different demographics, just as proper handwashing and social distancing techniques have been taught.

References

Jason Abaluck, Judith A. Chevalier, Nicholas A. Christakis, Howard Paul Forman, Edward H. Kaplan, Albert Ko, and Sten H. Vermund. The Case for Universal Cloth Mask Adoption and Policies to Increase Supply of Medical Masks for Health Workers. SSRN Scholarly Paper ID 3567438, Social Science Research Network, Rochester, NY, April 2020.

Acadmie nationale de mdecine. Communiqu de lAcadmie : "Pandmie de Covid-19 : mesures barrires renforces pendant le confinement et en phase de sortie de confinement". Technical report, Acadmie nationale de mdecine, April 2020.

Eric Bonabeau. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America*, 99(Suppl 3):7280–7287, May 2002.

Jane Burch and Christopher Bunt. Can physical interventions help reduce the spread of respiratory viruses? *Cochrane Clinical Answers*, 2020. Publisher: John Wiley & Sons, Ltd.

Adam Burgess and Mitsutoshi Horii. Risk, ritual and health responsibilisation: Japans safety blanket of surgical face mask-wearing. *Sociology of Health and Illness*, 34(8):11841198, 2012.

Danson Cheong. Coronavirus: Most workplaces to close, schools will move to full home-based learning from next week, says pm lee. *The Straits Times*, Apr 2020. https://www.straitstimes.com/singapore/health/most-workplaces-to-close-schools-will-move-to-full-home-based-learning-from-next.

Benjamin J. Cowling, Sheikh Taslim Ali, Tiffany W. Y. Ng, Tim K. Tsang, Julian C. M. Li, Min Whui Fong, Qiuyan Liao, Mike YW Kwan, So Lun Lee, Susan S. Chiu, Joseph T. Wu, Peng Wu, and Gabriel M. Leung. Impact assessment of non-pharmaceutical interventions against coronavirus disease 2019 and influenza in Hong Kong: an observational study. *The Lancet Public Health*, 0(0), April 2020. Publisher: Elsevier.

Anna Davies, Katy-Anne Thompson, Karthika Giri, George Kafatos, Jimmy Walker, and Allan Bennett. Testing the efficacy of homemade masks: would they protect in an influenza pandemic? *Disaster Medicine and Public Health Preparedness*, 7(4):413–418, August 2013.

De Kai. The disastrous consequences of information disorder erupting around COVID-19: AI is preying upon our unconscious cognitive biases. In *Boma COVID-19 Summit*, March 2020. `https://youtu.be/ZidC7oRd7Pc`, transcript at `http://dek.ai/unbias`.

Shuo Feng, Chen Shen, Nan Xia, Wei Song, Mengzhen Fan, and Benjamin J. Cowling. Rational use of face masks in the COVID-19 pandemic. *The Lancet Respiratory Medicine*, 0(0), March 2020. Publisher: Elsevier.

Harvey V. Fineberg. Ten Weeks to Crush the Curve | NEJM. *New England Journal of Medicine*, April 2020.

Tapiwa Ganyani, Ccile Kremer, Dongxuan Chen, Andrea Torneri, Christel Faes, Jacco Wallinga, and Niel Hens. Estimating the generation interval for COVID-19 based on symptom onset data. *medRxiv*, 2020.

Scott Gottlieb and Caitlin M. Rivers. Quarantining cities isnt needed. But a fast, coordinated response to covid-19 is essential. *Washington Post*, March 2020.

Scott Gottlieb, Caitlin Rivers, Mark B. McClellan, Lauren Silvis, and Crystal Watson. National coronavirus response: A road map to reopening. Technical report, American Enterprise Institute (AEI0, March 2020.

Francesca Valeria Hansstein and Fabin Echegaray. Exploring motivations behind pollution-mask use in a sample of young adults in urban china. *Globalization and Health*, 14(1), Dec 2018.

John H. Holland and John H. Miller. Artificial Adaptive Agents in Economic Theory. *The American Economic Review*, 81(2):365–370, 1991. Publisher: American Economic Association.

Hong Kong Department of Health. Latest recommendations by scientific committee on emerging and zoonotic diseases and scientific committee on infection control after reviewing cases of novel coronavirus infection. Technical report, The Government of the Hong Kong Special Administration Region, Jan 2020. Press Release, Scientific Committee on Emerging and Zoonotic Diseases and the Scientific Committee on Infection Control under the Centre for Health Protection (CHP) of the Department of Health. https://www.info.gov.hk/gia/general/202001/24/P2020012400762.htm.

Jeremy Howard and Fast.ai team. Make and wear a homemade mask to slow the spread of COVID-19. *#Masks4All*, 2020. https://masks4all.co.

Elizabeth Hunter, Brian Mac Namee, and John D. Kelleher. A Taxonomy for Agent-Based Models in Human Infectious Disease Epidemiology. *Journal of Artificial Societies and Social Simulation*, 20(3):2, 2017.

Elizabeth Hunter, Brian Mac Namee, and John Kelleher. An open-data-driven agent-based model to simulate infectious disease outbreaks. *PLOS ONE*, 13(12):e0208775, December 2018.

Ralph Jennings. Not just coronavirus: Asians have worn face masks for decades. *Voice of America*, Mar 2020. https://www.voanews.com/science-health/coronavirus-outbreak/not-just-coronavirus-asians-have-worn-face-masks-decades.

Lily Kuo. Chinese urbanites are spending millions on anti-pollution masks-and most of them don't do anything. *Quartz*, Feb 2014. https://qz.com/180830/chinese-urbanites-are-spending-millions-on-anti-pollution-masks-and-most-of-them-dont-do-anything/.

Nancy H. L. Leung, Daniel K. W. Chu, Eunice Y. C. Shiu, Kwok-Hung Chan, James J. McDevitt, Benien J. P. Hau, Hui-Ling Yen, Yuguo Li, Dennis K. M. Ip, J. S. Malik Peiris, Wing-Hong Seto, Gabriel M. Leung, Donald K. Milton, and Benjamin J. Cowling. Respiratory virus shedding in exhaled breath and efficacy of face masks. *Nature Medicine*, pages 1–5, April 2020. Publisher: Nature Publishing Group.

Hillary Leung. Why Face Masks Are Encouraged in Asia, but Shunned in the U.S. *Time*, March 2020.

Grace Li. China's face mask industry under scrutiny as pollution worsens. *Reuters*, Mar 2014. https://www.reuters.com/article/us-china-mask-pollution/chinas-face-mask-industry-under-scrutiny-as-pollution-worsens-idUSBREA2O0GI20140325.

Yuan Liu, Zhi Ning, Yu Chen, Ming Guo, Yingle Liu, Nirmal Kumar Gali, Li Sun, Yusen Duan, Jing Cai, Dane Westerdahl, Xinjin Liu, Kin-fai Ho, Haidong Kan, Qingyan Fu, and Ke Lan. Aerodynamic Characteristics and RNA Concentration of SARS-CoV-2 Aerosol in Wuhan Hospitals during COVID-19 Outbreak | bioRxiv. *bioRxiv*, March 2020.

C. Raina MacIntyre, Holly Seale, Tham Chi Dung, Nguyen Tran Hien, Phan Thi Nga, Abrar Ahmad Chughtai, Bayzidur Rahman, Dominic E. Dwyer, and Quanyi Wang. A cluster randomised trial of cloth masks compared with medical masks in healthcare workers. *BMJ Open*, 5(4):e006577, April 2015. Publisher: British Medical Journal Publishing Group Section: Infectious diseases.

Farhad Manjoo. Its Time to Make Your Own Face Mask. *New York Times*, March 2020.

Alexey Morgunov, Z. Bayno, and R. Manawis. Status of face mask wearing around the world, March 2020. https://docs.google.com/spreadsheets/d/1bzrUZe7qGGuYrHBrYwdjpUkh7tHW7NuZM_rkdGACR9Dc.

Stephanie Nebehay and Andrea Shalal. WHO opens door to broader use of masks to limit spread of coronavirus. *Reuters*, April 2020.

Stuart Russell and Peter Norvig. *Artificial Intelligence: A Modern Approach*. Pearson, Upper Saddle River, 3 edition edition, December 2009.

Marianne van der Sande, Peter Teunis, and Rob Sabel. Professional and Home-Made Face Masks Reduce Exposure to Respiratory Infections among the General Population. *PLOS ONE*, 3(7):e2618, July 2008.

Joshua L. Santarpia, Danielle N. Rivera, Vicki Herrera, M. Jane Morwitzer, Hannah Creager, George W. Santarpia, Kevin K. Crown, David Brett-Major, Elizabeth Schnaubelt, M. Jana Broadhurst, James V. Lawler, St. Patrick Reid, and John J. Lowe. Transmission Potential of SARS-CoV-2 in Viral Shedding Observed at the University of Nebraska Medical Center | medRxiv. *medRxiv*, March 2020.

Robert F. Service. You may be able to spread coronavirus just by breathing, new report finds. *Science*, April 2020.

Kelly Servick. Would everyone wearing face masks help us slow the pandemic? *Science*, March 2020.

Samantha M. Tracht, Sara Y. Del Valle, and James M. Hyman. Mathematical Modeling of the Effectiveness of Facemasks in Reducing the Spread of Novel Influenza A (H1N1). *PLOS ONE*, 5(2):e9018, February 2010.

Melissa Tracy, Magdalena Cerd, and Katherine M. Keyes. Agent-Based Modeling in Public Health: Current Applications and Future Directions. *Annual review of public health*, 39:77–94, April 2018.

Zeynep Tufekci. Why Telling People They Dont Need Masks Backfired. *New York Times*, March 2020. https://www.nytimes.com/2020/03/17/opinion/coronavirus-face-masks.html.

Neeltje van Doremalen, Trenton Bushmaker, Dylan H. Morris, Myndi G. Holbrook, Amandine Gamble, Brandi N. Williamson, Azaibi Tamin, Jennifer L. Harcourt, Natalie J. Thornburg, Susan I. Gerber, James O. Lloyd-Smith, Emmie de Wit, and Vincent J. Munster. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. *New England Journal of Medicine*, 382(16):1564–1567, April 2020. Publisher: Massachusetts Medical Society _eprint: https://doi.org/10.1056/NEJMc2004973.

World Health Organization. Coronavirus disease (COVID-19) advice for the public: When and how to use masks. World Health Organization, 2019. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public/when-and-how-to-use-masks.

World Health Organization. Advice on the use of masks in the context of COVID-19: interim guidance, 6 April 2020. Technical Report WHO/2019-nCov/IPC_Masks/2020.3, World Health Organization, April 2020. Accepted: 2020-04-06T20:48:18Z Number: WHO/2019-nCov/IPC_Masks/2020.3 Publisher: World Health Organization.

Jing Yan, Suvajyoti Guha, Prasanna Hariharan, and Matthew Myers. Modeling the Effectiveness of Respiratory Protective Devices in Reducing Influenza Outbreak. *Risk Analysis*, 39(3):647–661, 2019. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1111/risa.13181.

Jeff Yang. A quick history of why asians wear surgical masks in public. *Quartz*, Nov 2014. https://qz.com/299003/a-quick-history-of-why-asians-wear-surgical-masks-in-public/.