Air Safety to Combat Global Catastrophic Biorisk

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Executive Summary

Top-line summary

- Most efforts to address indoor air quality (IAQ) do not address airborne pathogen levels, and creating indoor air quality standards that include airborne pathogen levels could meaningfully reduce global catastrophic biorisk from pandemics.
- We estimate that an ideal adoption of indoor air quality interventions, like ventilation, filtration, and ultraviolet germicidal irradiation (GUV) in all public buildings in the US, would reduce overall population transmission of respiratory illnesses by 30-75%, with a median estimate of 52.5%.
- Bottlenecks inhibiting the mass deployment of these technologies include a lack of clear standards, cost of implementation, and difficulty changing regulation/public attitudes.
- The following actions can accelerate deployment and improve IAQ to reduce biorisk:
  - Funders can support advocacy efforts, initiatives to reduce cost and manufacturing issues, and research with contributions ranging from $25,000-$200M. Applied research projects can be funded to show the efficacy of ventilation, filtration, and GUV in field applications.
  - Businesses and nonprofits can become early adopters of GUV technology by installing it in their offices and allowing effectiveness data to be collected.
  - Researchers can develop models that better tie built-environment interventions to population-level effects, conduct further GUV safety testing, and do fundamental materials and manufacturing research for GUV interventions. Applied research can be conducted on ventilation, filtration, and GUV applications in real settings.

The problem: airborne pathogens

Infectious diseases pose a global catastrophic risk. The risk is especially severe, and we are far less prepared, if it involves bioengineered pathogens. Out of the various methods of pathogen transmission, airborne pathogens, particularly viruses, are especially dangerous, as they are easy to spread and difficult to combat. Airborne pathogens are significantly more likely to spread indoors than outdoors, so reducing indoor respiratory pathogen transmission could substantially reduce global catastrophic biorisk by:

- Reducing the probability that a disease has an effective reproduction number >1 and will spread at all, or if not,
- Limiting the number of infections that occur, "flattening the curve" so as not to overwhelm medical systems.
- Slowing the spread of disease to
  - Provide more time for countermeasure development, and
  - Discuss and implement non-pharmaceutical interventions, like limiting large gatherings and requiring masks.

Current indoor air standards do not consider infectious disease risk, whereas waterborne and foodborne pathogen deaths have been largely eliminated in many areas due to improved water and food sanitation. Indoor air quality, especially concerning infectious diseases, should be a priority public good, like fire safety, food safety, and potable water.

How to fix indoor air contamination

Known effective interventions to reduce indoor air pathogen contamination include increased outdoor air ventilation, high-efficiency particulate air (HEPA) filtering, and germicidal ultraviolet (GUV) light. Of these, GUV technology is the most promising for pathogen control because it can reach considerably higher levels of equivalent air changes per hour (eACH) than filtration or ventilation by directly inactivating pathogens, could in principle be more energy efficient, is straightforward to install as a retrofit, and produces no noise pollution.[1] Filtration is a viable option for high levels of eACH up to CDC hospital standards (8-12 eACH), where it is still relatively cost-effective. It also helps to reduce particulate and chemical pollution, which is relevant for immediate health concerns, such as chronic

1 Air quality standards are typically set in terms of air changes per hour (ACH) and equivalent air changes per hour (eACH).

respiratory health and everyday cognitive functioning. By contrast, high-volume ventilation is expensive, or even impossible in many buildings due to the difficulty of retrofitting or upgrading HVAC systems.

Currently, two different wavelengths of GUV are utilized: 254 nm UVC and 222 nm UVC, also known as far-UVC. People should not be directly exposed to 254 nm UVC, since it can cause skin and eye damage, but 222 nm UVC is likely safe for direct interaction. Most current germicidal light fixtures are 254 nm, and therefore installed as an upper-room or in-duct system, shielded from room occupants.

- 254 nm UVC is already more cost-effective than other IAQ interventions and, if installed correctly, is safe due to lack of interaction with a room's occupants.
- Far-UVC can be used to reduce surface and close contact transmission as well as airborne transmission, making it potentially the most effective intervention for reducing global catastrophic biorisk, with a recent review indicating strong safety evidence in humans even after prolonged exposure. The price of current systems is currently too high for at-scale deployment, though there are reasons to think the price can be lowered significantly.

We estimate that the ideal mass deployment of indoor air quality interventions, like ventilation, filtration, and GUV, would reduce overall population transmission of respiratory illnesses by 30-75%, with a median estimate of 52.5%. (Described in the "Rough Estimate of Impact" section.) This could completely prevent many current diseases from spreading, and even for the most transmissible diseases, like measles, it likely amounts to a great reduction in transmission speed, and would serve as an important layer of biodefense.

Overall, we can be confident that these interventions effectively reduce pathogen load in the air, and some previous work has been done investigating the impact of ventilation on population-level transmission.

How can we accelerate the deployment of IAQ-related interventions?

Despite the existence of promising technologies, several bottlenecks are preventing the mass deployment of IAQ interventions. Some significant ones include:

- Expense of improving and implementing air cleaning technology.
- Difficulty of wide-scale change in regulations and public attitudes towards indoor air quality.
- Difficulty in understanding the relationship between pathogen load and infection cases.

However, significant opportunities exist to accelerate deployment via advocacy, cost and manufacturing improvements, and research.

- **Advocacy:** Some presently attractive advocacy projects include: development of an anti-infection standard by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); promoting use of the recently released (Non-infectious Air Delivery Rate) NADR standard from the Lancet COVID Commission; recruiting high-status businesses as early adopters who can conduct and fund pilots; improving air quality in schools through private and public investments; and creating an umbrella group to coordinate efforts.
- **Costs and manufacturing:** Advanced market commitments and other forms of investment could drive down the cost of far-UVC solid-state emitters and other interventions. Investments in training could also increase expertise in design and installation of GUV systems.
- **Research:** Attractive research opportunities include: (a) further establishing the long-term safety of far-UVC, which can help with international deployment, (b) creating reliable ways to test intervention efficacy, which could include applied research programs or controlled natural exposure challenge studies, (c) developing guides to help organizations optimally deploy IAQ fixtures, and (d) social research to improve public advocacy efforts around IAQ.

We provide a conservative estimate that the total cost of upgrading air quality systems in all public buildings in the US to be $120-$420 billion (CI:90%).

We give a conservative estimate that reducing the risk of a future pandemic as bad as COVID by 1% would be worth $100 billion, and it seems highly likely that this program would reduce the risk or severity of a pandemic by more than 1%.

We think significant action to accelerate deployment of IAQ interventions to reduce biorisk would benefit from philanthropic funding in the range of $25,000-200M:

- $25,000 could fund the development of a detailed population transmission model or message-testing surveys for IAQ public advocacy.
- $5M could fund the development of new solid-state far-UVC light sources.
- $20M could fund a single dedicated clinical project (e.g. something like EMIT-2) or a field demonstration of GUV efficacy in reducing transmission in high risk areas.
- $200M could fund a program combining studies to ascertain and demonstrate the effect of indoor air interventions with advocacy to lead to broad adoption (e.g. far-UVC light safety studies, real-world efficacy studies for IAQ interventions, advocacy for improved pandemic preparedness standards, etc.).

Background

Poor indoor air quality adversely impacts health, yet has historically been ignored compared with other health interventions (such as surface cleaning, handwashing, or spray barriers). However, COVID-19 has created a significant change in scientific attitudes towards aerosol transmission of respiratory disease, and the harmful impact of chemical and particulate indoor air pollution continues to be documented in greater and greater detail. In this brief investigation-style report, we explore the case for funders, founders, researchers, and existing organizations to reduce respiratory pathogen burden and global catastrophic biorisk (GCBR) by improving indoor air quality. While there would be benefits to implementation in other countries, we focus on the United States for a few reasons[2]:

1. American standards tend to influence other countries (e.g. car emissions standards).
2. Globally, 1.2 billion people live in high-income countries, for which deployment should be roughly similar to the US.
3. We expect building changes to be implemented first in richer countries because of their greater resources and institutional capacity.
4. People in high-income countries fly more often on average, so blocking or reducing pathogen transmission in these countries, including the US, would do more to reduce air travel spread.[3]
5. Technological investments by wealthy countries will reduce costs, which would facilitate later deployment in developing countries.

In addition, focusing on the US allows us to provide a more detailed cost-benefit analysis, as the US is well-studied and has data on important items such as the composition of building stock.

Existing IAQ Policy and Regulation: The majority of air quality guidance is aimed at chemical pollutants, with little if any focus on infectious disease.

- **World Health Organization:** The WHO Guidelines for Indoor Air Quality exclusively references dangerous chemicals and gasses such as benzene, carbon monoxide, and formaldehyde.
- **State and Local Government:** In the United States, IAQ standards are typically set by individual states and refer only to ventilation, not pollutants or pathogens. These policies tend to derive from guidelines published by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), an influential industry group, or they are omitted from building codes entirely.
- **ASHRAE:** The majority of buildings fall under the

2 E.g. implementing GUV in countries where TB is endemic, we could expect to see reduction in TB transmission as a near-term benefit, regardless of the timing of a respiratory pandemic.

3 8 out of 10 top airports for passenger traffic are in the US.

remit of ASHRAE Standards 62.1 and 62.2, last updated in 2022. They call for varying amounts of ventilation based on occupancy, use, and a constant for area - working out to be approximately 1-2 ACH in residences and offices (though half of studied buildings fall below ASHRAE standards). The current standards do not consider airborne pathogens, though they are currently being updated to do so. More stringent requirements can be found for healthcare settings, defined in ASHRAE 170.

- **Occupational Safety and Health Administration:** OSHA has authority to regulate air in indoor workplace settings. Its regulations tend to be fairly weak, only address particulate and chemical pollutants, and are primarily based upon ASHRAE guidelines. They only apply to a healthy working adult population and should not be considered for the general public, which includes children and the elderly. In facilities that are not expected to produce large amounts of pollutants, OSHA demands only a self-certification form, and in environments where pollutants might be more common, only some chemicals are regulated, with a generic requirement for employers to protect against known harms.
- **Environmental Protection Agency:** The EPA is responsible for outdoor air quality but does not regulate indoor air quality; it primarily focuses on greenhouse gasses, radiation, and common hazardous gaseous and particulate pollutants. However, it does provide resources for people seeking to independently improve their indoor air quality. The National Ambient Air Quality Standards (NAAQS) are health-based, and as such should be applicable to those air pollutants for which there is a standard in all environments.
- **CDC:** The CDC is responsible for guidance related to infectious disease, but is not a regulatory agency. Its suggestions are very high-level and do not address businesses or standards.
- **Lancet COVID-19 Commission:** The Lancet Commission recently released its recommendations for Non-Infectious Air Delivery Rates (NADR), benchmarks for ensuring good indoor air quality that are intended for universal application. Based on a review of existing literature, the report proposes potential target measures for NADR for reducing transmission of airborne pathogens, such as volumetric flow rate per person, per floor area, or per volume. For NADR measured by volumetric flow rate per volume, the report proposes that a "good" target for volumetric flow rate per volume is 4 air changes per hour equivalents (ACHe), with increasing benefits in transmission reduction continuing to at least 6 ACHe.

Prior to COVID-19, the dominant public health paradigm treated airborne transmission as negligible for most major respiratory diseases. This resulted in a historical reluctance to implement air hygiene controls. However, interdisciplinary research inspired by the COVID-19 pandemic has shown that airborne transmission is a major mode of transmission for this disease, and likely a significant one for many other respiratory infectious diseases.

Federal efforts have been proposed to improve US indoor air quality: the American Pandemic Preparedness Plan (AP3) proposed allocating $3.1B for "next-gen PPE and built environment improvements" (with no indication of the split between the two), and requested that the 2023 budget include $88.2 billion in mandatory funding for biodefense purposes, but neither was enacted. Despite these setbacks, the Biden administration released a plan to advance indoor air quality nationwide by upgrading the filtration and ventilation of federally owned buildings, funding air quality research and identifying gaps, and providing resources and incentives for upgrades in schools and residential buildings. Additionally, organizations that want to upgrade their ventilation and air cleaning systems are encouraged to use funds from the American Rescue Plan and Bipartisan Infrastructure Law to do so.

In this report, we use two primary metrics for air quality: air changes per hour (ACH), referring to the outdoor air supply airflow rate normalized by room volume, and equivalent air changes per hour (eACH),[4] which similarly measures the volumetric rate at which air is made non-infectious, rather than replaced by outdoor air. Aside from eACH, indoor air standards may also be measured by the clean air delivery rate (CADR) calculated by a filter's air flow rate in cubic feet per minute, or by concentration in units such as micrograms/m^3 (ug/m^3) or parts per million (ppm) in the case of particulate and chemical pollutants. All air cleanliness measurements are imperfect proxies for assessing the safety of a room with respect to disease transmission. First, the relationship between amount of pathogen inhaled and cases of infection is only partially understood, and varies for different pathogens and individual susceptibility. Second, because some IAQ interventions like germicidal ultraviolet light disinfection inactivate different pathogens at different rates, the eACH will vary by pathogen, and will not reduce pollution.

What is the Problem?

Pandemic respiratory disease

The COVID-19 pandemic has caused significant damage worldwide but was by no means unusually destructive. There have been far more lethal historical pandemics, such as the Black Death, which killed 25-200 million people worldwide (estimated to be 5-40% of the global population at the time), and the 1918 Spanish Flu, which likely killed about 17.4-100 million people worldwide (estimated to be 1-5.4% of the global population at the time). While the burden of endemic infectious disease has trended downward, it is unclear whether the risk of natural catastrophic pandemics is increasing or decreasing. Factors seem to point in both directions, with the development of vaccinations and therapeutics and greater understanding of disease transmission reducing the risk. Increased trade and air travel allow for quicker and wider transmission, and there are larger domestic animal reservoirs, which may increase the likelihood of zoonotic spillovers.

While naturally evolved pathogens could lead to globally catastrophic pandemics (i.e. destabilizing enough to threaten the entire future of humanity), evolution tends to optimize for reproductive fitness, rather than maximum virulence. On the other hand, bioengineered pathogens could be developed that would be much more dangerous than any with natural origins. As biotechnology progresses and biotechnological capacity diffuses more widely, the accidental or deliberate release of an engineered pathogen becomes increasingly likely.

Given these factors, addressing pandemic threats is an urgent need for our own generation that can also improve the wellbeing of future generations. Regardless of whether a pathogen is natural or engineered, deliberately or accidentally released, some attributes are likely to be essential components of catastrophic pathogens. A report from the Johns Hopkins Center for Health Security notes that a global catastrophic-risk level pathogen is most likely to be a virus, due to viruses' higher capacity for genetic mutability compared with other pathogens, and to have respiratory transmission routes, since this is the mechanism most likely to lead to pandemic spread. Current interventions to interrupt respiratory transmission are more difficult to implement than with vector-borne, sexually transmitted, or fecal-oral routes.[5] The "Delay, Detect, Defend" Geneva Paper focuses on viruses as the primary source of GCBRs, especially bioengineered viruses, due to widespread knowledge of viruses and the relative ease of manipulating them. We also spoke with experts who expressed the view that pandemic risks from fungi and spore-bearing bacteria (such as anthrax, used in traditional bioweapons) were negligible in comparison. Based on these sources and conversations, we will focus on the risk from respiratory viruses as by far the primary contributor to GCBR.

4 In some literature, such as the Lancet COVID-19 Commission report, this is abbreviated ACHe.

5 Of the "environmental" pathogens, waterborne and foodborne pathogen deaths have been largely eliminated in wealthy nations due to improvements in sanitation and broad access to treatment. However, air sanitation has yet to reach the same standards as water and food sanitation, even in wealthy nations.

The majority of aerosolized respiratory pathogen transmission occurs indoors; in the COVID-19 pandemic it is estimated that likely more than 90% of transmission has occurred indoors, that the odds of transmission are at least 20 times higher indoors than outdoors, and superspreading events happened indoors in locations with inadequate ventilation.

Given the above, improving indoor air quality, i.e. reducing indoor respiratory pathogen transmission, could substantially reduce global catastrophic biorisk by:

1. Reducing the probability that a disease has an effective reproduction number >1 and will spread at all, or if not,
2. Limiting the number of infections that occur, "flattening the curve" so as not to overwhelm medical systems
3. Slowing the spread of disease to
   - Provide more time for countermeasure development, and
   - Discuss and implement policies, like limiting large gatherings and requiring masks.

Ideally, improving indoor air quality is only a part of a portfolio for reducing global catastrophic biorisk, alongside other interventions like advanced PPE, vaccinations and medications, improving early pandemic detection, and advocacy to better manage dual-use research of concern.

How important is risk from respiratory pathogens?

We estimate that 90-99% of COVID-19 infections come from aerosol sources, between 40-80% of influenza transmission, and much[6] of the overall disease burden of other common cold viruses. The relative importance of modes of transmission between pathogens is very poorly quantified. For most common respiratory pathogens (aside from COVID-19 and to an extent, influenza) the data required to make meaningful quantitative predictions does not currently exist.

IAQ interventions to prevent disease primarily act on aerosolized particles. The impact of IAQ on disease transmission is dependent on the fraction of pathogen transmission attributable to airborne transmission. While some diseases, most notably COVID-19, TB, measles, and chickenpox, are widely accepted to be dominantly airborne, most respiratory pathogens have historically been assumed to be primarily driven by large droplet/fomite transmission. This assumption now seems highly uncertain given updated research avenues.

Respiratory pathogens

COVID-19: The vast majority of COVID-19 infection is transmitted via aerosols, primarily indoors. Early studies were mostly observational, with notable early studies showing a clear case of aerosol transmission in a restaurant and at a choir practice. Aerosol transmission proved so efficient that COVID was even transmitted between individuals in rooms across the hall from each other in a quarantine facility when their doors were simultaneously open for under a minute.

Measles: Measles is the most contagious known airborne pathogen, making it an important benchmark for air safety measures. Although vaccination is the preferred public health measure to prevent the spread of measles, vaccine hesitancy has contributed to recent outbreaks in some communities, indicating the need for alternative interventions. In 2019, a series of measles outbreaks led to 1,274 reported cases in the US. As has long been recognized, measles is easily transmitted through aerosols, contributing to its high contagiousness. Case studies of superspreader events suggest rapid measles recirculation throughout buildings by unfiltered central ventilation systems, with one case study indicating 35-78% of infections occurring without close contact with the initial case. The impact of GUV on preventing measles transmission has also been long-studied, with scientific literature dating to

6 Our research indicates numbers between 20% and 90% of disease burden; figures depend highly on the specific models and scenarios in which infections take place. Generally, substantial evidence underlies the hypothesis that all respiratory infections can be transmitted via aerosol to some degree or another.

the 1940s. A landmark UVGI study found strong positive effects of upper-room irradiation in preventing transmission in classrooms, but later studies indicated much weaker effects in experimental setups where subjects also congregated in other settings, such as on the schoolbus to and from school, indicating the need for comprehensive treatment of all sites of congregation.

Influenza: Over the last decades, large amounts of research have been conducted on influenza transmission, but consensus is far from clear. Literature reviews provide convincing evidence of both closer-range/fomite transmission, and transmission via aerosols (though not without divergent opinions). Computational models can also predict dominant aerosol transmission of influenza.

Appendix 2.2: Summary of studies examining the epidemiology of disease in closed or semi-closed settings

Author	Setting	Virus (year)	Special features / identified risks	Likely dominant route(s) of transmission
Blumenfeld	Hospital ward	H2N2 (1957)	Pandemic virus	All routes possible
McLean	Hospital Ward	H2N2 (1957)	UV light, pandemic virus	Aerosol
Moser	Aircraft	H3N2 (1977)	Point source, no ventilation	Aerosol
Klontz	Barracks and aircraft	H1N1 (1986)	Outbreak amongst a squadron	All routes possible
Morens	Nursing Home	H3N2 (1989)	High level care patients	Contact
Cunney	Neonatal Unit	H3N2 (1998)	Twins, mechanical ventilation	Contact / Droplet
Awofeso	Prison	H3N2 (2000)	Infection introduced into a closed community	All routes possible
Han	Tour group + aircraft	H1N1 (2009)	Talking with index case, pandemic virus	All routes possible
Baker	Aircraft	H1N1 (2009)	Pandemic virus	All routes possible
Apisarnthanarak	Hospital ward	H1N1 (2009)	HCW providing direct care, pandemic virus	Contact / Droplet
Wong	Hospital ward	H3N2 (2008)	Aerosol generating procedure and airflows	Aerosol
Cui	Train	H1N1 (2009)	Close contact and prolonged exposure associated with transmission	All routes possible
Piso	Bus	H1N1 (2009)	Very low secondary attack rate	All routes possible
Magill	Hospital	H1N1 (2009)	Transmission amongst HCWs significant	All routes possible

Killingley, B. (2012) Investigations into Human Influenza Transmission. [Unpublished PhD thesis]

Various real-world interventions and controlled studies have been completed:

- Deployment of upper-room GUV in a hospital during a 1957 influenza outbreak almost completely prevented transmission, suggesting the vast majority of transmission is airborne.
- Studies in Bangkok and Hong Kong estimated (albeit speculatively) 41-52% of transmission in control arms was via the aerosol route, due to increased symptoms potentially consistent with airborne infection in the intervention households.
- A recent study attempted to cause flu transmission from deliberately infected research participants, but (in contrast to an earlier pilot study) very few infections occurred, meaning no firm conclusions were drawn. A US-based followup, launched this year, hopes to improve on this design by using donors with community-acquired infections (removing the possibility of an experimental infection affecting shedding characteristics).

There exists highly convincing evidence of all major transmission routes for influenza. However, it seems reasonable to take as a lower bound 40% airborne transmission (the lowest value in the Bangkok/Hong Kong intervention study), and an upper bound of 80% (based on the success of the Livermore hospital study).

Tuberculosis: TB stands out for having a potentially indefinite incubation period. Only 5-10% of people infected with the bacteria ever develop symptoms, so many carry the disease for long periods without knowing. TB is transmitted through the air by aerosol droplets from people with active symptoms, and may even be transmitted by some asymptomatic carriers.

It is extremely infectious; fewer than ten bacteria may cause an infection, compared to as many as 40,000 bacteria in a single sneeze. As a result, a quarter of the world's population has been infected. In a 1961 study, a team from Johns Hopkins exposed two groups of guinea pigs to air from a TB ward, the air going to one group having been irradiated with UV light first, in order to demonstrate airborne transmission. Infections only appeared in the group with untreated air, showing that UV light is effective at killing the pathogen. Many other studies are available showing the effectiveness of building-level interventions on TB.

Common cold viruses: From the 1970s to the 1980s, two teams carried out human challenge trials on rhinovirus, where volunteers challenged with rhinovirus interacted with healthy volunteers. The first, in 1978 in Virginia, found that hand-to-hand transmission is an efficient way to transfer rhinovirus infection, while attempts to cause large droplet and aerosol spread mostly failed. Then in a three-study series running through 1987, a Wisconsin team built a challenge model, found virucidal treated tissues were effective in preventing transmission of rhinovirus, and found that inducing infection via a fomite and large droplet route was ineffective, while measures designed to specifically induce aerosol routes of transmission maintained high attack rates.

The two teams came to two separate determinations of the importance of aerosol transmission. However, the Wisconsin studies seem more likely to have generated accurate results. For example, efforts (not described in the paper) were made to reduce air leakage in the Wisconsin study[7]. Despite these controlled natural exposure studies being some of the highest-quality research ever performed on pathogen transmission, the results have not caused significant change.

Another study in Army barracks demonstrated a newer building with a lower ventilation rate was associated with an average of 45% higher risk of common cold infection (typically adenovirus), providing strong evidence that aerosol transmission is important for other common cold pathogens.

In general, despite the more limited range of studies, convincing evidence shows a significantly higher fraction of transmission might be via the aerosol route than has historically been acknowledged. We think it is reasonable to say that between 20% and 90% of common cold transmission occurs through the aerosol route.

Limitations

The body of work on this topic is of limited size and quality. Simply isolating a mode of transmission (even before attempting to quantify importance) outside of a highly controlled environment is difficult, and many observational studies suffer from confounding variables or lack of important data, such as ventilation rates. Methods exist to retrospectively model the importance of various transmission routes based on previous data, but suffer from significant gaps, limiting their use.

Another challenge for both the interpretation and usability of data is the development of pervasive errors in the medical literature, significant enough to obviate the results of some studies. Some of the most common are:

- **Aerosol particle size:** Many studies assume a binary cutoff of 5um for aerosolized pathogens, and assume that every other pathogen acts ballistically (following a trajectory towards the ground as opposed to remaining suspended in air). This is due to a nomenclature confusion, whereas in reality, particles up to at least 100um can act as inhalable aerosols, settling towards the top of the respiratory tract. Speaking, singing, or shouting can produce more of these larger particles.
- **Close-range aerosol contact:** Many studies assume that all transmission that happens at short range (shorter than 1-2m) is due to large droplet transmission, when in fact aerosol transmission can account for up to 90% of exposure at 0.3m, and close prox-

7 We received this information from an expert in the field who had personal knowledge of the study design.

imity can cause more efficient aerosol transmission due to higher pathogen concentrations nearer to the source.

Despite the above limits and scientific issues, it is effectively certain that some significant portion of respiratory disease transmission is via indoor air. The uncertainties are critical for estimating cost-effectiveness of interventions, and for understanding what other mitigations are helpful for reducing the burden of respiratory diseases, if non-airborne transmission is significant.

Mechanical Interventions to Improve Air Quality

Summary of options

Known effective interventions to improve indoor air quality include increased outdoor air ventilation, high-efficiency particulate air (HEPA) filtration, and germicidal ultraviolet (GUV) light. Within GUV, there are two main relevant interventions: 254 nm light, typically generated by mercury vapor lamps, and far-UVC (primarily 222 nm), typically generated by krypton chloride excimer lamps. These interventions are valuable because they are relatively pathogen agnostic and can act as a layer of passive biodefense (compared to developing a specific vaccine).

Ventilation exchanging outdoor air with indoor directly achieves true air turnover, whereas filtration and GUV impact is measured in equivalent air changes per hour (eACH). The resultant eACH in a room outfitted with filters or GUV lights depends on several different factors, including the quality of the filter or power of the lights, the number and placement of lights or filters, and air mixing. In addition, for GUV application, the pathogen in question is relevant since the eACH calculation depends on the percentage of pathogens deactivated over the course of the time frame.

Ventilation and filtration

Ventilation: Strong evidence exists that increased ventilation has a marked effect on infection rates (and health more generally), supporting the efficacy of ventilation as a general method to reduce the prevalence of pathogens. Ventilation also reduces gaseous pollutants, and is the only way to remove CO_2 efficiently. However, in order for ventilation to be effective, the air entering a room must be of higher quality than the air leaving. Outdoor air is an easy source, provided it is of reasonable quality, meaning this strategy can be less effective in highly polluted areas, including many cities. In addition, outdoor air often requires temperature changes to be acceptable indoors, which means expending significant amounts of energy on climate control. Retrofitting an already established ventilation system to provide higher airflow rates can often be very expensive. Ventilation is therefore likely to be a less attractive option for organizations attempting to provide building occupants with cleaner air, given the permanent and continuous added cost of energy use and the fact that increased energy use would work against building standards such as LEED standard compliance. Significantly improved ventilation is also infeasible for many older buildings, which often do not have the infrastructure to support centralized HVAC systems.

In general, mechanical ventilation can follow one of three overall strategies: mixing, displacement, and personalization. Mixing ventilation simply adds clean air to dirty air, where displacement ventilation aims to take advantage of the effect caused by pathogens being emitted in a warm plume, combined with the natural heating effect of humans, which likely creates a thermally stratified layer above head height with a higher concentration of pathogens. This process theoretically results in a risk reduction factor of 1.2-2 for influenza. Personalized ventilation gives each occupant a designated ventilation flow, creating a similar risk reduction factor, though it is likely viable only in environments where people are stationary, like airplane cabins or cubicles. These strategies, or similar variants, may be effective at reducing pathogen transmission, but data is limited.

Of the three categories of mechanical interventions, ventilation seems least relevant for reducing global catastrophic biorisk. Mechanical ventilation has much higher operating costs than filtration and GUV (mostly because of building retrofitting and energy consumption related to climate control). Natural ventilation through open windows and doors is also used in many buildings but is often less reliable due to weather considerations.

Filtration: Filtration involves passing air through a filter designed to remove some proportion of particles from the air. This method is effective in reducing both pathogen transmission and some indoor air pollution, including PM2.5. In addition, outdoor air can be filtered in ventilation systems before being introduced indoors to improve quality. In-duct filters cause a pressure drop; the higher the filtration rate, the higher the pressure drop, meaning more energy is required to move the same amount of air through a building. HVAC filter efficiencies are graded using the MERV rating scale from ASHRAE.

Standalone filtration units (HEPA filters are the most efficient, removing >99.9% of small particles) have been shown to reduce the exposure to pathogenic aerosols under controlled conditions, with 5 eACH HEPA filtration in classrooms being enough to cause a 4-5 fold drop in pathogen dose. In a model of a 30 person restaurant, with baseline US prevalence, increasing ACH of 0.8 to 12 eACH using HEPA filters averted an estimated 54 COVID-19 infections per year, with a gain of 1.35 QALYs.

The addition of filters to existing ventilation systems in a typical model scenario has been shown to reduce the relative risk of infection from influenza by up to 47%, at a total annual cost of $352 (when centrally installed in a hypothetical office environment assuming 25 occupants) for HEPA filters, with MERV 13/14 filters (removing a lower fraction of particles) shown to be nearly as effective at considerably lower costs (total annual cost $156 in the aforementioned scenario, equivalent to $119 per year per unit risk reduction for MERV, compared with $232/year/unit risk reduction for HEPA).

DIY box filters using MERV-13 filters, such as Corsi-Rosenthal filters, have also been reviewed for filtration efficiency and cost-effectiveness and are claimed to exhibit superior performance to commercially available HEPA air cleaners at one-tenth the cost, <$0.072 per cubic foot per minute, versus >$0.7 cubic foot per minute for HEPA air cleaners. Such improvised solutions suggest a potential floor price for scaling up commercially-available filtration.

In addition to reducing pathogen transmission, filtration has benefits for respiratory health and cognition, due to its ability to remove harmful particulate, gaseous, and chemical pollutants. While gaseous pollutants are not removed by HEPA filters, an additional filtration layer, such as an activated carbon filter, can be added. Given these benefits, widely investing in improved filtration in built environments is likely to help the population even in non-pandemic years.

Filtration (particularly using portable air cleaners) is a viable option for high levels of eACH up to CDC hospital standards (8-12 eACH), where it is still relatively cost-effective. It also helps to reduce particulate and chemical pollution, which is relevant for immediate health concerns, such as chronic respiratory health and everyday cognitive functioning. However, portable air cleaners can be inconveniently noisy and therefore unattractive for widespread long-term use, suggesting that efforts to reduce noise pollution might be an avenue for increased adoption.

Germicidal Ultraviolet (GUV) Light

GUV technology uses light in the UVC band, up to 280 nm in wavelength. It seems to be the most promising technology for GCBR reduction because it can clean air considerably more quickly than filtration or ventilation, by directly inactivating pathogens through protein and DNA damage. It could also be more energy efficient in principle, is straightforward to install as a retrofit, and produces no noise pollution. At very low wavelengths (far-UVC), it can be used to reduce surface and close contact transmission as well.

Wavelengths at the higher end of the UVC spectrum are easier to produce via lamps, but are harmful when aimed at humans, causing corneal and skin damage, so protective installation is necessary. Additionally, given that GUV produces non-trivial amounts of "smog," filtration and ventilation are complementary to remove any additional indoor air pollutants created through the use of GUV itself.

254 nm UVC: 254 nm UVC[8] is often deployed in an upper-room system or in a ventilation duct. In upper-room systems, light fixtures direct UVC light to the top of the room, so harmful UVC does not intersect with humans below. Upper-room UVC also requires some airflow (equivalent to fans at low speed) to ensure that the 'breathing zone' is receiving sufficient disinfected air. In-duct systems are designed to disinfect air as it passes through the HVAC system. Studies have shown 80% efficacy in TB transmission reduction with guinea pigs exposed to hospital air, with strong evidence demonstrating reduction of various pathogens' concentrations under laboratory conditions. Models predict between a 1.6 and 3.4-fold decrease of TB infection in a hospital waiting room using lighting with eACH 7.5 and 31.7, respectively. Another model predicts a 90% decrease in infection risk over six hours in a classroom outfitted with 254 nm light, either as an in-duct installation or as an addition to a portable air filter. Strong knowledge of the mechanisms of UVC allows the creation of predictive models for inactivation ability by pathogen. 254 nm light is also used to disinfect surfaces in unoccupied spaces. 254 nm UVC is already more cost-effective than other IAQ interventions and is safe if installed correctly, so as not to interact with room occupants. However, safety issues must be taken into account during design and installation. While cost is reasonable for at-scale deployment, more expertise in design and installation is necessary.

Far-UVC: Recently, significant interest has grown in a narrow band of UVC light of 200-230 nm, which is ionizing enough to inactivate pathogens, but not to penetrate the outer layers of human skin or the corneal layer. Far-UVC can be used much more easily in many environments to inactivate pathogens without harming humans, so installation does not have to direct light only to the upper part of the room or within air ducts. It can be used to interrupt surface, short-range aerosol, and droplet transmission, which is difficult to prevent via other mechanical interventions, making it potentially the most effective intervention for reducing existential biorisk. Far-UVC lamps have been so recently developed that this end of the spectrum is generally not included in analysis of current interventions, and lacks long-term human safety data.

Far-UVC has broad germicidal activity, with low doses (permitted under current regulations) sufficient to inactivate 90% aerosolized coronaviruses in eight minutes, and 99.9% in 25 minutes. Efficacy can vary from pathogen to pathogen, but far-UVC causes no currently known significant damage (1, 2) to human skin and cell models even at doses significantly higher than required germicidal doses.

Long-term exposure studies in humans and adjustment of regulations could be required for widespread acceptance, and further studies are warranted. Given that far-UVC (under test conditions) provided up to 184 eACH at an irradiation level already permitted in the US for eight continuous hours, no evidence has yet raised concrete safety concerns. A recent review indicates strong safety evidence for 222 nm far-UVC light for both skin and eyes. Far-UVC lamps also generate ozone and oxidized organic aerosols, which must be mitigated by ventilation and filtration for safe far-UVC use. Safe levels/limits of pollutant exposure are already regulated by a number of bodies, although no standard procedure exists for testing purposes, and estimates for production vary widely, so quantification is difficult.

Far-UVC light is difficult to produce and current lamps

8 254 nm is the wavelength emitted by readily available low-pressure mercury lamps. The DNA absorption peak, and thus peak germicidal effectiveness, is at 265 nm, which provides 15 % higher disinfection efficiency compared to the same dose of 254 nm light. LEDs can easily be tuned to 265 nm and start to see cost-competitive adoption in, e.g., water disinfection.

are expensive, strictly limiting the consumer base for far-UVC lamps so far. Krypton chloride excimer lamps, which are commercially available, emit light in the far-UVC range at 222 nm, which Blatchley et al. found to provide roughly twice as efficient inactivation of viruses, including SARS-COV-2, as light emitted at 254 nm from standard low-pressure mercury lamps. The cost per mW of krypton chloride excimer lamps was 100-500 times that of low pressure mercury as of 2022.

Widespread commercialization would greatly benefit from the development of solid-state emitters in the correct light band, but it is difficult to estimate when these will become commercially available. Far-UVC LED technology requires further fundamental research into materials and manufacturing techniques in order to improve efficiency and cost. For an extremely rough estimate, we can say that discovery and characterization of a novel LED material might be accomplished in about 5-10 years (assuming multiple streams of research running in parallel) and the requisite production research, which would need to take place following at least the initial demonstration of a useful material, would take another 4-6 years. Achieving design and manufacturing breakthroughs with current UV LED materials may also take 4-6 years. Assuming that some of those research pathways are successful, demonstrating that efficient, cost-effective far-UVC LEDs are feasible, it might take a further 4-6 years to achieve full commercialization. This leads to a rough estimate of between one and two decades until we expect to see widespread impact of LEDs. Commercial investment could accelerate this somewhat if safety studies are very promising, and given proven commercial viability of existing lamp-based systems in hospitals.

Earlier market-readiness of solid-state far-UVC emitters might be achieved by using blue lasers, a more mature technology, and frequency-doubling their output into the far-UVC wavelength range. Frequency-doubling crystals have been demonstrated in isolation, and combining them with the laser into a single monolithic chip requires no fundamental engineering breakthroughs as with far-UVC LEDs. This frequency-doubling technology could be demonstrated within two years and be commercially available within three years.[9] Modest funding could potentially accelerate these timelines.

Cost and cost-effectiveness of different mechanical interventions

While the potential and expected impact on airborne pathogen transmission matter more for assessing the attractiveness of different mechanical interventions from an x-risk perspective, cost and cost-effectiveness matters to government and corporate adopters since these potential adopters are more likely to adopt these interventions at particular price points.

As a case study in the cost of upgrading ventilation for a large public space, the Center for Health Security report on school ventilation (Appendix F) focuses on a direct comparison between the cost-effectiveness of ventilation versus the early CDC surface cleaning guidelines. A more comprehensive analysis was prevented by the knowledge gaps in aerosol transmission discussed below. Based on expert interviews, the report estimates that a school would need at least $6,000 per classroom for upgrading HVAC systems to provide air quality equivalent to about 5 to 7 air changes per hour (ACH). At an estimate of 2.5 million public school classrooms nationwide, the cost of upgrading all schools would be at least $15 billion (although students in each upgraded school would benefit before all schools were upgraded, so the total outlay is not needed for intermediate benefits). Rothamer et al. show that increasing airflow in a schoolroom from their measured baseline of 1.34 ACH to 5 ACH[10] reduces the probability of infection by about half.

This report only includes the cost for upgrading systems and running new systems at a basic level, but does

9 This approach is currently being pursued by the startup Uviquity; timeline estimate provided in personal communication.

10 Using the Lancet Commission standards, these goals would allow the school to achieve the NADR category “Better”, and if >6 ACH, then category “Best”.

not include the costs of post-upgrade energy consumption or increased operation and maintenance. If upgrades are done primarily through ventilation, there is substantial added energy consumption, estimated by one expert at a 15-20% overall energy cost increase for 10 eACH[11] throughout a school, especially if the upgrade does not explicitly target energy efficiency through mechanisms like installing energy recovery ventilators.

In order to estimate the cost of upgrading the general stock of public buildings in the US, we start from a published estimate that educational space uses 14% of commercial floorspace in the US, and estimate that it is between 10-20% of commercial floorspace (CI:90%). We'll additionally estimate that public K-12 buildings are 30%-70% of educational floorspace (CI:90%). Using this and a cost-estimate drawn from the earlier CHS report on school ventilation, we estimate the total cost of upgrading air quality systems in all the commercial buildings in the US to be $120-$420 billion (CI:90%).

This figure is prohibitively expensive for rapid implementation. However, it assumes the cost of upgrading systems stays fixed, but given that this field is getting increased attention and investment, costs might come down considerably over the next decade. For example, we use the $15 billion estimate for upgrading school HVAC systems. However, if air quality improvements included GUV to achieve target standards, rather than relying on HVAC alone, the cost could be significantly lower due to the higher cost-effectiveness of GUV. Also, more targeted programs addressing high-priority public spaces as an intermediate step would be less expensive and still reduce pandemic risk and improve everyday health. For example, building on the estimate of $15 billion to upgrade public primary education facilities, we can produce the following upgrade cost estimates using the percentage breakdown of commercial building stock:

- Healthcare facilities and hospitals, 4.7% of commercial floorspace: $10 billion
- Food service, 2.1% of commercial floorspace: $4 billion
- Public assembly space, 6.4% of commercial floorspace: $14 billion
- Malls, 6.8% of commercial floorspace: $15 billion
- Offices, 18.3% of commercial floorspace: $39 billion
- Religious institutions, 5.2% of commercial floorspace: $11 billion

If upgrades to public buildings were to be implemented across a decade in the US, ~$20 billion a year would be spent on a complete air quality upgrade program. For comparison, in 2021 alone, the US Department of Defense spent $10 billion on facilities maintenance and construction and $141 billion on weapons and systems procurement. We use the comparison with defense spending because biosecurity is an important component of national security and these figures demonstrate what people are willing to spend on defense, not because we would expect government spending to fully fund this program.

Researchers from the Institute for Progress and the Johns Hopkins Center for Health Security demonstrate that the COVID pandemic cost the US at least $10 trillion in combined economic and health losses.[12] Using their lower-bound numbers and lenient assumptions for a future pandemic (half as destructive as COVID), they estimate that it would be worth $50 billion to reduce the risk of a future pandemic by 1%. Naturally, given the optimism of these assumptions, pandemic reduction efforts are potentially worth much more. Based on this CHS report, we estimate that reducing the risk of a future pandemic that is as bad as COVID by 1% would be worth $100 billion, and it seems highly

11 Although the expert provided the energy cost estimate for 10 eACH, it is uncommon for buildings to have the HVAC capacity to achieve over 6 eACH through ventilation alone, as stated below in Table 1.

12 Order-of-magnitude check: In the US, about 1 million people have died of COVID. Government agencies typically use $1-10 million for the value of a statistical life, i.e., how much should be spent to save a life. These figures would place the cost of COVID at $1-10 trillion in life loss alone, so hypothetically the US government should be willing to spend up to $10 trillion to fully avert another COVID-size pandemic.

likely that this program would reduce the risk or severity of a pandemic by more than 1%.[13] We use COVID as a baseline for simplicity of comparison, but given that future pandemics could be much more severe, the benefits of IAQ interventions should not be limited to COVID-like pandemics.

The below studies give some indications of cost and cost-effectiveness (in terms of ACH/eACH) for different IAQ interventions. While actual implementation costs vary somewhat depending on the installation, the following points and Table 1 broadly summarize cost and cost-effectiveness[14]:

- Upper-room UVC with 254 nm light looks to be roughly nine times as cost-effective as mechanical ventilation, and filtration ranged from being half as cost-effective to about the same cost-effectiveness as mechanical ventilation.
- GUV and filtration are likely to have predictable annual costs, whereas mechanical ventilation costs will vary seasonally (related to outdoor temperatures).
- GUV is easier to retrofit compared with HVAC systems in many cases.
- Operating costs of GUV technology scale much better at higher levels of eACH than ventilation or filtration alone.
    - For ventilation, operating costs can be high due to large amounts of energy spent on climate control and air mixing.
    - For filtration, operating costs can be high as a higher number of filters reduces air pressure, so more energy is used to move the same amount of air through a building, or a fan upgrade is needed.

Nardell (2021) compares the cost-effectiveness of different mechanical interventions, determining that upper-room 254 nm UV is the best option when comparing it against mechanical ventilation and filtration (portable air cleaners). Upper-room UVC was calculated to produce up to 24 eACH under standard air mixing conditions (i.e., air mixing resulting from convection currents and people moving through the room), and was estimated to cost roughly $14 per eACH in a hospital room, making it over nine times more cost-effective than mechanical ventilation. By contrast, three portable air filters that were compared against mechanical ventilation and upper-room UVC were estimated to cost $100-$300 per eACH, ranging from about half as cost-effective as mechanical ventilation to about the same cost-effectiveness. As a baseline, the model estimates that mechanical ventilation alone provides approximately one air change for about $135.

13 See estimate in "Rough Estimate of Impact" section.

14 In the table, we focus on upper-room UVC and portable air cleaners and not in-duct UVC and filtration attached to HVAC systems because the Nardell (2021) paper, on which we base the cost-effectiveness for various intervention, does not examine these options, and it is difficult to replicate the procedure used for their cost-effectiveness calculations.

Intervention	Upper-bound of effectiveness (ACH/ eACH)	Installation cost per ~70m² room ($ USD)	Relative operational cost	Cost-effectiveness[15] ($/ACH or eACH)
Mechanical ventilation	6 ACH[16]	$6000 (modern HVAC system, to provide air quality equivalent to 5-7 ACH)	High, as many HVAC systems must be updated to meet current standards for filtration and flow rate. Increased ventilation may also dramatically increase costs of climate control.	~$135 per ACH
In-duct 254 nm UVC	6 ACH (limited by HVAC efficiency)[17]	$40-150[18]	Medium, as can be retrofitted into systems with inadequate power for sufficient filtration at a given flow rate.	$7-$25 per ACH
Portable air cleaners	12 eACH[19]	$1000-1500 (multiple HEPA purifiers equivalent to 4-6 ACH)[20]	Medium. Draws more energy than central filtration due to lower fan efficiency, but units can be selectively placed.	~$110 per eACH
254 nm UVC as upper room	24-100 eACH[21]	$1500-2500 (8-12 incremental eACH)[22]	Low, and costs are likely to be stable annually since there is no need for climate control.	~$14 per eACH

15 The dollar cost of one equivalent ACH for the first year, including installation/start-up costs. We were unable to find sufficient information to amortize costs over subsequent years; we believe that amortization would make options other than ventilation even more cost-effective.

16 Most HVAC systems in public buildings in the US do not have the duct or blower capacity to be increased to 6 ACH

17 In-duct UVC systems can reach very high levels of air cleanliness, but the eACH is limited by air delivery rate into the target room.

18 Estimated from various commercial quotes ($800, $3000); installed in central HVAC that can already provide 6 ACH, assuming an average of 20 such rooms per such HVAC installation given average commercial building size.

19 This is the preferred ACH level recommended by the CDC for an airborne isolation rooms in hospitals and is achievable via filtration, but cost and noise may be prohibitive beyond this level.

20 Source is the same as above, hypothetically using MERV filters could achieve similar eACH at a tenth of the cost of current commercial models.

21 Upper-room UVC, with good air mixing, has been shown in the real world to achieve 24 eACH and studies suggest it's possible to achieve >100 eACH when paired with adequate ventilation.

22 Source.

Intervention	Upper-bound of effectiveness (ACH/ eACH)	Installation cost per ~70m^2 room ($ USD)	Relative operational cost	Cost-effectiveness[15] ($/ACH or eACH)
Far-UVC	128-322 eACH[23]	$2500-5000 (10 incremental eACH or 30 "breathing zone" eACH)[24]	Similar to upper-room, but higher due to current bulbs being less efficient.	$15-46 per eACH[25]

Table 1: Summary of different mechanical IAQ interventions in terms of upper-bound effectiveness, installation cost, relative operating costs, and cost-effectiveness [various sources].[26]

Given the pollution that far-UVC produces, rooms outfitted with far-UVC would also need to have appropriate ventilation or filtration to limit harms from pollutants. These mitigation measures would contribute to the eACH and raise the cost of far-UVC installation, so although we do not know the extent of ventilation/filtration needed, we can assume that far-UVC is somewhat less cost-effective than described in Table 1. However, we are primarily interested in far-UVC for its capacity to address aerosolized pathogens in breath plumes. Although 254 nm UVC installed in an upper-room fixture is sufficient to minimize ambient pathogen load from aerosol persistence, much higher eACH, or more directed UVC, is necessary to minimize spread at close conversational distance, like at a party or between children working together in a schoolroom.

Modeling the efficacy of interventions

There are several models to predict the efficacy of air quality interventions, particularly within a given room or building. However, building-scale models have not been linked with population-scale transmission reduction for a robust set of infection scenarios. Ideally, policy and funding would be informed by a comprehensive set of estimates on how different programs of built-environment air quality improvements impact pathogen transmission in the general population. In order to develop such estimates, we need a detailed population model with a wide array of varying built-environment inputs created using experimental data from observed transmissions.

Room-scale models

Room-scale models predict the efficacy of interventions on a small scale. Specifically, they assess the probability of infection based on the mix of susceptible and infectious people occupying a space, and the rate at which an infectious person is able to infect susceptibles. This type of environment-specific model can be extraordinarily detailed, including factors such as mask effectiveness, different air cleaning interventions, and airflow in and out of different sections of a given environment.

The most common method is based on the Wells-Riley equation, which expresses pathogen emission from infectors in terms of quanta, a single quantum being the average amount of pathogens required to cause an infection. The standard equation assumes a perfectly well-mixed room, meaning that each emitted quantum

23 322 eACH is the top end of the estimated ACH in a "high" exposure scenario using five lamps, though this did not exceed the ACGIH threshold limit value for the skin. This could potentially be even higher. For any scenario, the eACH will depend strongly on the number of lamps used.

24 Price range from conversation with a low-wavelength light vendor.

25 Very rough calculation based on upper-bound eACH and installation cost ranging from $5000-15,000, does not include operating costs or pollution mitigation.

26 These costs are very rough and actual installation and operational costs are highly variable, depending on room size, electricity prices, and outside temperature.

has a 63% chance to cause infection in a susceptible individual, assuming no removal of pathogens from the air.

The difficulty with this model is estimating the quantum generation rate, which is calculated backward from epidemiological studies, but involves a significant amount of inherent uncertainty. In general, the rest of the model (assuming a well-mixed environment) follows numerically from this quantum generation rate, meaning most of the uncertainty in the model (such as pathogen emission and infectivity) is included in this number.

Additionally, assuming a well-mixed environment can cause some errors. While most indoor spaces are reasonably represented by the well-mixed assumption, there are many situations where this assumption is not accurate, particularly at the level of interpersonal interaction such as close conversation. There are efforts to improve upon the basic model by estimating the quantum emission rate from the fraction of air that is rebreathed, based on real-world examination of CO_2 levels.

City-scale models

Many population models use the SEIR model, which stands for "susceptible, exposed, infected, recovered." (The simplified version, the SIR model, omits the "exposed" classification.) This model typically uses a set of differential equations that dictates the chance of a susceptible person becoming infected based upon number of exposures to infectors in a simulated population, and adjusts this chance based on the proportion of the population that is currently infectious.

However, to model the effect of the deployment of air safety interventions, assuming a homogeneous population is not appropriate. Unlike a universal masking policy, or vaccination, which can be modeled to have more general effects, air safety interventions may have very different impacts on the progression of a pandemic depending on the environment of deployment (e.g. installations in a restaurant may have very different effects to installation in schools).

To avoid this problem, an SEIR model can be modified to have compartments for different parts of a population, where the population is split up into different classes of people (such as children, teachers, workers, stay-at-homes, etc.) and different environments (such as supermarkets, schools, offices, homes, etc.). By modeling populations in this way, the effect of reducing spread in particular areas can be estimated. Constraints on computing power are a problem for more complex models that involve modeling of different types of populations, such as the variance between large cities in different countries or the difference between a city and a rural environment.

Integration of room- and city-scale models

Currently, literature using integrated models is sparse. One simplified model of Hong Kong predicts that increasing ventilation rates by 5 ACH in all public buildings reduces the attack rate of smallpox by ~80% and total infection by ~97% in a medium transmission scenario. The same model showed that a similar increase in ventilation rates had significant effects on reducing peak and total infections in simulated influenza outbreaks even with varying proportions of airborne transmission. A later, more detailed Wells-Riley/human behavior integrated model predicted that increasing ventilation in all buildings threefold (to 3-6 ACH depending on building) would suppress a smallpox outbreak, given estimated disease transmission as a function of ventilation rates. These papers provide specific examples of an end-to-end generated model, but they use pathogen and intervention strategies different enough from a catastrophic outbreak that the results are not particularly generalizable.

Studies using a Wells-Riley equation to model the effect of ventilation on population transmission predicted that ventilation rates up to 12 ACH brought a hypothetical airborne virus with a quantum emission rate of ~26 from an R_0 of ~10 to <1. A second Wells-Riley/SEIR model predicted a 60-80% reduction in R_0 for a hypothetical airborne pathogen with 15 additional

ACH. These models, aiming to provide a more general estimation technique, do not simulate a population; rather, they integrate the Wells-Riley with a standard SEIR model and implicitly assume that all transmission is airborne, and that it all occurs in places where the improved ventilation reduces transmission. In addition, unlike many models focused on current endemic pathogens, these do not account for cost-effectiveness.

How could models be improved?

Indoor air quality is a public good, as the greatest benefits of indoor air quality improvements will come from widespread adoption and accrue to the general public. Demonstrating the connection between indoor air quality improvements and population-level pathogen transmission is important to drive policy changes and large-scale government investment.

Ideally, a model would be able to predict the efficacy of air quality interventions, taking into account:

- Infectivity of a pathogen, including shedding rates of an infected person, infectious dose, and incubation period.
- Uncertainty about the relative importance of transmission routes and locations, such as inclusion of non-indoor air transmission.
- Consideration of close-range mitigation.
- Effectiveness of air quality interventions (most likely in terms of a general factor such as eACH).
- Effectiveness of air quality interventions taking into account the adoption rate and environment.
- Effectiveness of air quality interventions when combined with other interventions (such as masking, lockdowns, medical countermeasures), even when these might be deployed later on in pandemic progression.

A model should then be able to produce estimates for:

- Effect of air safety interventions on reducing R_0 in a certain population, given infectivity of a pathogen.
- Extent of pandemic control of air safety interventions, both alone and with other pandemic control measures (how much more infectious a pathogen would need to be in order to become a global catastrophic pandemic after deployment of air safety interventions).
- Ability of air safety interventions to buy time to implement other measures (what range of pathogens humanity will have time to respond to which we would not have absent air safety interventions).
- Effect of air safety interventions on other pandemic control measures (if e.g. supermarkets and hospitals have stringent air safety interventions, could a lockdown have a greater chance of bringing a pandemic under control than you would predict on transmission reduction alone?).

Existing efficacy studies: Studies investigating various interventions are largely unhelpful for validating models or understanding the effect of those interventions at a population level. For example, recent studies in laboratory chambers clearly demonstrates how far-UVC light greatly reduces pathogen load in the air, but that reduction in pathogen load has not been directly connected to precise reduction in transmission. There are studies that estimate the infectious dose of various pathogens, but they provide an imperfect bridge to population-level intervention efficacy models, due to the wide range of estimates and the variation among individuals. On the other hand, several studies intended to directly investigate the effects of interventions have serious issues with methodology and practicality that limit their usefulness.

Rough Estimate of Impact

In this section we hope to provide a reasonable sketch of how much air quality improvements in public spaces can reduce disease transmission across a population. The following calculation is extremely rough, and a more informative, detailed model is sorely needed for a full analysis of possible public health measures.

When considering air quality upgrades in built environments, we focus on public spaces where superspreader events are more likely and improvements are easier to confirm. This focus on superspreader events seems especially important for reducing the impact of pandemic-capable pathogens, as superspreading appears to drive the large outbreaks that lead to pandemics and serious epidemics. In other words, diseases that exhibit high variation in transmission patterns are associated with larger outbreaks. For this reason, we base our following assumptions on COVID transmission research, since it seems likely that respiratory virus pandemics will obey high-variance dynamics similar to those of COVID.

Assume that 85-98% of transmission occurs indoors,[27] that 50-80% of respiratory virus transmission occurs in public spaces[28] (including offices, schools, gyms, theaters, eateries, etc.), and that ideal adoption of current pathogen mitigation measures in all public environments (including ventilation, filtration, and especially use of GUV light) can reduce transmission by 70-95% in each of these spaces.[29] Each of these factors is independent of the others,[30] so by using the complete described program of air quality interventions to address transmission in public spaces, overall transmission in the population can be reduced by 30-75%, with a median estimate of 52.5%.

	Low	High
Proportion of transmission occurring indoors	**85%**	**98%**
Proportion of indoor transmission from public spaces	**50%**	**80%**
Transmission reduction (in these spaces) from ideal intervention adoption	**70%**	**95%**
Total transmission reduction in population	**30%**	**75%**

To illustrate the impact of this reduction on the spread of cases, we use an SIR model provided by Witold Wiecek. Consider the case of an epidemic sharing the features of the first wave of COVID, particularly with $R_0 = 3$. We have modeled the spread of this epidemic in a population of 2 million people, a city roughly between the sizes of Chicago and Philadelphia.

For an R_0 of 3, we see:

- Over 356,000 infections after three weeks, representing about 18% of the city's population.
- Over 1.8 million infections after four weeks, representing about 90% of the city's population.

Considering the median case of transmission reduction, where an ideal intervention program reduces R_0 by roughly 50%, we see:

- 624 infections after three weeks, representing about 0.03% of the city's population.
- 1,893 infections after four weeks, representing about 0.1% of the city's population.

Even in the low estimate of transmission reduction, where an ideal intervention program reduces R_0 by roughly 30%, we see:

- 9,797 infections after three weeks, representing about 0.5% of the city's population.
- Over 84,000 infections after four weeks, representing about 4% of the city's population.

In addition, for the median case with an $R_0 = 1.5$, it would take 65 days to reach over 18% of the city's population, over three times as long as the original case of $R_0 = 3$.

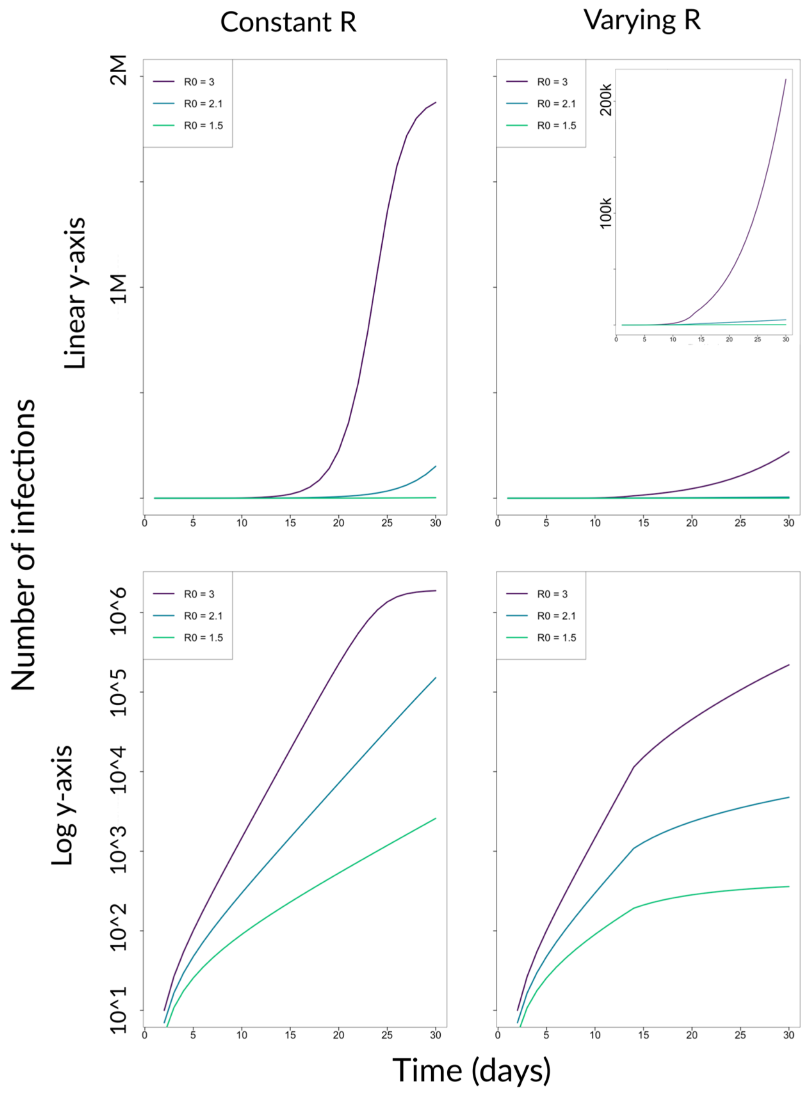
The figure below shows two SIR examples, each plotted on both a linear and logarithmic scale for clarity. The first example echoes the description above, where we show how R_0 affects pathogen transmission, given a single R_0 over 30 days. However, the reproduction

27 For COVID, it appears that 86-98% of transmission occurs indoors.

28 It is difficult to know how much transmission generally occurs in public spaces. However, for the high end of the estimate, we refer to this estimate of where study participants contracted COVID. Additionally, early in the COVID pandemic, it was estimated that around 80% of new infections were generated by about 10% of cases (Nature, Science), implying public settings and especially superspreader events had a very large role in spread. A low end is even less clear, but as stated above, other viral pandemics are likely to follow similar dynamics as COVID.

29 This rough estimate is based on the studies linked in previous sections on the efficacy of various indoor air quality interventions; we assume that studies are mostly, though imperfectly, reflective of real-world use cases.

30 I.e., in order to find overall transmission reduction, we just multiplied the listed factors.



number may be reduced in a given population over the month due to behavioral changes. To provide a very rough sense of a changing epidemic, the second example (labeled "Varying R") uses R_0 until day 14, at which point we replace R_0 in the model with Rt = ½ R_0. The code used to generate these plots can be seen here.

This transmission sketch is extremely rough on many counts, and illustrates the need for greatly improved models connecting building improvements with population transmission. The elements that especially contribute to the inaccuracy:

- As described in the introductory paragraphs, the factors that went into the table had to be roughly estimated from proxies.
- We cannot expect ideal adoption of mitigation measures.
- Other pandemic-capable respiratory viruses might have dramatically different dynamics from SARS-CoV-2.
- Further technological development of interventions could reduce transmission even further.
- We assume there is no self-correcting behavior in the population as a result of IAQ interventions.[31]

31 Self-correcting refers to situations like during the COVID-19 pandemic, when people appeared to dynamically adjust their behavior based on apparent COVID-19 prevalence.

We prioritize this program not because of obvious cost favorability,[32] but because of its capacity to address superspreader events and international spread (e.g., by greatly reducing transmission in airports), and because it is a program of "passive" interventions, which do not rely on individuals' actions to achieve the majority of the gains. (Contrast this with the "active" interventions described in Kevin Esvelt's "Delay, Detect, Defend" Geneva Paper, such as equipment, resilient production, and diagnostics.) Comprehensive pandemic defense programs should "stack" interventions for dramatic reduction in transmission. The most transmissible pathogen we know of is measles, which is estimated to have an R_0 of around 20, so an ambitious pandemic prevention program might aim to reduce pathogen transmission by 98%, bringing R_0 of measles to 0.4. This target would prevent a pandemic of any measles-like or even significantly more transmissible pathogen.

Overall, we can be confident that these interventions effectively reduce pathogen load in the air, but we cannot precisely estimate their impact on population-level transmission without a more robust and detailed model.

Bottlenecks and Funding Opportunities

What are the bottlenecks?

1. **Highly general, imperfect metrics:** Existing air quality metrics, such as those set by ASHRAE, are not ideal targets for air quality interventions with the goal of reduced infection. Targets should be founded on both pathogen load in a room and pathogen load that an individual receives. The Lancet Commision's NADR may be a good metric to implement widely.
2. **Difficulty in understanding the relationship between pathogen load and infection cases:** The relationship between inhaled pathogen load and infection cases is unclear in general, and will be different for different pathogens. Even given better estimates of pathogen load through a detailed model, the research necessary to experimentally determine the relationship between air quality and infection rates will be complex and costly.
3. **Expense of existing air cleaning systems:** Installing GUV lights and more portable air cleaners in rooms is expensive on a per-unit basis, and upgrading ventilation systems by increasing filtration capacity and/or outdoor air supply involves not only upfront expense, but the additional increase in energy costs over the lifetime of a building. Retrofits must be made with energy efficiency in mind. In many cases, the party responsible for such upgrades/installations may not be the party to benefit from the upgrades, or may consider the benefits uncertain.
4. **Expense of improving air cleaning technology:** Improving air cleaning technology will require large investments, particularly when considering that the far-UVC systems needed to eliminate pathogens at a conversational distance requires both technological development and safety/efficacy testing. Investments in both certification and testing of systems is needed so that consumers know that they are getting a quality product when purchasing.
5. **Difficulty of wide-scale change:** Wide-scale improvements in air quality may require changes to building codes, similar to improvements in fire safety. Policy change can be enormously slow, and building codes are typically the purview of individual municipalities or counties, which would fragment a push for any policy beyond the adoption of ASHRAE standards. Alternatively, there could be a campaign for voluntary corporate adoption, which would require expensive indoor air quality improvements to carry a significant positive reputation.
6. **Public distrust of UV light:** People may primarily associate UV light with cancer risk, and it may be difficult to communicate technical safety details, such as the safety of upper-room installations or the difference between bands in the UV spectrum.
7. **Public acceptance and excitement about clean indoor air:** Greater public awareness, understanding, and support for indoor air quality among

32 We have not done a cost comparison with other programs.

members of the public, as exists for other causes like cancer awareness, would create strong signals for policymakers and firms to invest in relevant technology and regulation. Public perception should regard clean indoor air as a public good, like clean water.

Each of the recommendations below will be associated by number with the bottlenecks we believe are addressed through that recommendation.

What can new funding accomplish?

Funding opportunities exist in advocacy, changing costs and manufacturing, and research.

1. **Advocacy:** Some presently attractive advocacy projects include: development of an ASHRAE anti-infection standard, promoting use of the recently released NADR standard from the Lancet COVID Commission, recruiting high-status businesses to conduct and fund pilots, improving air quality in schools through private and public investments, and creating an umbrella group to coordinate efforts.
2. **Costs and manufacturing:** Advanced market commitments and other forms of investment could drive down the cost of far-UVC solid-state emitters and other interventions. Investments in training could also increase expertise in design and installation of GUV systems.
3. **Research:** Attractive research opportunities include: (a) further establishing the long-term safety of far-UVC, which can help with international deployment, (b) creating reliable ways to test intervention efficacy, which could include applied research programs or controlled natural exposure challenge studies, (c) developing guides to help organizations optimally deploy IAQ fixtures, and (d) social research to improve public advocacy efforts around IAQ.

Advocacy

IAQ policymaking occurs along an adoption curve that includes implementation by businesses, voluntary certification codes, retrofitting government buildings (like schools), subsidies for private renovations, building code requirements for new construction, and codes requiring implementation in existing buildings. We see three advocacy opportunities as immediately attractive:

- **Corporate early adopters:** Promoting the piloting of air quality measures by pro-science corporate and educational institutions (like Google or Stanford) can generate experimental evidence, define templates for intervention programs, establish interventions as desirable, and build a constituency for further advocacy. Independent researchers could also assess and publish the efficacy of such interventions. To give an example, a rough highest cost estimate for fitting out Google's primary campus with upper-room GUV comes to \$5.5m (based on \$2500 per 500ft over 1.1m ft^2). While a large sum, this represents less than 0.06% of Google's annual budget for offices and data center space for 2022. *(Addresses bottlenecks 2, 5, and 6.)*
- **Organizational standards:** ASHRAE standards for indoor air quality are widely adopted by state and local governments, and ASHRAE has an incentive to promote business for its members. Generating a voluntary ASHRAE standard on pathogen content in the air will de-risk adoption for government and corporate decision-makers. Alternatively, the Lancet COVID-19 Commission recently proposed a metric for non-infectious air delivery rates (NADR) that could be incorporated more widely. *(Addresses bottlenecks 5 and 6.)*
- **School deployment in pilot jurisdictions:** Pandemic-proofing schools to prevent learning loss is a timely political goal, and some state and local governments may have COVID relief funds they will need to return if unspent. *(Addresses bottlenecks 2, 5, and 6.)*

Other potentially attractive opportunities are:

- **Attaching IAQ projects to anti-recessionary policies:** A perennial problem for anti-recessionary fiscal policy is a lack of "shovel-ready" projects to fund during an economic downturn. Maintaining a warm base of renovation and construction capacity for IAQ retrofits could then be tied into stabilizer legislation that would automatically purchase tens of billions of dollars worth of IAQ installation in the event of a downturn. *(Addresses bottlenecks 3 and 5.)*

- **Tax subsidies:** Governments could subsidize installation of basic, known effective interventions in schools, offices, restaurants, and other congregate settings. *(Addresses bottlenecks 3, 5, and 6.)*
- **Inspections and data collection on IAQ:** Establishments are already subject to regular health and safety inspections, so it could be mandated that inspectors carry a suite of indoor air quality monitors that measure key air pollutants such as PM2.5, TVOC, CO, NO_2, and carbon dioxide will generate baseline data that serves as a proxy measure for eACH and improved indoor air quality. *(Addresses bottleneck 5.)*
- **Establishing an umbrella organization for IAQ coordination:** If effective leadership can be found, it could be useful to develop a central organization to manage the IAQ projects above, funnel funding to projects, publish analyses of projects' effectiveness, and oversee research and market-shaping activities. *(Could address all bottlenecks.)*

Cost and manufacturing

Two of the key bottlenecks to the mass deployment of IAQ interventions are the costs of existing air cleaning systems and the costs associated with improving air cleaning technology. There are funding opportunities and mechanisms that could address these bottlenecks. Given the current high relative cost of far-UVC lamps, funding could be targeted at developing solid-state far-UVC emitters to replace KrCl lamps (currently expensive and produced by only a few manufacturers[33]). As described above, frequency-doubling blue lasers on monolithic chips is one such promising approach that could significantly reduce the cost and increase the efficiency and reliability of far-UVC emitters relative to KrCl lamps. If prototypes are successful, it will be possible to rapidly scale up manufacturing to produce a high volume of these chips, as they are based on common materials used for existing ubiquitous white LEDs. In the case of 254 nm fixtures, there are also high-power UVC-LEDs that have been recently developed that use relatively little energy to operate and have a long operational lifespan. These may benefit from additional investment to reduce the costs of at-scale production. There could be research subsidies and prizes for fundamental materials and manufacturing research. At later stages of technological readiness, an advanced market commitment (AMC), funded by government, philanthropy, or business, could spur development of a product by committing to a purchase once technology meets certain specifications. AMCs already have a track record, including examples such as Operation Warp Speed, which incentivized COVID vaccine development and acquired COVID vaccines in the US.

As of right now, it is possible to create far-UVC LEDs, but their efficiency is very low and it is unclear whether they can be manufactured in a reliable and cost-effective way. The blue LED was only developed in the 1990s and was considered a major breakthrough at the time; even lower-wavelength LEDs are likely to require the development of new semiconductors and new manufacturing methods. However, if far-UVC LED manufacturing can be made reliable at a high quality, it will be possible to meet mass demand. Another option for supporting this LED development is direct investment or funding for fundamental materials and manufacturing research. Such funding could take the form of, for example, support for PhD students or other researchers working in the field, which is well within the normal activities of several philanthropic or governmental organizations.

There may also be relatively expensive products in the filtration and ventilation space, where costs could be reduced, particularly by increasing the energy efficiency associated with HVAC systems. Expanding the use of energy recovery ventilators (ERVS), which allow exhausted cooling or heating energy to be recovered, should reduce the cost of climate control.

Research

There are opportunities to conduct both life sciences and social research to address the bottlenecks men-

33 Some known manufacturers include: Ushio, Eden Park Illumination, and Sterilray. Ushio is the current leader in terms of lamp efficacy/lifetime/filter quality, and was on the scene earliest.

tioned earlier.

Far-UVC safety testing: Far-UVC is a potentially transformative intervention, and studies to develop a safety record sufficient for wide use in humans should be a high priority. Studies have already been successfully conducted on realistic 3D skin models, with intense monitoring for damage, and some longer-term studies on mice made deliberately susceptible to tumors. Interventions of a similar risk have been proposed based on the evidence of models. In-human longer-term studies could be feasible on a dedicated population (possibly an office block), with monitoring for early signs of damage, combined with an early efficacy study.

Valid efficacy models: Creating a way to experimentally test the efficacy of various IAQ interventions will be a necessary component of engendering and optimizing implementation over the long-term. One model for doing so is the idea described above of randomizing experimental pilots in early adopters.

CNE studies: Another approach is to utilize controlled natural exposure (CNE) studies, which are a version of human challenge studies where uninfected "recipient" volunteers are exposed to infected "donor" volunteers. Despite their ability to provide some of the highest-quality, cleanest quantitative data of aerosols, transmission routes, and interventions, they are uncommon, with only two large-scale studies in the last two decades - one in 2010, finishing with an attack rate too low to be of use and one additional study planned over the next five years.

We think that exploration of CNE studies stands to be a valuable research contribution requiring a high level of cooperation between fields. That said, these studies are still in their infancy; using them to experimentally test intervention efficacy may require significant investment on the order of tens of millions of dollars.

Implementation research: There are fundable opportunities around improving the implementation of IAQ interventions such as the development of guidelines for setting up IAQ systems to optimize performance and address safety concerns. Another set of projects could be centered around developing industry standards for testing products and reporting output values (e.g. Watts) for fixtures.

Public advocacy-related research: There are a range of research projects that could inform public advocacy around indoor air quality as a visible, salient cause. This includes public attitudes surveys around indoor air quality as a cause and support for specific technologies like GUV; early surveys already show broad support for GUV. There could also be research around ways to best educate the public and policymakers about indoor air quality issues, and message-testing to encourage adoption of indoor air quality measures.

Coordination

To provide a rough estimate of the impact of a widespread air quality campaign in the US on endemic disease burden, we made some basic assumptions about the timeline and possible impact of a campaign, and compared the result against a counterfactual baseline. You can see our calculation here and input new assumptions to see how they affect a campaign's impact. This calculation demonstrates that there is a strong benefit from widespread indoor air quality improvements on endemic respiratory disease burden, even before accounting for catastrophic pandemics. This benefit should make indoor air quality improvements more politically viable.

Many indoor air quality projects could build on each other and create momentum for further efforts, and a dedicated funding pathway could coordinate several complementary projects. For example, a useful long-term path might start by funding a set of scientific studies. As research produces further data on interventions and optimal programs, funding could be used for dedicated advocacy and deployment in partnership with early organizational adopters. This implementation would in turn lead to iterative research and wider deployment.

Projects in these areas could absorb significant amounts of funding along a wide range. For example:

- $25,000 could fund the development of a detailed infection model.
- $20M could fund a single dedicated clinical project (e.g. something like EMIT-2).
- $200M could fund a program consisting of several complementary projects (e.g. far-UVC light safety studies, real-world efficacy studies for IAQ interventions, advocacy for improved pandemic preparedness standards, etc.).

Possibilities for immediate action

- Early adopters will be an important part of any push for improvements in indoor air quality, and organizations could begin to install upper-room GUV light and low-wave light immediately. Philanthropists or government bodies can be helpful here by providing partial or full funding to corporate partners who might not undertake this effort alone. Early adoption would allow efficacy data to be collected for different offices, providing real-world data to incorporate into detailed models.
- Far-UVC light still needs extensive safety testing. We are aware of collaborators who are interested in designing and running a safety test in the near future.
- Far-UVC light still needs to be assessed for use in close-range transmission mitigation.
- More detailed models are needed to form the basis for improved standards; we know of at least one researcher, Jacob Bueno de Mesquita of Lawrence Berkeley National Laboratory, who is in the process of developing such a model and is seeking funding to invest more time in it. A funder could provide funding to complete his model for about $25,000.[34]
- More investment is needed in solid-state far-UVC technology, including in fundamental research of the type normally done through academic institutions. There are companies working on improving far-UVC technology, but funders could add to this effort by supporting academic research in the area. As a basic heuristic, a PhD student costs roughly $70,000 per year, and an applied research project in this field might take about two years to demonstrate promise and another two to come to fruition. An example philanthropic program to support fundamental research in this area might therefore support five students for two years each, and then choose two out of those five to support for another two years, for a total cost under $1 million. Alternatively, a philanthropic funder might make an investment in a tech startup, prioritizing impact over returns (unlike typical private investors).

Risk Factors

There are a few reasons ways IAQ interventions could fail or even be harmful:

- IAQ interventions fail to substantially reduce global catastrophic biorisk due to incomplete coverage, e.g., some studies of GUV in schools find no effect on measles incidence because students end up catching measles in transit to school.
- It may turn out that for catastrophic pandemic-class pathogens, IAQ interventions are not as effective as planned because reducing pathogen levels in the air might not substantially reduce transmission and infection rates, e.g., it could be the case that it is easy to be infected by very low doses.
  - It is unlikely, given the dose-infection patterns of known pathogens, that reducing pathogens doses would be totally ineffective. Although transmission sites can shift without reducing overall transmission, reducing the speed of transmission can still buy valuable time for countermeasures to be enacted.
- IAQ interventions could reduce population immunity due to a lack of ordinary virus exposure such that the transmissibility of biothreats is not much reduced. It might even be the case that ordinary airborne pathogens, like the common cold, become more destructive to those who contract them.
  - Typically, this concern does not arise when discussing other pathogen routes. Environmental

34 We were recently informed that Prof. Ernest P. Blatchley III of Purdue University is working on something similar, although we have not spoken with him.

pathogen reduction has historically been enormously beneficial for humanity, as demonstrated by the vast life quality and longevity increases coming from the reduction in waterborne pathogens.
- Far-UVC light might result in long-term safety issues, such as effects on the skin microbiome, that are difficult to resolve in safety studies.
  - If there are long-term health issues, it may still be the case that the expected value of mass deployment of this system reduces global catastrophic biological risk to the degree that it's still better to have it than not.
  - However, health issues (even if they are relatively minor) introduce legal liabilities for organizations producing, selling, and employing this technology and may result in consumer and public sentiment being hostile to this technology and any associated organizations.
- GUV could produce harmful pollutants through interaction with particles and gasses in the air, which negatively impact respiratory health.
  - These pollutants could be addressed by filtration, but filtration would have to be used comprehensively in order to completely counteract the effect, which would correspondingly raise the price of UV light installation.
  - It is likely that it would still be net beneficial to install far-UVC lights in high-risk places; detailed cost-benefit analyses are needed for various environments.
- There could be some form of risk compensation, where people overestimate the benefit of this technology and after adopting it, become less inclined to use other biorisk-reducing measures (e.g. PPE, social distancing).
- Encouraging the adoption of filtration and upper-room UV now may make it more difficult to get far-UVC light installed in public indoor spaces later because of an infrastructure "lock-in" effect, where an incumbent technology prevents the take-up of potentially superior alternatives.
- Regulation on dosage for far-UVC light could be set at levels that are too low for reducing the chance of existential biorisk (e.g. reducing transmissibility of a measles-equivalent agent).
- There could be a negative shift in public perception of IAQ interventions unrelated to actual health issues, which prevents mass deployment (similar to anti-vaccine sentiment).
- The FDA could classify specific IAQ interventions as medical devices, subjecting them to constraining regulations and making widespread deployment more difficult.
- Doing a poor job with the rollout of IAQ interventions or attempts at altering standards and regulations might "poison the well" for better attempts later, e.g. due to a very small number of high-profile failures.
- Adversaries could start incorporating IAQ interventions into their plans for developing and deploying pandemic-class agents.
  - This is probably minimally relevant as GUV denies adversaries several attack vectors, making the chance of a successful attack less likely.
  - It is probably difficult to develop agents that can withstand high enough levels of UVC light, but if placement is partial then adversaries may be able to exploit gaps. Multi-wavelength systems would be even more difficult to work around.
- UV light degrades plastics over time and plastic is ubiquitous in our daily environments.
  - Boeing found no mechanical degradation in plastics from simulating an airplane interior disinfection process using far-UVC (although the exposure time was significantly lower than would occur if far-UVC were broadly implemented for reduction in disease transmission).
  - Different plastics are affected to different degrees and strengthening/protective additives can avert the degradation, so much of the issue could be avoided through careful materials choice.
  - Generally, the rate of degradation may overall be negligible compared with the standard lifetime of consumer products.

Many of these risk factors can be mitigated by the activities recommended in this report (e.g., developing better models and metrics, real-world efficacy studies, robust safety studies, monitoring public attitudes, and advocacy efforts).

Appendices

Appendix 1: Report for Open Philanthropy Cause Exploration Prize, which formed the first draft of this report, although less focused on catastrophic pandemic risk and pilot programs.
Appendix 2: Summaries of EA organizations' work on indoor air quality.
Appendix 3: Notes from Henna Dattani on far-UVC.
Appendix 4: Convergent Research's executive summary on germicidal UV.
Appendix 5: Sketch of possible UVC pilot program for a given office space.
Appendix 6: Code to generate population transmission curves.

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