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# Thinking green: respirator reuse strategies to reduce cost and waste

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**Thinking green: respirator reuse strategies to reduce cost and waste**

Jacqueline N. Chu, MD (1,2), Omkar Ghenand (3), Joy Collins, MPH (2,4), James Byrne, MD, PhD (2,5), Adam Wentworth, MS (2,4), Peter R Chai, MD MMS (2,6), Farah Dadabhoy, MD (2,6), Chin Hur, MD, MPH (7,8), Giovanni Traverso, MB, BChir, PhD* (4,9)

*1 Division of Gastroenterology, Massachusetts General Hospital, Harvard Medical School, Boston, MA 02114, USA. Correspondence to: ctraverso@bwh.harvard.edu

2 David H. Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, MA 02142, USA

3 Massachusetts Institute of Technology, Cambridge, MA 02142, USA

4 Division of Gastroenterology, Brigham and Women's Hospital, Harvard Medical School, Boston, MA 02115, USA

5 Harvard Radiation Oncology Program, Boston, MA 02114, USA

6 Department of Emergency Medicine, Brigham and Women's Hospital

7 Department of Medicine, Columbia University Medical Center, New York, NY 10032, USA

8 Department of Epidemiology, Mailman School of Public Health and Herbert Irving Comprehensive Cancer Center, Columbia University Medical Center, New York, NY 10032, USA

9 Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139, USA

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**Abstract:**

**Objectives** To compare the impact of respirator extended use and reuse strategies with regard to cost and sustainability during the COVID-19 pandemic.

**Design** Cost analysis

**Setting** United States

**Participants** All healthcare workers within the United States

**Interventions** Not applicable

**Main outcome measures** A model was developed to estimate usage, costs, and waste incurred by several respirator usage strategies over the first 6-months of the pandemic in the United States. This model assumed universal masking of all healthcare workers. Estimates were taken from the literature, government databases, and commercially available data from approved vendors.

**Results** A new N95 respirator per patient encounter would require 7.41 billion respirators, cost $6.38 billion, and generate 84.0 million kg of waste in the U.S. over 6-months. One respirator per day per healthcare worker would require 3.29 billion respirators, $2.83 billion, and 37.22 million kg of waste. Decontamination by ultraviolet germicidal irradiation would require 1.64 billion respirators, $1.41 billion, and 18.61 million kg of waste. $H_2O_2$ vapor decontamination would require 1.15 billion respirators, $1.40 billion, and 13.03 million kg of waste. One reusable respirator with daily disposable filters would require 18 million respirators, $1.24 billion, and generate 15.73 million kg of waste. Pairing a reusable respirator with UVGI or $H_2O_2$ vapor-decontaminatable filters would reduce cost to $581.48 million and generate 1.58 million kg of waste. The use of one surgical mask per day would require 3.29 billion masks, cost $493 million, and generate 20.86 million kg of waste.

**Conclusions** Reuse-based strategies decreased the number of respirators used, costs, and waste generated compared to single- or daily extended-use of disposable respirators. Future development of low-cost, low-tech technologies to enable respirator and/or filter decontamination is needed to further minimize the economic and environmental costs of masks.

**Trial registration** Not applicable

**Keywords** Covid-19, environmental health, health economics

**Strengths and limitations of this study**

- To our knowledge, this study is one of the first to assess the economic and environmental impact of different respirator reuse strategies to accommodate widespread respirator use among healthcare workers on a national scale in the United States.
- This study reviews cost and waste estimates specific to respirator use in order to meet the demands of the COVID-19 pandemic. Potential cost and waste reductions as a result of reuse strategies were explored, including more recently developed technologies such as ultraviolet germicidal irradiation, hydrogen peroxide vapor decontamination, and reusable respirators.
- This study could help inform optimal respirator reuse strategies to reduce the economic and environmental toll during the COVID-19 pandemic.
- This study estimates only a few respirator strategies and decontamination methods. Other methods for extended respirator use and reuse, the implementation of different reusable respirator designs, and inexpensive, low tech methods for decontamination should be evaluated.

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- This study was conducted from a US perspective and input parameters such as the number of healthcare workers, rates of infection, hospitalization rates, etc. will be different for other countries. Also, this did not include costs such as installation, maintenance, distribution, or personnel.

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## Introduction

The COVID-19 pandemic has led to personal protective equipment (PPE) shortages worldwide, including shortage of N95 respirators and surgical masks.[1-3] In order to maximize resources, many hospitals have adopted extended use of masks or decontamination and reuse strategies, particularly of N95 respirators.[1, 4, 5] Prior to the pandemic, a new N95 respirator was typically used for each patient encounter and then discarded.[5, 6] In light of the PPE shortage, some hospitals have now moved to using one respirator per several encounters or even several days.[4, 6] Decontamination strategies such as hydrogen peroxide vapor ($H_2O_2$) and ultraviolet germicidal irradiation (UVGI) are being adopted and thus far appear effective, but concerns about decontamination reducing mask fit and integrity remain, as well as concerns regarding cost of the technology.[5-9]

The United States government recently awarded a $415 million contract to Battelle to deploy 60 hydrogen peroxide vapor decontamination sites across the country.[6, 7] While this may be feasible in resource-rich settings, the hydrogen peroxide system requires significant infrastructure and trained personnel, limiting its translation to resource-constrained areas.[7, 9] There is therefore a need for simpler methods of respirator decontamination that can be deployed on a large scale.[10] Investigations into heat, steam, and detergent decontamination are ongoing; however, these have thus far been shown to compromise mask integrity.[3, 5] Nebraska Medicine has recently piloted a UVGI system that has been approved by the United States Centers for Disease Control and Prevention (CDC), which may be easier to deploy for hospitals that already have UV decontamination systems in place.[11] Reusable respirators such as half-mask elastomeric respirators are available but have not been heavily adopted due to challenges with sterilization, cost, and bulky size.[10] Several scalable, less expensive reusable respirators have been recently developed that can be easier to decontaminate using standard hospital equipment to try to address the respirator shortage.[10, 12] The Pneumask project for example, which repurposes snorkel masks, has already distributed more than 23,000 masks internationally.[12, 13] Potential benefits of such reusable respirators compared to disposable respirators could include reduced cost and waste. Rough estimates show the COVID-19 pandemic is expected to generate up to 7,200 tons a day in medical waste, a sizable portion of which comes from masks.[14, 15] A reusable respirator could be a more sustainable alternative to disposable respirators, particularly if respirator and mask usage becomes more commonplace post-pandemic, such as in Asia.[16-18] Already environmentalists have noted a surge in plastic pollution from discarded masks in the ocean and continued heavy use of disposable PPE is unlikely to be sustainable.[14, 15, 19]

The optimal respirator use strategy that maximizes supply, minimizes cost, and minimizes waste is unknown. This analysis estimates respirator use, cost, and waste generation in the United States over the course of the first six months of the COVID-19 pandemic to explore the optimal strategy for respirator use.

## Methods

*Data sources*

We estimated respirator usage, cost and waste from late March 2020 to late September 2020. The input parameters for the model are found in Tables 1-3. Data was sourced and adapted from the scientific literature or national databases. Base case respirator cost and waste estimates used the 3M 1860 disposable respirator as well as a recently published reusable respirator.[10]

**Table 1 Parameters used to estimate respirator usage, costs, and waste generation**

| Parameter | Value | Reference |
|---|---|---|
| US Population as of 2019 | 328.2 million | [20] |
| Total number of healthcare and frontline workers in US as of 2020 | 18 (17-19) million | [21-23] |
| Weight of one N95 respirator | 11.33 g | [24] |
| Weight of one surgical mask | 6.35 g | [25] |

| | | |
|---|---|---|
| Total cost of assembled reusable respirator (minus filters) | $6.11 USD | [10] |
| Weight of one reusable respirator | 46.5 g | [10] |
| Weight of one reusable respirator filter | 2.26 g | [10] |
| Cost of one pair of filters required per reusable respirator | $0.34 USD | [10] |
| Cost of one surgical mask | $0.15 USD | [26] |
| Cost of one Standard N95 respirator | $0.86 USD | [26] |
| Cost of the National Battelle System Funded by the FDA | 415 million USD | [6] |
| Reduction in the number of respirators required for HCW population in the US by the use of $H_2O_2$ Vapor Decontamination | 20-fold | [6] |
| Reduction in the number of respirators required for HCW population in the US by the use of UVGI | 5-fold | [11] |

*Respirator usage*

We considered seven respirator usage strategies: one respirator per patient encounter, one respirator per healthcare worker (HCW) per day, extended use of one respirator per HCW per day enabled by daily $H_2O_2$ vapor decontamination, extended use of one respirator per HCW per day enabled by daily UVGI decontamination, one reusable respirator with disposable filters per HCW, one reusable respirator with $H_2O_2$ vapor-decontaminated filters per HCW, and one surgical mask per HCW per day. We assumed that HCWs would be masked for all patient encounters (universal masking) given ongoing limited access to rapid COVID-19 testing nationally.[27-29] For the $H_2O_2$ and UVGI decontamination strategies, we accounted for a 30% respirator discard rate due to soiled or damaged respirators as has previously been reported.[30] For each usage strategy, we considered low, average and high estimates for the size of the HCW population (17-19 million) based on estimates from the CDC, the Bureau of Labor Statistics, and published literature.[21-23]

For the one respirator per patient encounter strategy, we estimated respirators required by HCWs with exposure to patients and those without. The number of respirators required for HCWs due to patient contact were based on the number of hospitalized patients (COVID and non-COVID), average length of stay (LOS), and average number of visits from HCWs per day (Table 2).[21] Data for the number of respirators required per patient per day, LOS per patient, and the number of ICU and hospital admissions was extracted from the recent COVID-19 literature, government reports and a previous influenza study estimating respirator usage to prevent aerosol transmission.[21, 31-34] To estimate the number of overall hospitalized patients, we incorporated drops in hospital admission rates due to the pandemic, which were as high as 42.8% below usual rates of admissions in April before rebounding down to about 15.9% below usual rates in June/July.[35] In addition, HCWs with patient contact were estimated to be using 4 respirators per day in between direct patient care. [21, 36] HCWs without patient contact were assumed to be using 1 respirator per day (Table 3).

**Table 2 Hospitalization-specific parameters used to estimate number of respirators required by the one respirator per patient encounter strategy over 6-months**

| Parameter | Total | Reference |
|---|---|---|
| Number of hospital admissions | 14,227,773 | [37] |
| Number of patients admitted to the general ward | 12,583,927 | [31, 37] |
| Number of patients admitted to the ICU | 1,643,846 | [31, 37] |

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|---|---|---|
| Number of hospitalizations due to COVID-19 | 396,355 | [34] |
| Average length of stay for general ward patients | 4.6 days | [32] |
| Average length of stay for patients admitted to the ICU | 3.3 days | [32] |
| Median length of stay for non-ICU COVID-19 patients | 10.1 days | [34] |
| Median length of stay for COVID-19 patients admitted to the ICU | 10.5 days | [34] |
| Number of respirators required per day for interactions with general ward patients | 8 | [21] |
| Number of respirators required per day for interactions with ICU patients | 14 (12-16) | [21] |

**Table 3 HCW-specific parameters used to estimate number of respirators required by the one respirator per patient encounter strategy**

| Parameter | Total | Number of workers w/ patient contact | Number of workers w/o patient contact | Reference |
|---|---|---|---|---|
| Number of nursing home workers | 3,427,000 | 856,750 | 2,570,250 | [21] |
| Number of emergency medicine service workers | 297,000 | 267,300 | 29,700 | [21] |
| Number of emergency department workers | 132,000 | 132,000 | 0 | [21] |
| Number of hospital workers | 6,053,000 | 1,997,490 | 4,055,510 | [21] |
| Number of outpatient workers | 3,206,000 | 2,148,020 | 1,057,980 | [21] |
| Number of other healthcare workers in other occupations | 6,000,000 | 0 | 6,000,000 | [21, 22] |

We then used these results to infer estimates for extended use and reuse of respirators enabled by the alternate respirator strategies. For our one disposable respirator per HCW per day strategy, we assumed that each HCW (with or without patient contact) would use one, new respirator per day.

For the daily $H_2O_2$ vapor decontamination strategy, using currently available data on respirator integrity and efficiency after multiple cycles of $H_2O_2$ vapor decontamination, we assumed that a respirator could be decontaminated for up to 20 cycles, with a 30% discard rate per day due to damaged or visibly soiled respirators after each cycle of decontamination.[30] Therefore, to form our estimates for $H_2O_2$ vapor decontamination-enabled extended use of respirators, we divided the one respirator per HCW worker per day usage estimates by 20 and assumed 30% of respirators would need to be replaced after each decontamination cycle/per day to account for the estimated discard rate.

To model usage estimates for extended use of respirators enabled by daily UVGI decontamination, we used currently available data on respirator integrity and efficiency after multiple cycles of UVGI. Based on these estimates, we assumed that a respirator could be decontaminated for up to 5 cycles.[38] Therefore, to form our estimates for UVGI-enabled extended use of respirators, we divided the one respirator per healthcare worker per day usage estimates by 5 and assumed 30% of respirators would need to be replaced after each decontamination cycle/per day due to the estimated discard rate.[30, 39, 40]

For the reusable respirators with disposable or $H_2O_2$ vapor-decontaminated filter strategies, we assumed that every healthcare worker in the US will use one reusable respirator and replace or decontaminate the filters daily. Based on a recently published low-cost reusable respirator, we estimated costs and waste from a pair of filters to be approximately ⅖ of the cost and waste generated from an N95 respirator.[10] If filters were to be decontaminated using $H_2O_2$ vapor, we also assumed that filters could be reused for a maximum of 20 days (20 decontamination cycles).

*Cost estimate*

To estimate the cost accumulated by each usage method, we used the following costs, which were found in the literature and converted to 2020 US dollars: 3M respirator, $0.86, multiplied by the number of respirators

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required;[26] one surgical mask, \$0.15, multiplied by the number of surgical masks required;[26] reusable respirator, \$6.11, multiplied by the number of reusable respirators required;[10] a pair of filters for reusable respirators, \$0.34, multiplied by the number of pairs of filters required; and nationally distributed $H_2O_2$ vapor decontamination systems across 60 sites, \$415 million.[6] We assumed the base cost of the UVGI system to only include the cost of the respirators required, as many hospitals are already equipped with UV systems that could be repurposed for respirator decontamination.[41] However, we also performed a sensitivity analysis to account for the varying costs and sophistication of UVGI systems, ranging from the installation of a brand new, high volume system to a less expensive, lower volume system that utilizes repurposed materials.[9, 41] Supplementary Table 1 explores a range of UVGI system costs which do not include installation, maintenance, distribution, energy, or personnel costs.[9, 11, 38, 41, 42]

*Waste estimate*

Waste estimates for each usage method measured the mass of the total respirators, surgical masks, and filters used and disposed of through the 6-month duration. The mass of 3M's 1860 respirator, a standard surgical mask, and a reusable respirator are 11.33 grams, 6.35 grams and 46.5 grams, respectively.[10, 24, 25] Single filters for reusable respirators were estimated using ⅕ of a respirator (2.26 grams per a single filter, 4.53 grams per pair of filters).[10] Thus, to form our waste estimates, we multiplied respirator, surgical mask and reusable respirator usage by their respective masses.

*Patient and Public Involvement*

Patients or the public were not involved in the design, or conduct, or reporting, or dissemination plans of our research. It was not appropriate or possible to involve patients or the public in the design, or conduct, or reporting, or dissemination plans of our research.

**Results**

*Mask usage*

The estimated numbers of respirators required in the United States for each strategy are shown in Table 4 and Figure 1A. The use of a new respirator per patient encounter in the U.S. would require 7.41 billion respirators. An extended-use strategy of one respirator per day per HCW would reduce need by over 50% to 3.29 billion respirators. Decontamination by UVGI would further reduce the need to 1.64 billion respirators. Employing a $H_2O_2$ vapor decontamination strategy would further reduce need by 84% to only 1.15 billion respirators. A reusable respirator strategy (with either disposable or decontaminated filters), where one respirator is assigned to each HCW for the duration of the pandemic, would further reduce need to approximately 18 million respirators, for a total reduction in respirator need by over 99%. Using a new surgical mask daily would require 3.29 billion surgical masks.

*Cost estimate*

The estimated costs for each respirator use strategy are summarized in Table 4 and Figure 1B. The use of a new respirator per patient per HCW would cost an average of \$6.38 billion. Extended use of one respirator per day would reduce the cost to \$2.83 billion, saving approximately \$3.55 billion. The decontamination by UVGI strategy would reduce the cost to \$1.41 billion, saving an additional \$1.42 billion. An $H_2O_2$ vapor decontamination strategy would be comparable to the cost of UVGI at \$1.40 billion. A reusable respirator with disposable filters would cost \$1.24 billion, though this is almost entirely filter costs (\$1.13 billion). A reusable respirator with a decontaminated filter and surgical mask strategies would be the least costly strategies at \$581 million dollars and \$493 million dollars, respectively, which is a total cost savings of over \$5.79 billion (Figure 1B). This is more than the amount of money provided by the CARES Act to support the CDC's pandemic response efforts and programs.[43]

*Waste estimate*

The estimated waste generated by each respirator use strategy is summarized in Table 4 and Figure 1C-D. The use of a new respirator per patient encounter per HCW would generate 84.0 million kg of waste. Extended use of one respirator per day would reduce waste to 37.22 million kg. The decontamination by UVGI strategy would reduce waste to 18.61 million kg. A $H_2O_2$ vapor decontamination (with a 30% discard rate) strategy would reduce waste to 13.03 million kg. A reusable respirator with disposable filters would generate 15.73 million kg of waste (14.88 million kg from filters). Pairing the reusable respirator with a decontaminated filter would significantly reduce generated waste to 1.58 million kg, for an overall reduction in waste generation by roughly 82.42 million kg, equivalent to going from a mass of 252 Boeing 747 airplanes to five (Figure 1D). The surgical mask strategy would generate 20.86 million kg of waste.

Cost and waste estimates for commercially available reusable half-facepiece elastomeric respirators (3M 7500 series) with P100 filters (assuming that each HCW uses one pair of filters per week) were also explored (Supplementary Table 2).[24, 25, 44] Low and high cost estimates of $2.02 and $2.26 billion were calculated using sources from the commercial manufacturer 3M,[24] with reusable respirator costs ranging from $25 to $45 per respirator with a single disposable P100 filter cost of $7.00.[24, 25] These cost estimates of $2.02-$2.26 billion were lower than the one respirator per day reuse strategy, but higher than the $H_2O_2$ decontamination, UVGI decontamination, reusable respirator, reusable respirator with decontaminated filters, and surgical mask strategies (Table 4, Supplementary Table 2). Low and high waste estimates of 3.22 million kg and 3.59 million kg were calculated using a respirator weight of 135 grams and filter weight of 4.54 grams (Supplementary Table 2). These waste estimates were lower than the one per day reuse strategy, $H_2O_2$ decontamination, UVGI, reusable respirator, and surgical mask strategies, but higher than the reusable respirator with decontaminated filters strategy (Table 4, Supplementary Table 2).

**Table 4 Numbers of respirators, cost accumulated, and waste generated per strategy over a duration of 6-months**

| Respirator strategy | Number of respirators required | Cost accumulated (USD) | Waste generated (kg) |
|---|---|---|---|
| 1 per patient encounter | 7.41 (7.22-7.59) billion | $6.38 (6.21-6.52) billion | 84.0 (81.79-85.96) million |
| 1 per day | 3.29 (3.10-3.47) billion | $2.83 (2.67-2.98) billion | 37.22 (35.15-39.29) million |
| UVGI-decontaminated respirator | 1.64 (1.55-1.73) billion | $1.41 (1.33-1.49) billion | 18.61 (17.58-19.64) million |
| $H_2O_2$ decontaminated N95 respirators | 1.15 (1.09-1.21) billion | $1.40 (1.35-1.46) billion | 13.03 (12.30-13.75) million |
| Reusable respirator + disposable filters | 0.018 (0.017-0.019) billion | $1.24 (1.17-1.31) billion | 15.73 (14.85-16.60) million |
| Reusable respirator + decontaminated filters | 0.018 (0.017-0.019) billion | $0.581 (0.572-0.591) billion | 1.58 (1.49-1.67) million |
| Surgical mask, 1 per day | 3.29 (3.10-3.47) billion (surgical masks) | $0.493 (0.465-0.520) billion | 20.86 (19.70-22.02) million |

## Discussion

*Principal Findings*

The COVID-19 pandemic has dramatically increased the demand for respirators across the world, leading to supply shortages, spending in the billions of dollars, and generation of large amounts of medical waste. Even after the successful release of an FDA approved vaccine, masks will likely continue to be required due to factors such as variable vaccine uptake, incomplete vaccinations, lack of knowledge as to who has received a vaccine, the possibility of reinfection, and unclear duration of vaccination efficacy.[45, 46] Additionally, even after the pandemic, respirator and mask usage both in healthcare settings and among the general public may persist. The continued use of disposable respirators and masks is unlikely to be sustainable and will have significant environmental consequences. With this in mind, it is critical to understand the best strategy to maximize respirator and mask availability while minimizing costs and waste generation.

Of the strategies compared, we find that all reuse strategies (UVGI decontamination, $H_2O_2$ vapor decontamination, reusable respirators with disposable filters, or reusable respirators with decontaminated filters), could significantly decrease the number of respirators required compared to single- or extended-use mask strategies by at least 1.65 billion respirators in the United States alone. This would greatly increase availability and access of respirators worldwide. In addition, reuse strategies could save at least $1.42 billion dollars in costs nationally over the course of the pandemic. Finally, reuse strategies significantly reduce waste generation in the United States by at least 18.61 million kg. These estimates from our study only capture the economic and environmental impact over the first six months of the COVID-19 pandemic in the US and suggest that the long-term and global impact of reuse strategies are even higher, especially when considering respirators and masks used by the general population.

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Our analyses found that while UVGI and $H_2O_2$ vapor decontamination required more respirators overall compared to the reusable respirator with disposable filters, they were less costly and generated less waste as they did not require the use of disposable filters. Combining the strategies by utilizing a reusable respirator with either UVGI- or $H_2O_2$ vapor-decontaminated filters was the least costly of all strategies compared and generated the least amount of waste. This finding suggests that even with UVGI and $H_2O_2$ vapor decontamination strategies, the adoption of a reusable respirator can have a significant impact in both cost and waste generation. Our findings support a combination of UVGI or $H_2O_2$ vapor and reusable respirator strategy to provide respirators in healthcare settings.

*Limitations of the study*

In settings where UVGI or $H_2O_2$ vapor decontamination are not feasible, such as in resource-constrained settings where installation and maintenance of such systems are challenging, reusable respirators with disposable filters may be preferable to disposable respirators. These respirators may also be decontaminated with standard hospital equipment such as alcohol and bleach wipes, which may be more readily available in settings with limited resources.[10, 12] Anticipatory investment in a reusable respirator may not only provide access to high-quality PPE for COVID-19 in such settings but reduce overall waste and injury to our environment. Development of technologies to facilitate decontamination of respirators and/or filters that do not require special equipment, training, or infrastructure could even further reduce costs and waste as in the reusable respirator with decontaminated filters strategy.

Our study had several limitations. We estimated only a few respirator strategies, and other methods for extended respirator use and reuse across the world were not captured in our analysis. Furthermore, our estimates were performed from a US perspective, and these numbers will be different for other countries depending on parameters such as number of healthcare workers, rates of infection, and number of hospitalized patients, though we suspect that the relative benefit of reuse strategies compared to single- or extended-use respirator strategies will persist. Additionally, our cost estimates did not include installation, maintenance, distribution, or personnel costs associated with various strategies. Furthermore, our analysis measured only the waste generated by masks themselves and did not study the environmental impact of manufacturing or decontamination processes, which should be further investigated. Finally, our estimates for the reusable respirator strategy was based on a recently published prototype.[10] Updated analyses should be performed as these and other low-cost reusable respirators and masks become more available.[12, 47]

While our analysis measured the economic and environmental impact of several mask reuse strategies, there are several areas of investigation that may contribute to further reductions in cost and environmental impact. For example, our analysis highlighted the importance of considering not only reusable respirators, but reusable or decontaminatable filters, as these drove the cost and waste of reusable respirator/disposable filter strategies. Inexpensive, low-tech methods for filter decontamination are needed. Alternatively, redesign of reusable respirators to require smaller filters or development of fully reusable respirators would greatly reduce cost and waste. Additionally, the development of novel materials for masks to increase durability of these systems after repeated exposures to $H_2O_2$ vapor or other decontamination techniques may increase the lifespan of masks and decrease the volume of masks used. Incorporation of bactericidal or antiviral agents into masks may also increase their reusability and potentially decrease the need for cleaning agents in regions where there may be concomitant shortages of these solutions. This strategy may also decrease waste of common hospital-based wipes used to decontaminate masks, which was not included in this analysis. Finally, the development of biodegradable or recyclable materials that provide efficient particle protection may minimize the environmental effects of discarded masks.

*Conclusions*

In summary, respirator reuse technologies are critical to meet the supply demands imparted by COVID-19, especially in low-resource settings. This need is emphasized by the likelihood that respirators will continue to be commonly used after the release of a vaccine, as well as post-pandemic in certain populations. Furthermore, these technologies can save billions of dollars that can be redistributed toward other efforts to combat the pandemic and enable more sustainable use of respirators moving forward. Future development of low-cost, low-tech technologies to enable respirator and/or filter decontamination is needed to further minimize the economic and environmental costs of respirators.

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**What is already known on this topic**

-We searched the existing peer-reviewed literature using Google Scholar, PubMed, Scopus and Elsevier. As of November 2020, we found several studies supporting the widespread use of masks as an effective method of protection for healthcare workers against COVID-19. The use of face masks can prevent particle emissions by more than 90% and studies have shown that they significantly reduce risk of infection. Additionally, face masks provide critical protection for frontline healthcare workers who are at a greater risk of becoming infected with COVID-19.

-The high-demand for masks as a result of universal masking as a protective measure against COVID-19 has led to global mask shortages, particularly of N95 respirators. This has required many healthcare workers to strategically reuse and disinfect their disposable respirators over prolonged periods of time. Different extended mask-use strategies of surgical masks and N95 respirators have been compared in the literature, yet more recent developments such as ultraviolet germicidal irradiation, hydrogen peroxide vapor decontamination, and low-cost reusable masks require further evaluation.

-Studies on the economic and environmental impacts of the drastic surge in PPE and mask usage as a result of the COVID-19 pandemic are limited, with estimates showing up to 7,200 tons of generated medical waste per day. This is especially important as the use of face masks will likely be required globally for a prolonged period of time even after the successful release of a vaccine.

**What this study adds**

-To our knowledge, this study is one of the first to assess the economic and environmental impact of different respirator reuse strategies to accommodate widespread respirator use among healthcare workers on a national scale in the United States.

-Cost and waste estimations are specific to respirator use in order to meet the demands of the COVID-19 pandemic. Potential cost and waste reductions as a result of reuse strategies, which include more recently developed technologies such as ultraviolet germicidal irradiation, hydrogen peroxide vapor decontamination, and reusable respirators were explored.

-We hope that this study will provide evidence to inform an optimal respirator reuse strategy to reduce the economic and environmental toll during the COVID-19 pandemic.

**Footnotes**

**Contributors:** JNC, OG, JC, CH, and GT conceived and designed the analysis. JB, AW, PRC, and FD contributed data. JNC, OG, and JC collected data and performed the analysis. JNC, OG, JC, and GT wrote the manuscript. JNC, OG, JC, JB, AW, PRC, FD, CH, and GT interpreted the data and reviewed and approved the manuscript. The corresponding author, GT, provided supervision over the study and is the guarantor. GT confirms that all authors meet the authorship criteria and no contributing authors have been omitted.

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**Competing interests:** The authors declare the following competing financial interest(s): AJW, JDB, and GT have filed multiple patents surrounding the respirator and sensors. In addition, AJW, JDB and GT have a financial interest in TEAL Bio, a biotechnology company focused on developing the next generation of personal protective equipment. JNC, PRC, OG, JC, FD, and CH declare no competing interests.

**Data Sharing:** All data is included in the manuscript and/or supplementary materials, no additional data is available.

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GT provides attestation that this study reflects honest and accurate data and transparent disclosure of all relevant information. Nothing has been omitted or withheld from this study.

**Fig. 1** Comparison of the following per respirator reuse strategy: A) number of respirators or surgical masks used, B) costs in billions of USD, C) waste generated in millions of kg, D) waste generated per strategy in the equivalent number of 747 airplanes by mass (mass of one 747 airplane, 333,000 kg).

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A
Respirator and surgical mask use per strategy (billions)
1 respirator per patient encounter
7.41
1 respirator per day
3.29
1 surgical mask per day
3.29
UVGI decontamination
1.64
H2O2 vapor decontamination
1.15
Reusable respirator
0.018
B
Cost per strategy (billions, USD)
1 respirator per patient encounter
6.38
1 respirator per day
2.83
UVGI decontamination
1.41
H2O2 vapor decontamination
1.4
Reusable respirator + disposable filters
1.24
Reusable respirator + decontaminated filters
0.581
1 surgical mask per day
0.493
C
Waste per strategy (millions, kg)
1 respirator per patient encounter
84
1 respirator per day
37.22
1 surgical mask per day
20.86
UVGI decontamination
18.61
Reusable respirator + disposable filters
15.73
H2O2 vapor decontamination
13.03
Reusable respirator + decontaminated filters
1.58
D
Waste per strategy in number of 747 airplanes
1 Respirator per patient encounter
252
1 Respirator per day
112
1 surgical mask per day
63
UVGI decontamination
56
Reusable respirator + disposable filters
47
H2O2 vapor decontamination
39
Reusable respirator + decontaminated filters
5

**Supplementary Table 1 Sensitivity analysis of UVGI decontamination cost***

| Parameter | Value |
|---|---|
| Cost of 2 surgical suite UVGI system | $40,000.00[11] |
| Cost of repurposed or low tech UVGI lamp system | $50.00[9] |
| | |
| **Results** | |
| Base cost | $1.41 (1.33-1.49) billion |
| Base cost + cost of 2 surgical suite UVGI systems | $1.42 (1.34-1.49) billion |
| Base cost + cost of repurposed or low tech UVGI lamp system | $1.41 (1.33-1.49) billion |
| *Assuming distribution across hypothetical 60 sites across U.S. | |

**Supplementary Table 2 Reusable elastomeric respirator + disposable p100 filter usage, cost and waste sensitivity analysis**

| Parameter | Value |
|---|---|
| Respirator Usage | 18 (17-19) million |
| Filter Usage (by pair) | 108 (102-114) million |
| | |
| **Results** | |
| Reusable respirator + filter cost (USD) | $2.14 (2.02-2.26) billion |
| Reusable respirator + filter waste (kg) | 3.41 (3.22-3.59) million |

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# Thinking green: Modelling respirator reuse strategies to reduce cost and waste

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# Thinking green: Modelling respirator reuse strategies to reduce cost and waste

Jacqueline N. Chu, MD (1,2), Omkar Ghenand (3), Joy Collins, MPH (2,4), James Byrne, MD, PhD (2,5), Adam Wentworth, MS (2,4), Peter R Chai, MD MMS (2,6), Farah Dadabhoy, MD (2,6), Chin Hur, MD, MPH (7,8), Giovanni Traverso, MB, BChir, PhD* (4,9)

*1 Division of Gastroenterology, Massachusetts General Hospital, Harvard Medical School, Boston, MA 02114, USA. Correspondence to: ctraverso@bwh.harvard.edu, cgt20@mit.edu

2 David H. Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, MA 02142, USA

3 Massachusetts Institute of Technology, Cambridge, MA 02142, USA

4 Division of Gastroenterology, Brigham and Women's Hospital, Harvard Medical School, Boston, MA 02115, USA

5 Harvard Radiation Oncology Program, Boston, MA 02114, USA

6 Department of Emergency Medicine, Brigham and Women's Hospital

7 Department of Medicine, Columbia University Medical Center, New York, NY 10032, USA

8 Department of Epidemiology, Mailman School of Public Health and Herbert Irving Comprehensive Cancer Center, Columbia University Medical Center, New York, NY 10032, USA

9 Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139, USA

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**Abstract:**

**Objectives** To compare the impact of respirator extended use and reuse strategies with regard to cost and sustainability during the COVID-19 pandemic.

**Design** Cost analysis

**Setting** United States

**Participants** All healthcare workers within the United States

**Interventions** Not applicable

**Main outcome measures** A model was developed to estimate usage, costs, and waste incurred by several respirator usage strategies over the first 6-months of the pandemic in the United States. This model assumed universal masking of all healthcare workers. Estimates were taken from the literature, government databases, and commercially available data from approved vendors.

**Results** A new N95 respirator per patient encounter would require 7.41 billion respirators, cost $6.38 billion, and generate 84.0 million kg of waste in the U.S. over 6 months. One respirator per day per healthcare worker would require 3.29 billion respirators, $2.83 billion, and 37.22 million kg of waste. Decontamination by ultraviolet germicidal irradiation would require 1.64 billion respirators, $1.41 billion, and accumulate 18.61 million kg of waste. $H_2O_2$ vapor decontamination would require 1.15 billion respirators, $1.65 billion, and produce 13.03 million kg of waste. One reusable respirator with daily disposable filters would require 18 million respirators, cost $1.24 billion, and generate 15.73 million kg of waste. Pairing a reusable respirator with $H_2O_2$ vapor-decontaminatable filters would reduce cost to $831 million and generate 1.58 million kg of waste. The use of one surgical mask per healthcare worker per day would require 3.29 billion masks, cost $493 million, and generate 27.92 million kg of waste.

**Conclusions** Decontamination-and reusable respirator-based strategies decreased the number of respirators used, costs, and waste generated compared to single- or daily extended-use of disposable respirators. Future development of low-cost, low-tech technologies to enable respirator and/or filter decontamination is needed to further minimize the economic and environmental costs of masks.

**Trial registration** Not applicable

**Keywords** Covid-19, environmental health, health economics

**Strengths and limitations of this study**

- Describes the current economic and environmental impact of several mask reuse strategies on a national scale among healthcare workers.
- Estimates cost and waste specific to respirator use in order to meet the demands of COVID-19.
- Explores respirator reuse strategies to reduce the economic and environmental toll during COVID-19 and beyond.
- Only a few respirator strategies and decontamination methods are evaluated in this study.
- Conducted from a US perspective only; parameters are not applicable to other countries and did not include ancillary costs.



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## Introduction

The COVID-19 pandemic has led to personal protective equipment (PPE) shortages worldwide, including shortage of N95 respirators and surgical masks.[1-3] In order to maximize resources, many hospitals have adopted extended use of masks or decontamination and reuse strategies, particularly of N95 respirators.[1 ,4 ,5] Prior to the pandemic, a new N95 respirator was typically used for each patient encounter and then discarded.[5 ,6] In light of the PPE shortage, some hospitals have now moved to using one respirator per several encounters or even several days.[4 ,6] Decontamination strategies such as hydrogen peroxide vapor ($H_2O_2$) and ultraviolet germicidal irradiation (UVGI) are being adopted and thus far appear effective, but concerns about decontamination reducing mask fit and integrity remain, as well as concerns regarding cost of the technology.[5-9]

The United States government awarded a $415 million contract to Battelle in April 2020 to deploy 60 hydrogen peroxide vapor decontamination sites across the country.[6 ,7] While this may be feasible in resource-rich settings, the hydrogen peroxide system requires significant infrastructure and trained personnel, limiting its translation to resource-constrained areas.[7 ,9] There is therefore a need for simpler methods of respirator decontamination that can be deployed on a large scale.[10] Investigations into heat, steam, and detergent decontamination are ongoing; however, these have thus far been shown to compromise mask integrity.[3 ,5] Nebraska Medicine piloted a UVGI system that has been approved by the United States Centers for Disease Control and Prevention (CDC), which may be easier to deploy for hospitals that already have UV decontamination systems in place.[11]

Reusable respirators designed for prolonged use such as half-mask elastomeric respirators are available but have not been heavily adopted due to challenges with sterilization, cost, and bulky size.[10] Several scalable, less expensive reusable respirators have been recently developed that can be easier to decontaminate using standard hospital equipment to try to address the respirator shortage.[10 ,12] The Pneumask project for example, which repurposes snorkel masks, has already distributed more than 23,000 masks internationally.[12-15] Other types of reusable masks that aim to address barriers to communication, such as the Jelli M1 mask [16] and ClearMask, have recently been developed.[17] Potential benefits of reusable respirators compared to disposable respirators could include reduced cost and waste. The use of innovative filtration techniques and antimicrobial nanoparticles could also reduce viral spread, and when incorporated into reusable respirators, reduce cost and waste even further.[18] Introducing novel mask types, such as a variety of reusable masks, presents an opportunity to diversify the market, and in turn provide more flexibility within supply chains. This has the potential to increase efficiency and reduce cost, waste, and energy consumption associated with supply chain disruption.[19]

The global increase in the use of plastics for mask and PPE production has drastically increased medical waste, with countries such as Spain and China reporting increases of 350% and 370%, respectively.[20] As of February 2020, the production rate of face masks in China alone increased by 12 fold.[20] Rough estimates have shown the COVID-19 pandemic could generate up to 7,200 tons a day in medical waste, a sizable portion of which comes from masks.[21 ,22] A reusable respirator could be a more sustainable alternative to disposable respirators, particularly if respirator and mask usage becomes more commonplace post-pandemic, such as in Asia. [23-25] Already environmentalists have noted a surge in plastic pollution from discarded masks in the ocean and continued heavy use of disposable PPE is unlikely to be sustainable.[21 ,22 ,26]

The optimal respirator use strategy that maximizes supply, minimizes cost, and minimizes waste is unknown. This analysis estimates respirator use, cost, and waste generation in the United States over the course of the first six months of the COVID-19 pandemic to explore the optimal strategy for respirator use. For the purpose of this study, we used the following terms to describe the different respirator use and reuse strategies: single use refers to the use of one disposable respirator per patient encounter, followed by disposal; extended use refers to extended use of a disposable respirator for an entire day, followed by disposal; and reuse refers to strategies to decontaminate respirators or use of non-disposable respirators longer-term.

## Methods

*Data sources*



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We estimated respirator usage, cost and waste from late March 2020 to late September 2020. The input parameters for the model are found in Tables 1-3. Data was sourced and adapted from the scientific literature or national databases. Base case respirator cost and waste estimates used the 3M 1860 disposable respirator as well as a recently published reusable respirator.[10, 27-29]

**Table 1 Parameters used to estimate respirator usage, costs, and waste generation**

| Parameter | Value | Reference |
|---|---|---|
| US Population as of 2019 | 328.2 million | [30] |
| Total number of healthcare and frontline workers in US as of 2020 | 18 (17-19) million | [31-33] |
| Weight of one 3M 1860 N95 respirator | 11.3 g | [28] |
| Weight of one 3-ply disposable personal protective (PPE-100-50) surgical mask | 8.5 g | [34 ,35] |
| Total cost of assembled reusable Transparent Elastomeric Adaptable Long-Lasting (TEAL) respirator, minus filters | $6.11 USD ($4.42 GBP; $5.20 Euro) | [10] |
| Weight of one TEAL reusable respirator | 46.5 g | [10] |
| Weight of one reusable respirator filter | 2.26 g | [10] |
| Cost of one pair of filters required per reusable respirator | $0.34 USD ($0.25 GBP; $0.29 Euro) | [10] |
| Cost of one PPE-100-50 surgical mask | $0.15 USD ($0.11 GBP; $0.13 Euro) | [36] |
| Cost of one 3M 1860 N95 respirator | $0.86 USD ($0.62 GBP; $0.73 Euro) | [36] |
| Cost of the National Battelle System funded by the FDA | $415 million USD ($300.23 million GBP; $352.93 Euro) | [6] |
| Reduction in the number of respirators required for HCW population in the US by the use of $H_2O_2$ vapor decontamination | 20-fold | [6] |
| Reduction in the number of respirators required for HCW population in the US by the use of UVGI | 5-fold | [11] |

*Respirator usage*

We considered seven respirator usage strategies: one disposable respirator per patient encounter (single-use respirators), extended use of one disposable respirator per healthcare worker (HCW) per day, reuse of one respirator per HCW per day enabled by daily UVGI decontamination, reuse of one disposable respirator per HCW per day enabled by daily $H_2O_2$ vapor decontamination, one reusable respirator with disposable filters per HCW, one reusable respirator with $H_2O_2$ vapor-decontaminated filters per HCW, and one disposable surgical mask per HCW per day. We assumed that HCWs would be masked for all patient encounters (universal masking) given limited access to rapid COVID-19 testing nationally.[37-39] For the $H_2O_2$ and UVGI decontamination strategies, we accounted for a 30% respirator discard rate due to soiled or damaged respirators as has previously been reported.[40] For each usage strategy, we considered low, average and high estimates for the size of the HCW population (17-19 million) based on estimates from the CDC, the Bureau of Labor Statistics, and published literature.[31-33]



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For the one respirator per patient encounter strategy, we estimated respirators required by HCWs with exposure to patients and those without. The number of respirators required for HCWs due to patient contact was based on the number of hospitalized patients (COVID and non-COVID), average length of stay (LOS), and average number of visits from HCWs per day (Table 2).[31] Data for the number of respirators required per patient per day, LOS per patient, and the number of ICU and hospital admissions was extracted from the recent COVID-19 literature, government reports, and a previous influenza study estimating respirator usage to prevent aerosol transmission.[31 ,41-44] To estimate the number of overall hospitalized patients, we incorporated drops in hospital admission rates due to the pandemic, which were as high as 42.8% below usual rates of admissions in April, 2020 before rebounding down to 15.9% below usual rates in June/July, 2020.[45] In addition, HCWs with patient contact were estimated to be using 4 respirators per day in between direct patient care.[31 ,46] HCWs without patient contact were assumed to be using 1 respirator per day given universal masking (Table 3).

**Table 2 Hospitalization-specific parameters used to estimate number of respirators required by the one respirator per patient encounter strategy over 6-months**

| Parameter | Total | Reference |
|---|---|---|
| Number of hospital admissions | 14,227,773 | [47] |
| Number of patients admitted to the general ward | 12,583,927 | [41 ,47] |
| Number of patients admitted to the ICU | 1,643,846 | [41 ,47] |
| Number of hospitalizations due to COVID-19 | 396,355 | [45] |
| Average length of stay for general ward patients | 4.6 days | [42] |
| Average length of stay for patients admitted to the ICU | 3.3 days | [42] |
| Median length of stay for non-ICU COVID-19 patients | 10.1 days | [44] |
| Median length of stay for COVID-19 patients admitted to the ICU | 10.5 days | [44] |
| Number of respirators required per day for interactions with general ward patients | 8 | [31] |
| Number of respirators required per day for interactions with ICU patients | 14 (12-16) | [31] |

**Table 3 HCW-specific parameters used to estimate number of respirators required by the one respirator per patient encounter strategy**

| Parameter | Total | Number of workers w/ patient contact | Number of workers w/o patient contact | Reference |
|---|---|---|---|---|
| Number of nursing home workers | 3,427,000 | 856,750 | 2,570,250 | [31] |
| Number of emergency medicine service workers | 297,000 | 267,300 | 29,700 | [31] |
| Number of emergency department workers | 132,000 | 132,000 | 0 | [31] |
| Number of hospital workers | 6,053,000 | 1,997,490 | 4,055,510 | [31] |
| Number of outpatient workers | 3,206,000 | 2,148,020 | 1,057,980 | [31] |
| Number of other healthcare workers in other occupations | 6,000,000 | 0 | 6,000,000 | [31 ,32] |

We then used these results to infer estimates for extended use and reuse of respirators enabled by the alternate respirator strategies. For our one disposable respirator per HCW per day strategy, we assumed that each HCW (with or without patient contact) would use one, new respirator per day.

For the daily $H_2O_2$ vapor decontamination strategy, using currently available data on respirator integrity and efficiency after multiple cycles of $H_2O_2$ vapor decontamination, we assumed that a respirator could be decontaminated for up to 20 cycles, with a 30% discard rate per day due to damaged or visibly soiled respirators after each cycle of decontamination.[40] Therefore, to form our estimates for $H_2O_2$ vapor decontamination-enabled reuse of respirators, we divided the one respirator per HCW worker per day usage estimates by 20 and assumed 30% of respirators would need to be replaced after each decontamination cycle/per day to account for the estimated



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discard rate. Given uncertainty regarding discard rates and consistency in maximum number of cycles of decontamination nationally, we performed sensitivity analyses using 10% and 50% discard rates as well as a maximum of 10 cycles of $H_2O_2$ decontamination per respirator.

To model usage estimates for reuse of respirators enabled by daily UVGI decontamination, we used currently available data on respirator integrity and efficiency after multiple cycles of UVGI. Based on these estimates, we assumed that a respirator could be decontaminated for up to 5 cycles.[48] Therefore, to form our estimates for UVGI-enabled reuse of respirators, we divided the one respirator per healthcare worker per day usage estimates by 5 and assumed 30% of respirators would need to be replaced after each decontamination cycle/per day due to the estimated discard rate.[40 ,49 ,50] Given uncertainty regarding discard rates and consistency in maximum number of cycles of decontamination nationally, we performed sensitivity analyses using 10% and 50% discard rates as well as a maximum of 2 cycles of UVGI decontamination per respirator.

For the reusable respirators with disposable or $H_2O_2$ vapor-decontaminated filter strategies, we assumed that every healthcare worker in the US will use one reusable respirator and replace or decontaminate the filters daily. Based on a recently published low-cost reusable respirator, we estimated costs and waste from a pair of filters to be approximately ⅖ of the cost and waste generated from an N95 respirator.[10] If filters were to be decontaminated using $H_2O_2$ vapor, we also assumed that filters could be reused for a maximum of 20 days (20 decontamination cycles).

*Cost estimate*

To estimate the cost accumulated by each usage method, we used the following costs, which were found in the literature and converted to 2020 US dollars: 3M respirator, $0.86, multiplied by the number of respirators required;[36] one surgical mask, $0.15, multiplied by the number of surgical masks required;[36] reusable respirator, $6.11, multiplied by the number of reusable respirators required;[10] a pair of filters for reusable respirators, $0.34, multiplied by the number of pairs of filters required; and nationally distributed $H_2O_2$ vapor decontamination systems across 60 sites, $415 million.[6] Due to variation in implementation and maintenance costs for Battelle $H_2O_2$ vapor decontamination systems across sites, it was difficult to estimate exact costs.[51] We performed a sensitivity analysis to estimate lower and upper-bound costs based on data from the Battelle decontamination center in Somerville, MA and added them to the total cost of the respirators themselves. This decontamination center is capable of decontaminating 80,000 respirators per day and servicing up to roughly 157 hospitals. There are currently 6,090 hospitals across the United States.[47] For the lower bound, we estimated that if each site were able to service 157 hospitals, this would require approximately 39 decontamination centers and only 65% of the 415 million dollars to fund 60 sites across the United States. For the upper bound, we used a decontamination cost per respirator of $3.25 and multiplied that by the respirator usage required for the first 6 months of the pandemic.[52] In addition, we estimated the shipping costs from a large academic hospital here in Boston, MA (Massachusetts General Hospital) to the local Battelle decontamination center in Somerville, MA. The shipping costs for one day per each hospital were estimated to be $114 to and from the site (for a total of $228 in shipping costs; based on the estimated weight of 25 lbs. for shipping 1,000 masks over a distance of roughly 3.5 miles).[53] We scaled this cost by the number of hospitals and Battelle sites across the United States over the course of the first 6 months of the pandemic and arrived at a total nation-wide shipping cost of $250 million. We added this to the overall costs for lower, base-case, and upper bound costs. For the cost of the UVGI system, we assumed the base-case cost of the UVGI system to only include the cost of the respirators required as the literature suggests that UV systems are more readily available on site in many hospitals in comparison to $H_2O_2$ vapor decontamination systems. [39] This may be because UV systems require significantly less space and personnel than $H_2O_2$ vapor decontamination systems.[40] However, we also performed a sensitivity analysis to account for the varying costs and sophistication of UVGI systems, ranging from the installation of a brand new, high volume system [11] to a less expensive, lower volume system that utilizes repurposed materials.[9 ,54] In addition, we explored a range of UVGI system costs which do not include installation, maintenance, distribution, energy, or personnel costs.[9 ,11 ,48 ,54 ,55] We also estimated the average cost generated per patient for each strategy by dividing the total cost by the total number of hospitalized COVID-19 patients during the first 6 months of the pandemic.

*Waste estimate*

Waste estimates for each usage method measured the mass of the total respirators, surgical masks, and filters used and disposed of through the 6-month duration. The mass of 3M's 1860 respirator, a standard surgical mask, and a reusable respirator are 11.3 grams, 8.5 grams and 46.5 grams, respectively.[10 ,27-29] Single filters for reusable



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respirators were estimated using ⅕ of a respirator (2.26 grams per a single filter, 4.53 grams per pair of filters).[10] Thus, to form our waste estimates, we multiplied respirator, surgical mask and reusable respirator usage by their respective masses. We estimated the average waste generated per patient for each strategy by dividing the total amount of waste by the total number of hospitalized COVID-19 patients during the first 6 months of the pandemic. We also performed an additional sensitivity analyses using an alternate disposable respirator.

*Ethics Approval Statement*
This study did not require ethics approval as it did not involve human participants.

*Patient and Public Involvement*
Patients or the public were not involved in the design, or conduct, or reporting, or dissemination plans of our research. It was not appropriate or possible to involve patients or the public in the design, or conduct, or reporting, or dissemination plans of our research.

**Results**

*Mask usage*
The estimated numbers of respirators required in the United States for each strategy are shown in Table 4 and Figure 1A. The use of a new respirator per patient encounter in the U.S. would require 7.41 billion respirators. An extended-use strategy of one respirator per day per HCW would reduce need by over 50% to 3.29 billion respirators. Decontamination by UVGI would further reduce the need to 1.64 billion respirators. Employing a $H_2O_2$ vapor decontamination strategy would further reduce need by 84% to only 1.15 billion respirators. A reusable respirator strategy (with either disposable or decontaminated filters), where one respirator is assigned to each HCW for the duration of the pandemic, would further reduce need to approximately 18 million respirators, for a total reduction in respirator need by over 99%. Using a new surgical mask daily would require 3.29 billion surgical masks.

*Cost estimate*
The estimated costs for each respirator use strategy are summarized in Table 4 and Figure 1B. The use of a new respirator per patient per HCW would cost an average of $6.38 billion ($16 thousand (k) per patient). Extended use of one respirator per day would reduce the cost to $2.83 billion ($7.13k per patient), saving approximately $3.55 billion. The cost for the $H_2O_2$ vapor decontamination strategy would reduce cost to $1.65 billion ($4.17k per patient), saving approximately 1.18 billion, though sensitivity analyses estimated the cost of the $H_2O_2$ decontamination system could vary between $1.51-$4.98 billion (Supplementary Table 1). The decontamination by UVGI strategy would reduce the cost to $1.41 billion ($3.56k per patient), saving an additional $24 million. A reusable respirator with disposable filters would cost $1.24 billion ($3.13k per patient), though this is almost entirely filter costs ($1.13 billion). A reusable respirator with a decontaminated filter and surgical mask strategies would be the least costly strategies at $831 million dollars and $493 million dollars ($2.1k and $1.24k per patient, respectively), which is a total cost savings of over $5.50 billion (Figure 1B). This is more than the amount of money provided by the CARES Act to support the CDC's pandemic response efforts and programs.[56]

*Waste estimate*
The estimated waste generated by each respirator use strategy is summarized in Table 4 and Figure 1C-D. The use of a new respirator per patient encounter per HCW would generate 84.0 million kg of waste (211.93 kg of waste per patient). Extended use of one respirator per day would reduce waste to 37.22 million kg (93.90 kg per patient). The decontamination by UVGI strategy would reduce waste to 18.61 million kg (46.95 kg per patient). A $H_2O_2$ vapor decontamination (with a 30% discard rate) strategy would reduce waste to 13.03 million kg (32.87 kg per patient). A reusable respirator with disposable filters would generate 15.73 million kg of waste (14.88 million kg from filters, 39.68 kg total per patient). Pairing the reusable respirator with a decontaminated filter would significantly reduce generated waste to 1.58 million kg (3.99 kg per patient), for an overall reduction in waste generation by approximately 82.42 million kg, equivalent to going from a mass of 252 Boeing 747 airplanes to five (Figure 1D). The surgical mask strategy would generate 27.92 million kg of waste (70.45 kg per patient).

*Sensitivity analyses*
A sensitivity analysis of a larger commonly used disposable respirator (Gerson 1730) did not significantly change the estimated cost of the strategies or relative amounts of waste generation (Supplementary Table 2). Cost and waste



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estimates for commercially available reusable half-facepiece elastomeric respirators (3M 7500 series) with P100 filters (assuming that each HCW uses one pair of filters per week) were also explored (Supplementary Table 3).[27 ,28 ,34 ,57] Low and high cost estimates of $2.02 and $2.26 billion were calculated using sources from the commercial manufacturer 3M,[28] with reusable respirator costs ranging from $25 to $45 per respirator with a single disposable P100 filter cost of $7.00.[27 ,28] These cost estimates of $2.02-$2.26 billion were lower than the one respirator per day reuse strategy, but higher than the $H_2O_2$ decontamination, UVGI decontamination, reusable respirator, reusable respirator with decontaminated filters, and surgical mask strategies (Table 4, Supplementary Table 3). Low and high waste estimates of 3.22 million kg and 3.59 million kg were calculated using a respirator weight of 135 grams and filter weight of 4.54 grams (Supplementary Table 3). These waste estimates were lower than the one per day reuse strategy, $H_2O_2$ decontamination, UVGI, reusable respirator, and surgical mask strategies, but higher than the reusable respirator with decontaminated filters strategy (Table 4, Supplementary Table 3).

A sensitivity analysis of the $H_2O_2$ decontamination system costs estimated a range of $1.51-$4.98 billion, with variation in cost driven by differing estimates in the number of decontamination centers required to service all of the hospitals in the United States and in the cost of the decontamination per mask (Supplementary Table 1).

Sensitivity analyses of respirator discard rates and maximum cycles of $H_2O_2$ decontamination found that a 10% discard rate lowered respirator usage, cost, and waste generation by 657 million respirators, $601 million, and 7.45 million kg, respectively. A 50% discard rate would increase respirator usage, cost and waste generation by 660 million respirators, $570 million, and 7.44 million kg, respectively. Lowering maximum decontamination to 10 cycles increased respirator usage, cost and waste generation to 160 million respirators, $155 million, and 1.86 million kg, respectively (Supplementary Tables 4-5).

A sensitivity analysis of the UVGI decontamination system costs estimated a range of $1.41-1.42 billion, even accounting for variations in sophistication of technology installed (Supplementary Table 6). Sensitivity analyses of respirator discard rates and maximum cycles of UVGI decontamination found that a 10% discard rate reduced respirator usage, cost, and waste generation by 654 million respirators, $562 million, and 7.44 million kg, respectively. A 50% discard rate increased respirator usage, cost and waste generation by 660 million respirators, $570 million, and 7.44 million kg, respectively. Lowering maximum decontamination to 2 cycles increased respirator usage, cost, and waste generation by 990 million respirators, $850 million, and 11.17 million kg, respectively (Supplementary Tables 7-8).

**Table 4 Numbers of respirators, cost accumulated, and waste generated per strategy over a duration of 6-months per base, low, and high number of estimated HCWs**

| Respirator strategy | Number of respirators required | Cost accumulated (USD) | Cost accumulated (USD) per patient | Waste generated (kg) | Waste generated (kg) per patient |
|---|---|---|---|---|---|
| 1 per patient encounter | 7.41 (7.22-7.59) billion | $6.38 (6.21-6.52) billion | $16.09 (15.67-16.46) thousand | 84.0 (81.79-85.96) million | 211.94 (206.38-216.88) |
| 1 per day | 3.29 (3.10-3.47) billion | $2.83 (2.67-2.98) billion | $7.13 (6.73-7.52) thousand | 37.22 (35.15-39.29) million | 93.90 (88.69-99.12) |
| UVGI-decontaminated 3M 1860 N95 respirators | 1.64 (1.55-1.73) billion | $1.41 (1.33-1.49) billion | $3.56 (3.37-3.76) thousand | 18.61 (17.58-19.64) million | 46.95(44.34-49.56) |
| $H_2O_2$ decontaminated 3M 1860 N95 respirators | 1.15 (1.09-1.21) billion | $1.65 (1.60-1.71) billion | $4.17 (4.03-4.31) thousand | 13.03 (12.30-13.75) million | 32.87 (31.04-34.69) |
| Reusable TEAL respirator + disposable filters | 0.018 (0.017-0.019) billion | $1.24 (1.17-1.31) billion | $3.13 (2.96-3.30) thousand | 15.73 (14.85-16.60) million | 39.68 (37.47-41.88) |
| Reusable TEAL respirator + decontaminated filters | 0.018 (0.017-0.019) billion | $0.831 (0.822 -0.841) billion | $2.10 (2.07 -2.12) thousand | 1.58 (1.49-1.67) million | 3.99 (3.77-4.21) |
| Surgical mask, 1 per day | 3.29 (3.10-3.47) billion (surgical masks) | $0.493 (0.465-0.520) billion | $1.24 (1.17-1.31) thousand | 27.92 (26.37-29.47) million | 70.45 (66.53 -74.36) |



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## Discussion

*Principal findings*

The COVID-19 pandemic has dramatically increased the demand for respirators across the world, leading to supply shortages, spending in the billions of dollars, and generation of large amounts of medical waste. Even after widespread vaccination efforts, masks will likely continue to be required due to factors such as variable vaccine uptake, incomplete vaccinations, lack of knowledge as to who has received a vaccine, the possibility of reinfection, and unclear duration of vaccination efficacy.[58 ,59] Additionally, even after the pandemic, respirator and mask usage both in healthcare settings and among the general public may persist.[60] The continued use of disposable respirators and masks is unlikely to be sustainable and will have significant environmental consequences.[45] With this in mind, it is critical to understand the best strategy to maximize respirator and mask availability while minimizing costs and waste generation.

Of the strategies compared, we find that all reuse strategies (UVGI decontamination, $H_2O_2$ vapor decontamination, reusable respirators with disposable filters, or reusable respirators with decontaminated filters), could significantly decrease the number of respirators required compared to single- or extended-use mask strategies by at least 1.65 billion respirators in the United States alone. This would greatly increase availability and access of respirators worldwide. In addition, reuse strategies could save at least $1.18 billion dollars in costs nationally over the course of the pandemic. Finally, reuse strategies significantly reduce waste generation in the United States by at least 18.61 million kg. These estimates from our study only capture the economic and environmental impact over the first six months of the COVID-19 pandemic in the US and suggest that the long-term and global impact of reuse strategies are even higher, especially when considering respirators and masks used by the general population.

Our analyses found that UVGI decontamination, $H_2O_2$ vapor decontamination, and reusable respirators with disposable filters were similar in cost and waste generation. Combining the strategies by utilizing a reusable respirator with either $H_2O_2$ vapor-decontaminated filters was the least costly of all strategies compared and generated the least amount of waste. This finding suggests that even with UVGI and $H_2O_2$ vapor decontamination strategies, the adoption of a reusable respirator can have a significant impact in both cost and waste generation, though additional studies are needed to estimate the impact of additional costs, such as shipping to shared decontamination sites, installation costs, and time associated with decontamination or cleaning methods. Additional investigation is needed to capture other potential costs and benefits related to each mask-reuse strategy.

In settings where UVGI or $H_2O_2$ vapor decontamination are not feasible, such as in resource-constrained settings where installation and maintenance of such systems are challenging, reusable respirators with disposable filters may be preferable to disposable respirators. These respirators may also be decontaminated with standard hospital equipment such as alcohol and bleach wipes, which may be more readily available in settings with limited resources.[10 ,12] Anticipatory investment in a reusable respirator may not only provide access to high-quality PPE for COVID-19 in such settings but reduce overall waste and injury to our environment. Development of technologies to facilitate decontamination of respirators and/or filters that do not require special equipment, training, or infrastructure could even further reduce costs and waste as in the reusable respirator with decontaminated filters strategy.

*Limitations*

One potential limitation of our study is the assumption that all respirator strategies discussed are equally effective at protecting the user. The decision to employ decontamination methods for reuse should be weighed against the possibility for greater health risks incurred by incomplete decontamination or lowered respirator efficacy, which may incur additional costs. The CDC recommended extended respirator use and reuse strategies for N95 respirators if respirators maintained their fit and function after decontamination.[61] Several studies have evaluated the effect of extended use and re-use strategies that require multiple donning on the fit and efficacy of N95 respirators independent of decontamination. One study found that 48% of subjects failed a fit test after only one redonning of an N95 respirator. Additionally, another study found that among test subjects experienced in respirator donning, consecutively donning the same respirator 5 times was the threshold before mask-fit dropped below 100%.[62] Furthermore, both UVGI and $H_2O_2$ decontamination methods have shown to reduce filtration and mask performance after 3 rounds of decontamination in some studies.[63] Therefore, it is important to note that the efficacy of each reuse strategy may not be not equal and should be considered prior to implementation. Potential costs related to unequal respirator efficiency and protection were not estimated in our analysis.



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An additional limitation of our study is that we modelled one strategy for all HCWs, regardless of frequency and type of patient contact. For HCWs at low risk of contact with bodily fluids (including respiratory droplets), it may be possible to deploy alternate strategies such as extended use of disposable respirators or less frequent decontamination. This could potentially further reduce cost and waste and increase respirator availability without sacrificing protection.

We estimated only a few respirator strategies and decontamination methods, and other methods for extended respirator use and reuse across the world were not captured in our analysis. Furthermore, our estimates were performed from a US perspective, and these numbers will be different for other countries depending on parameters such as number of healthcare workers, rates of infection, and number of hospitalized patients, though we suspect that the relative benefit of reuse strategies compared to single- or extended-use respirator strategies will persist. Additionally, the number of COVID-19 hospitalizations were likely underestimated in this study, as only two-thirds of states and territories in the United States have reported this data during the COVID-19 pandemic; however, we suspect that this therefore underestimates the potential impact of mask reuse strategies.[46] Furthermore, our cost estimates did not include installation, maintenance, distribution, or personnel costs associated with various strategies, and additional studies should be performed. In addition, our analysis measured only the waste generated by masks themselves and did not study the environmental impact of manufacturing, packaging or waste generation from decontamination processes, which some studies estimate could generate up to 90% of greenhouse gas emissions.[19] Furthermore, the environmental impact of single-use plastics generated from packaging related to mask use, estimated to have increased by up to 40% during the pandemic, may contribute a significant amount of additional environmental waste.[64] These aspects were not included in our analyses and require further quantification. Finally, our estimates for the reusable respirator strategy was based on a recently published prototype.[10] Updated analyses should be performed as these and other low-cost reusable respirators and masks become more available.[12 ,65]

*Implications and future research*

While our analysis measured the economic and environmental impact of several mask reuse strategies, there are several areas of investigation that may contribute to further reductions in cost and environmental impact. For example, our analysis highlighted the importance of considering not only reusable respirators, but reusable or decontaminatable filters, as these drove the cost and waste of reusable respirator/disposable filter strategies. Inexpensive, low-tech methods for filter decontamination are needed. Alternatively, redesign of reusable respirators to require smaller filters or development of fully reusable respirators would greatly reduce cost, waste and potentially the need for single-use plastics. Additionally, the development of novel materials for masks to increase durability of these systems after repeated exposures to $H_2O_2$ vapor or other decontamination techniques may increase the lifespan of masks and decrease the volume of masks used. Incorporation of bactericidal or antiviral agents, nanoparticles, or nanotechnology into masks may also increase their reusability and potentially decrease the need for cleaning agents in regions where there may be concomitant shortages of these solutions. Antimicrobial agents derived from natural products (tea tree oil, grapefruit seed extract, etc.) as well as nanoparticles (NPs) from different metals and metal compounds (copper, silver, zinc oxide, etc.) have also been shown to improve filtration and reduce viral load on mask surfaces.[14 ,15] There are a variety of masks now commercially available that use nanotechnology and range from disposable surgical masks, washable masks, and reusable respirators such as Innonix RespoKare (citric acid NPs), Cupron Inc. (copper NPs), and Argaman BioBlockX ™ (silver NPs).[14 ,15 ,18] These strategies may also decrease waste of common hospital-based wipes used to decontaminate masks, which was not included in this analysis. Finally, the development of biodegradable or recyclable materials that provide efficient particle protection may minimize the environmental effects of discarded masks.

Our analysis raises key questions for stakeholders regarding the optimal strategy to both provide sufficient protection for healthcare workers and patients while also assuring equitable access to PPE and reducing environmental harm. Given our findings that reusable respirator strategies greatly reduce the number of respirators required and medical waste generated, it is interesting that reusable respirators or decontamination strategies have largely not been adopted in the US prior to the COVID-19 pandemic. We hypothesize that this could be due to a number of reasons including cost and availability of reusable respirators, lack of recognition of the scale of medical waste and its impact on the environment, and individual healthcare systems' lack of accountability with regard to medical waste. We have reason to believe that the first two reasons will be addressed over the course of the pandemic. Given renewed interest in new technologies for PPE, we expect options and availability for reusable



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respirators to continue to expand.[15] We believe our study as well as others will increase public awareness of the environmental impact of disposable PPE, particularly masks.[22 ,38 ,64] In order to improve hospital system accountability over medical waste, however, we may need to turn to policymakers to consider nationwide incentives such as subsidies to transition to reusable PPE, taxes to offset medical waste generation, and other incentives as has been used to promote transition to green technologies in other fields.[66-68]

*Conclusions*

In summary, respirator reuse technologies are critical to meet the supply demands imparted by COVID-19, especially in low-resource settings. This need is emphasized by the likelihood that respirators will continue to be commonly used even after widespread vaccination and post-pandemic in certain scenarios, such as healthcare and crowded transportation areas, and such technologies can enable more sustainable use of respirators moving forward. Furthermore, these technologies can save billions of dollars that can be redistributed toward other efforts for economic and environmental recovery brought on by the pandemic. Further study is needed regarding reuse fit and filtration efficacy to minimize health risks associated with reuse strategies. Additionally, future development of low-cost, low-tech technologies to enable respirator and/or filter decontamination is needed to further minimize the economic and environmental costs of respirators.

**Footnotes**

**Contributors:** JNC, OG, JC, CH, and GT conceived and designed the analysis. JB, AW, PRC, and FD contributed data. JNC, OG, and JC collected data and performed the analysis. JNC, OG, JC, and GT wrote the manuscript. JNC, OG, JC, JB, AW, PRC, FD, CH, and GT interpreted the data and reviewed and approved the manuscript. The corresponding author, GT, provided supervision over the study and is the guarantor. GT confirms that all authors meet the authorship criteria and no contributing authors have been omitted.

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**Competing interests:** The authors declare the following competing financial interest(s): AJW, JDB, and GT have filed multiple patents surrounding the respirator and sensors. In addition, AJW, JDB and GT have a financial interest in TEAL Bio, a biotechnology company focused on developing the next generation of personal protective equipment. JNC, PRC, OG, JC, FD, and CH declare no competing interests.

**Data Sharing:** All data is included in the manuscript and/or supplementary materials, no additional data is available.

GT provides attestation that this study reflects honest and accurate data and transparent disclosure of all relevant information. Nothing has been omitted or withheld from this study.

**Fig. 1** Comparison of the following per respirator reuse strategy: A) number of respirators or surgical masks used, B) costs in billions of USD, C) waste generated in millions of kg, D) waste generated per strategy in the equivalent number of 747 airplanes by mass (mass of one 747 airplane, 333,000 kg).



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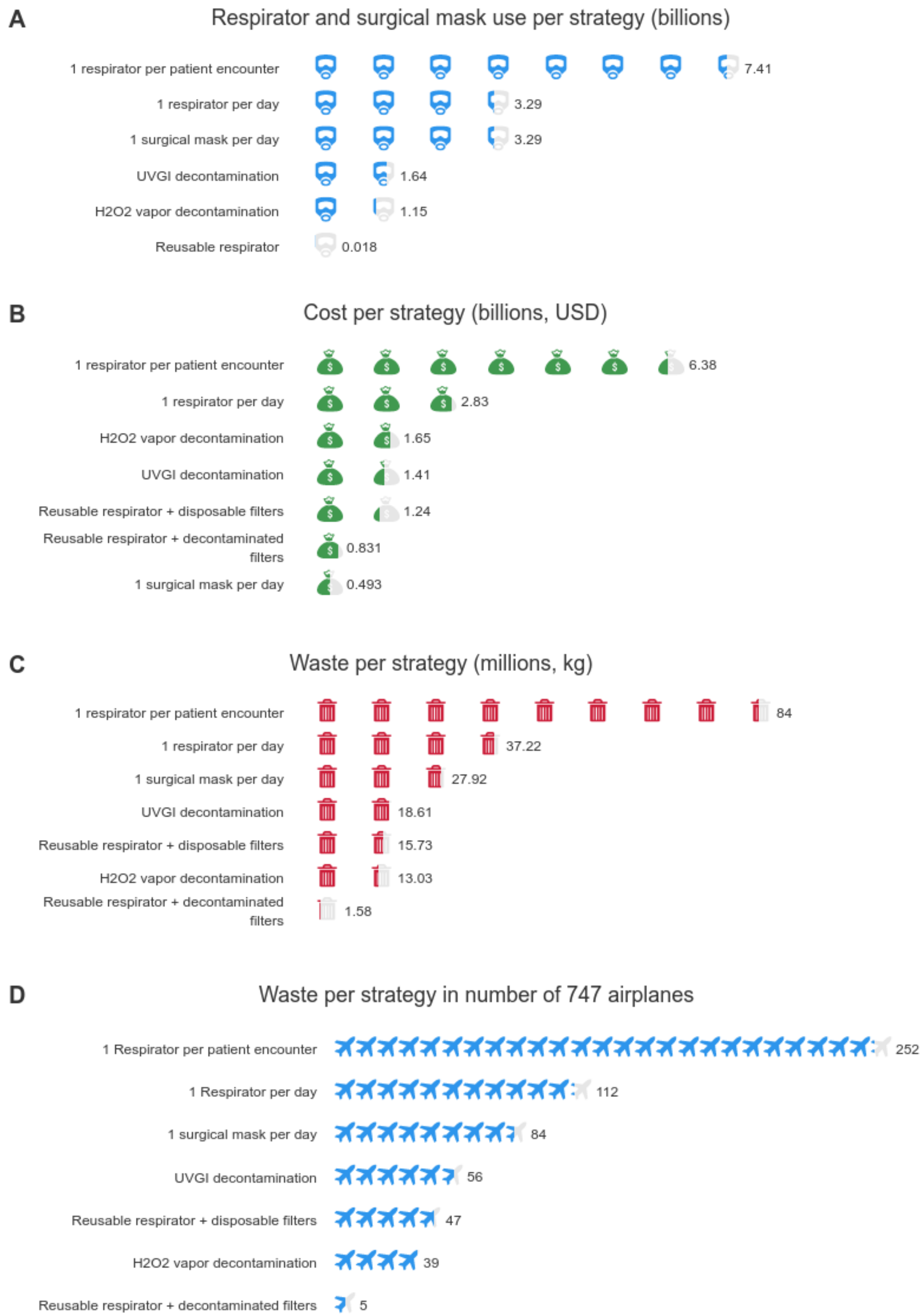


**Fig. 1** Comparison of the following per respirator reuse strategy: A) number of respirators or surgical masks used, B) costs in billions of USD, C) waste generated in millions of kg, D) waste generated per strategy in the equivalent number of 747 airplanes by mass (mass of one 747 airplane, 333,000 kg).

### Supplementary Table 1 Sensitivity analysis: $H_2O_2$ decontamination strategy cost

| Base system cost | Shipping cost | Respirator cost | Overall cost accumulated (USD) |
|---|---|---|---|
| $268 million | $250 million | $989 million | $1.51 billion |
| $415 million | $250 million | $989 million | $1.65 billion |
| $3.74 billion | $250 million | $989 million | $4.98 billion |

### Supplementary Table 2 Sensitivity analysis: Disposable Gerson 1730 respirator*

| Respirator strategy | Number of respirators required | Cost accumulated (USD) | Waste generated (kg) |
|---|---|---|---|
| 1 per patient (all hospitalized patients) | 7.41 (7.22-7.59) billion | $6.52 (6.35-6.68) billion | 126.0 (122.7-129.0) million |
| 1 per day | 3.29 (3.10-3.47) billion | $2.89 (2.73-3.05) billion | 55.85 (52.74-58.95) million |
| UVGI-decontaminated N95 respirators | 1.64 (1.55-1.73) billion | $1.45 (1.37-1.53) billion | 27.92 (26.37-29.47) million |
| $H_2O_2$-decontaminated N95 respirators | 1.15 (1.09-1.21) billion | $1.68 (1.62-1.73) billion | 19.55 (18.46-20.63) million |
| Reusable respirator + disposable filters | 0.018 (0.017-0.019) billion | $1.27 (1.20-1.34) billion | 23.18 (21.93-24.42) million |
| Reusable respirator + decontaminated filters | 0.018 (0.017-0.019) billion | $0.833 (0.824-0.842) billion | 1.955 (1.893-2.017) million |

**The weight of one Gerson 1730 N95 Respirator is equal to 17g*

### Supplementary Table 3 Sensitivity analysis: Reusable elastomeric respirator + disposable p100 filter

| Parameter | Value |
|---|---|
| Number of respirators required | 18 (17-19) million |
| Number of filters required (by pair) | 108 (102-114) million |
| | |
| **Results** | |
| Reusable respirator + filter cost (USD) | $2.14 (2.02-2.26) billion |
| Reusable respirator + filter waste (kg) | 3.41 (3.22-3.59) million |

### Supplementary Table 4 Sensitivity analysis: $H_2O_2$ decontamination system respirator discard rate

| Discard rate | Number of respirators required | Cost accumulated (USD) | Waste generated (kg) |
|---|---|---|---|
| 10% | 493 (465-520) million | $1.09 (1.07-1.11) billion | 5.58 (5.27-5.89) million |
| 30% | 1.15 (1.09-1.21) billion | $1.65 (1.60-1.71) billion | 13.03 (12.30-13.75) million |
| 50% | 1.81 (1.71-1.91) billion | $2.22 (2.13 -2.31) billion | 20.47 (19.33-21.61) million |

### Supplementary Table 5 Sensitivity analysis: Maximum cycles of decontamination per respirator for $H_2O_2$ decontamination system

| Number cycles | Number of respirators required | Cost accumulated (USD) | Waste generated (kg) |
|---|---|---|---|
| 10 | 1.31 (1.24-1.39) billion | $1.80 (1.73-1.86) billion | 14.89 (14.06-15.71) million |
| 20 | 1.15 (1.09-1.21) billion | $1.65 (1.60-1.71) billion | 13.03 (12.30-13.75) million |

### Supplementary Table 6 Sensitivity analysis: UVGI decontamination strategy cost*

| Parameter | Value |
|---|---|
| Cost of 2 surgical suite UVGI system | $40,000.00 |
| Cost of repurposed or low tech UVGI lamp system | $50.00 |
| | |
| **Results** | |
| Base cost | $1.41 (1.33-1.49) billion |
| Base cost + cost of 2 surgical suite UVGI systems | $1.42 (1.34-1.49) billion |

| | |
|---|---|
| Base cost + cost of repurposed or low tech UVGI lamp system | $1.41 (1.33-1.49) billion |
| *Assuming distribution across hypothetical 60 sites across U.S. | |

**Supplementary Table 7 Sensitivity analysis: UVGI decontamination system discard rate**

| Discard rate | Number of respirators required | Cost accumulated (USD) | Waste generated (kg) |
|---|---|---|---|
| 10% | 986 (931-1040) million | $848 (800-895) million | 11.17 (10.55-11.79) million |
| 30% | 1.64 (1.55-1.73) billion | $1.41 (1.33-1.49) billion | 18.61 (17.58-19.64) million |
| 50% | 2.30 (2.17-2.43) billion | $1.98 (1.87-2.09) billion | 26.05 (24.61-27.50) million |

**Supplementary Table 8 Sensitivity analysis: Maximum cycles of decontamination per respirator for UVGI decontamination system**

| Number cycles | Number of respirators required | Cost accumulated (USD) | Waste generated (kg) |
|---|---|---|---|
| 2 | 2.63 (2.48-2.77) billion | $2.26 (2.13-2.39) billion | 29.78 (28.12-31.43) million |
| 5 | 1.64 (1.55-1.73) billion | $1.41 (1.33-1.49) billion | 18.61 (17.58-19.64) million |

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# Thinking green: Modelling respirator reuse strategies to reduce cost and waste

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**Thinking green: Modelling respirator reuse strategies to reduce cost and waste**

Jacqueline N. Chu, MD (1,2), Omkar Ghenand (3), Joy Collins, MPH (2,4), James Byrne, MD, PhD (2,5), Adam Wentworth, MS (2,4), Peter R Chai, MD MMS (2,6), Farah Dadabhoy, MD (2,6), Chin Hur, MD, MPH (7,8), Giovanni Traverso, MB, BChir, PhD* (4,9)

1 Division of Gastroenterology, Massachusetts General Hospital, Harvard Medical School, Boston, MA 02114, USA.

2 David H. Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, MA 02142, USA

3 The Undergraduate Research Opportunities Program, Massachusetts Institute of Technology, Cambridge, MA 02142, USA

4 Division of Gastroenterology, Brigham and Women's Hospital, Harvard Medical School, Boston, MA 02115, USA

5 Harvard Radiation Oncology Program, Brigham and Women's Hospital, Harvard Medical School, Boston, MA 02114, USA

6 Department of Emergency Medicine, Brigham and Women's Hospital

7 Department of Medicine, Columbia University Medical Center, New York, NY 10032, USA

8 Department of Epidemiology, Mailman School of Public Health and Herbert Irving Comprehensive Cancer Center, Columbia University Medical Center, New York, NY 10032, USA

9 Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave, Cambridge, MA 02139, USA

*Correspondence to:

Giovanni Traverso MB, BChir, PhD
Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave., 3-340, Cambridge, MA 02139
Division of Gastroenterology, Brigham and Women's Hospital, 65 Landsdowne St, Suite 252, Cambridge, MA, 02139
ctraverso@bwh.harvard.edu, cgt20@mit.edu
(o) 617-417-8061
(f) 617-500-0631

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**Abstract:**

**Objectives** To compare the impact of respirator extended use and reuse strategies with regard to cost and sustainability during the COVID-19 pandemic.

**Design** Cost analysis

**Setting** United States

**Participants** All healthcare workers within the United States

**Interventions** Not applicable

**Main outcome measures** A model was developed to estimate usage, costs, and waste incurred by several respirator usage strategies over the first 6-months of the pandemic in the United States. This model assumed universal masking of all healthcare workers. Estimates were taken from the literature, government databases, and commercially available data from approved vendors.

**Results** A new N95 respirator per patient encounter would require 7.41 billion respirators, cost $6.38 billion, and generate 84.0 million kg of waste in the U.S. over 6 months. One respirator per day per healthcare worker would require 3.29 billion respirators, $2.83 billion, and 37.22 million kg of waste. Decontamination by ultraviolet germicidal irradiation would require 1.64 billion respirators, $1.41 billion, and accumulate 18.61 million kg of waste. $H_2O_2$ vapor decontamination would require 1.15 billion respirators, $1.65 billion, and produce 13.03 million kg of waste. One reusable respirator with daily disposable filters would require 18 million respirators, cost $1.24 billion, and generate 15.73 million kg of waste. Pairing a reusable respirator with $H_2O_2$ vapor-decontaminatable filters would reduce cost to $831 million and generate 1.58 million kg of waste. The use of one surgical mask per healthcare worker per day would require 3.29 billion masks, cost $460 million, and generate 27.92 million kg of waste.

**Conclusions** Decontamination-and reusable respirator-based strategies decreased the number of respirators used, costs, and waste generated compared to single- or daily extended-use of disposable respirators. Future development of low-cost, low-tech technologies to enable respirator and/or filter decontamination is needed to further minimize the economic and environmental costs of masks.

**Trial registration** Not applicable

**Keywords** Covid-19, environmental health, health economics

**Strengths and limitations of this study**

- Describes the current economic and environmental impact of several mask reuse strategies on a national scale among healthcare workers.
- Estimates cost and waste specific to respirator use in order to meet the demands of COVID-19.
- Explores respirator reuse strategies to reduce the economic and environmental toll during COVID-19 and beyond.
- Only a few respirator strategies and decontamination methods are evaluated in this study.
- Conducted from a US perspective only; parameters are not applicable to other countries and did not include ancillary costs.

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## Introduction

The COVID-19 pandemic has led to personal protective equipment (PPE) shortages worldwide, including shortage of N95 respirators and surgical masks.[1-3] In order to maximize resources, many hospitals have adopted extended use of masks or decontamination and reuse strategies, particularly of N95 respirators.[1 ,4 ,5] Prior to the pandemic, a new N95 respirator was typically used for each patient encounter and then discarded.[5 ,6] In light of the PPE shortage, some hospitals have now moved to using one respirator per several encounters or even several days.[4 ,6] Decontamination strategies such as hydrogen peroxide vapor ($H_2O_2$) and ultraviolet germicidal irradiation (UVGI) are being adopted and thus far appear effective, but concerns about decontamination reducing mask fit and integrity remain, as well as concerns regarding cost of the technology.[5-9]

The United States government awarded a $415 million contract to Battelle in April 2020 to deploy 60 hydrogen peroxide vapor decontamination sites across the country.[6 ,7] While this may be feasible in resource-rich settings, the hydrogen peroxide system requires significant infrastructure and trained personnel, limiting its translation to resource-constrained areas.[7 ,9] There is therefore a need for simpler methods of respirator decontamination that can be deployed on a large scale.[10] Investigations into heat, steam, and detergent decontamination are ongoing; however, these have thus far been shown to compromise mask integrity.[3 ,5] Nebraska Medicine piloted a UVGI system that has been approved by the United States Centers for Disease Control and Prevention (CDC), which may be easier to deploy for hospitals that already have UV decontamination systems in place.[11]

Reusable respirators designed for prolonged use such as half-mask elastomeric respirators are available but have not been heavily adopted due to challenges with sterilization, cost, and bulky size.[10] Several scalable, less expensive reusable respirators have been recently developed that can be easier to decontaminate using standard hospital equipment to try to address the respirator shortage.[10 ,12] The Pneumask project for example, which repurposes snorkel masks, has already distributed more than 23,000 masks internationally.[12-15] Other types of reusable masks that aim to address barriers to communication, such as the Jelli M1 mask [16] and ClearMask, have recently been developed.[17] Potential benefits of reusable respirators compared to disposable respirators could include reduced cost and waste. The use of innovative filtration techniques and antimicrobial nanoparticles could also reduce viral spread, and when incorporated into reusable respirators, reduce cost and waste even further.[18] Introducing novel mask types, such as a variety of reusable masks, presents an opportunity to diversify the market, and in turn provide more flexibility within supply chains. This has the potential to increase efficiency and reduce cost, waste, and energy consumption associated with supply chain disruption.[19]

The global increase in the use of plastics for mask and PPE production has drastically increased medical waste, with countries such as Spain and China reporting increases of 350% and 370%, respectively.[20 ,21] As of February 2020, the production rate of face masks in China alone increased by 12 fold.[22 ,23] Rough estimates have shown the COVID-19 pandemic could generate up to 7,200 tons a day in medical waste, a sizable portion of which comes from masks.[21 ,24] A reusable respirator could be a more sustainable alternative to disposable respirators, particularly if respirator and mask usage becomes more commonplace post-pandemic, such as in Asia. [25-27] Already environmentalists have noted a surge in plastic pollution from discarded masks in the ocean and continued heavy use of disposable PPE is unlikely to be sustainable.[21 ,24 ,28]

The optimal respirator use strategy that maximizes supply, minimizes cost, and minimizes waste is unknown. This analysis estimates respirator use, cost, and waste generation in the United States over the course of the first six months of the COVID-19 pandemic to explore the optimal strategy for respirator use. For the purpose of this study, we used the following terms to describe the different respirator use and reuse strategies: single use refers to the use of one disposable respirator per patient encounter, followed by disposal; extended use refers to extended use of a disposable respirator for an entire day, followed by disposal; and reuse refers to strategies to decontaminate respirators or use of non-disposable respirators longer-term.

## Methods

*Data sources*

We estimated respirator usage, cost and waste from late March 2020 to late September 2020. The input parameters for the model are found in Tables 1-3. Data was sourced and adapted from the scientific literature or national databases. Base case respirator cost and waste estimates used the 3M 1860 disposable respirator as well as a recently published reusable respirator.[10], [29]

**Table 1 Parameters used to estimate respirator usage, costs, and waste generation**

| Parameter | Value | Reference |
|---|---|---|
| US Population as of 2019 | 328.2 million | [30] |
| Total number of healthcare and frontline workers in US as of 2020 | 18 (17-19) million | [31-33] |
| Weight of one 3M 1860 N95 respirator | 11.3 g | [29] |
| Weight of one 3-ply disposable personal protective (PPE-100-50) surgical mask | 8.5 g | [34] |
| Total cost of assembled reusable Transparent Elastomeric Adaptable Long-Lasting (TEAL) respirator, minus filters | $6.11 USD ($4.42 GBP; $5.20 Euro) | [10] |
| Weight of one TEAL reusable respirator | 46.5 g | [10] |
| Weight of one reusable respirator filter | 2.26 g | [10] |
| Cost of one pair of filters required per reusable respirator | $0.34 USD ($0.25 GBP; $0.29 Euro) | [10] |
| Cost of one 3-ply surgical mask (Fluidshield Level 1) | $0.14 USD ($0.10 GBP; $0.12 Euro) | [35] |
| Cost of one 3M 1860 N95 respirator | $0.86 USD ($0.62 GBP; $0.73 Euro) | [36] |
| Cost of the National Battelle System funded by the FDA | $415 million USD ($300.23 million GBP; $352.93 Euro) | [6] |
| Reduction in the number of respirators required for HCW population in the US by the use of $H_2O_2$ vapor decontamination | 20-fold | [6] |
| Reduction in the number of respirators required for HCW population in the US by the use of UVGI | 5-fold | [11] |

*Respirator usage*

We considered seven respirator usage strategies: one disposable respirator per patient encounter (single-use respirators), extended use of one disposable respirator per healthcare worker (HCW) per day, reuse of one respirator per HCW per day enabled by daily UVGI decontamination, reuse of one disposable respirator per HCW per day enabled by daily $H_2O_2$ vapor decontamination, one reusable respirator with disposable filters per HCW, one reusable respirator with $H_2O_2$ vapor-decontaminated filters per HCW, and one disposable surgical mask per HCW per day. We assumed that HCWs would be masked for all patient encounters (universal masking) given limited access to rapid COVID-19 testing nationally.[37-39] For the $H_2O_2$ and UVGI decontamination strategies, we accounted for a 30% respirator discard rate due to soiled or damaged respirators as has previously been reported.[40] For each usage strategy, we considered low, average and high estimates for the size of the HCW population (17-19 million) based on estimates from the CDC, the Bureau of Labor Statistics, and published literature.[31-33]

For the one respirator per patient encounter strategy, we estimated respirators required by HCWs with exposure to patients and those without. The number of respirators required for HCWs due to patient contact was based on the



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number of hospitalized patients (COVID and non-COVID), average length of stay (LOS), and average number of visits from HCWs per day (Table 2).[31] Data for the number of respirators required per patient per day, LOS per patient, and the number of ICU and hospital admissions was extracted from the recent COVID-19 literature, government reports, and a previous influenza study estimating respirator usage to prevent aerosol transmission.[31 ,41-44] To estimate the number of overall hospitalized patients, we incorporated drops in hospital admission rates due to the pandemic, which were as high as 42.8% below usual rates of admissions in April, 2020 before rebounding down to 15.9% below usual rates in June/July, 2020.[45] In addition, HCWs with patient contact were estimated to be using 4 respirators per day in between direct patient care.[31 ,46] HCWs without patient contact were assumed to be using 1 respirator per day given universal masking (Table 3).

**Table 2 Hospitalization-specific parameters used to estimate number of respirators required by the one respirator per patient encounter strategy over 6-months**

| Parameter | Total | Reference |
|---|---|---|
| Number of hospital admissions | 14,227,773 | [47] |
| Number of patients admitted to the general ward | 12,583,927 | [41 ,47] |
| Number of patients admitted to the ICU | 1,643,846 | [41 ,47] |
| Number of hospitalizations due to COVID-19 | 396,355 | [45] |
| Average length of stay for general ward patients | 4.6 days | [42] |
| Average length of stay for patients admitted to the ICU | 3.3 days | [42] |
| Median length of stay for non-ICU COVID-19 patients | 10.1 days | [44] |
| Median length of stay for COVID-19 patients admitted to the ICU | 10.5 days | [44] |
| Number of respirators required per day for interactions with general ward patients | 8 | [31] |
| Number of respirators required per day for interactions with ICU patients | 14 (12-16) | [31] |

**Table 3 HCW-specific parameters used to estimate number of respirators required by the one respirator per patient encounter strategy**

| Parameter | Total | Number of workers w/ patient contact | Number of workers w/o patient contact | Reference |
|---|---|---|---|---|
| Number of nursing home workers | 3,427,000 | 856,750 | 2,570,250 | [31] |
| Number of emergency medicine service workers | 297,000 | 267,300 | 29,700 | [31] |
| Number of emergency department workers | 132,000 | 132,000 | 0 | [31] |
| Number of hospital workers | 6,053,000 | 1,997,490 | 4,055,510 | [31] |
| Number of outpatient workers | 3,206,000 | 2,148,020 | 1,057,980 | [31] |
| Number of other healthcare workers in other occupations | 6,000,000 | 0 | 6,000,000 | [31 ,32] |

We then used these results to infer estimates for extended use and reuse of respirators enabled by the alternate respirator strategies. For our one disposable respirator per HCW per day strategy, we assumed that each HCW (with or without patient contact) would use one, new respirator per day.

For the daily $H_2O_2$ vapor decontamination strategy, using currently available data on respirator integrity and efficiency after multiple cycles of $H_2O_2$ vapor decontamination, we assumed that a respirator could be decontaminated for up to 20 cycles, with a 30% discard rate per day due to damaged or visibly soiled respirators after each cycle of decontamination.[40] Therefore, to form our estimates for $H_2O_2$ vapor decontamination-enabled reuse of respirators, we divided the one respirator per HCW worker per day usage estimates by 20 and assumed 30% of respirators would need to be replaced after each decontamination cycle/per day to account for the estimated discard rate. Given uncertainty regarding discard rates and consistency in maximum number of cycles of



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decontamination nationally, we performed sensitivity analyses using 10% and 50% discard rates as well as a maximum of 10 cycles of $H_2O_2$ decontamination per respirator.

To model usage estimates for reuse of respirators enabled by daily UVGI decontamination, we used currently available data on respirator integrity and efficiency after multiple cycles of UVGI. Based on these estimates, we assumed that a respirator could be decontaminated for up to 5 cycles.[48] Therefore, to form our estimates for UVGI-enabled reuse of respirators, we divided the one respirator per healthcare worker per day usage estimates by 5 and assumed 30% of respirators would need to be replaced after each decontamination cycle/per day due to the estimated discard rate.[40 ,49 ,50] Given uncertainty regarding discard rates and consistency in maximum number of cycles of decontamination nationally, we performed sensitivity analyses using 10% and 50% discard rates as well as a maximum of 2 cycles of UVGI decontamination per respirator.

For the reusable respirators with disposable or $H_2O_2$ vapor-decontaminated filter strategies, we assumed that every healthcare worker in the US will use one reusable respirator and replace or decontaminate the filters daily. Based on a recently published low-cost reusable respirator, we estimated costs and waste from a pair of filters to be approximately ⅖ of the cost and waste generated from an N95 respirator.[10] If filters were to be decontaminated using $H_2O_2$ vapor, we also assumed that filters could be reused for a maximum of 20 days (20 decontamination cycles).

*Cost estimate*

To estimate the cost accumulated by each usage method, we used the following costs, which were found in the literature and converted to 2020 US dollars: 3M respirator, $0.86 (converted from $0.79 USD 2014 to 2020 USD), multiplied by the number of respirators required; [36] one surgical mask, $0.14, multiplied by the number of surgical masks required;[35] reusable respirator, $6.11, multiplied by the number of reusable respirators required;[10] a pair of filters for reusable respirators, $0.34, multiplied by the number of pairs of filters required; and nationally distributed $H_2O_2$ vapor decontamination systems across 60 sites, $415 million.[6] Due to variation in implementation and maintenance costs for Battelle $H_2O_2$ vapor decontamination systems across sites, it was difficult to estimate exact costs.[51] We performed a sensitivity analysis to estimate lower and upper-bound costs based on data from the Battelle decontamination center in Somerville, MA and added them to the total cost of the respirators themselves. This decontamination center is capable of decontaminating 80,000 respirators per day and servicing up to roughly 157 hospitals. There are currently 6,090 hospitals across the United States.[47] For the lower bound, we estimated that if each site were able to service 157 hospitals, this would require approximately 39 decontamination centers and only 65% of the 415 million dollars to fund 60 sites across the United States. For the upper bound, we used a decontamination cost per respirator of $3.25 and multiplied that by the respirator usage required for the first 6 months of the pandemic.[52] We performed the sensitivity analysis varying different parameters for the upper and lower bounds in order to test the widest range for the cost of the $H_2O_2$ decontamination strategy. In addition, we estimated the shipping costs from a large academic hospital here in Boston, MA (Massachusetts General Hospital) to the local Battelle decontamination center in Somerville, MA. The shipping costs for one day per each hospital were estimated to be $114 to and from the site (for a total of $228 in shipping costs; based on the estimated weight of 25 lbs. for shipping 1,000 masks over a distance of roughly 3.5 miles).[53] We scaled this cost by the number of hospitals and Battelle sites across the United States over the course of the first 6 months of the pandemic and arrived at a total nation-wide shipping cost of $250 million. We added this to the overall costs for lower, base-case, and upper bound costs. For the cost of the UVGI system, we assumed the base-case cost of the UVGI system to only include the cost of the respirators required as the literature suggests that UV systems are more readily available on site in many hospitals in comparison to $H_2O_2$ vapor decontamination systems. [39] This may be because UV systems require significantly less space and personnel than $H_2O_2$ vapor decontamination systems.[40] However, we also performed a sensitivity analysis to account for the varying costs and sophistication of UVGI systems, ranging from the installation of a brand new, high volume system [11] to a less expensive, lower volume system that utilizes repurposed materials.[9 ,54] In addition, we explored a range of UVGI system costs which do not include installation, maintenance, distribution, energy, or personnel costs.[9 ,11 ,48 ,54 ,55] We also estimated the average cost generated per patient for each strategy by dividing the total cost by the total number of hospitalized COVID-19 patients during the first 6 months of the pandemic.

*Waste estimate*

Waste estimates for each usage method measured the mass of the total respirators, surgical masks, and filters used and disposed of through the 6-month duration. The mass of 3M's 1860 respirator, a standard surgical mask, and a



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reusable respirator are 11.3 grams, 8.5 grams and 46.5 grams, respectively [10 ,29 ,34]. Single filters for reusable respirators were estimated using ⅕ of a respirator (2.26 grams per a single filter, 4.53 grams per pair of filters).[10 ,29] Thus, to form our waste estimates, we multiplied respirator, surgical mask and reusable respirator usage by their respective masses. We estimated the average waste generated per patient for each strategy by dividing the total amount of waste by the total number of hospitalized COVID-19 patients during the first 6 months of the pandemic. We also performed an additional sensitivity analyses using an alternate disposable respirator.

*Ethics Approval Statement*
This study did not require ethics approval as it did not involve human participants.

*Patient and Public Involvement*
Patients or the public were not involved in the design, or conduct, or reporting, or dissemination plans of our research. It was not appropriate or possible to involve patients or the public in the design, or conduct, or reporting, or dissemination plans of our research.

**Results**

*Mask usage*
The estimated numbers of respirators required in the United States for each strategy are shown in Table 4 and Figure 1A. The use of a new respirator per patient encounter in the U.S. would require 7.41 billion respirators. An extended-use strategy of one respirator per day per HCW would reduce need by over 50% to 3.29 billion respirators. Decontamination by UVGI would further reduce the need to 1.64 billion respirators. Employing a $H_2O_2$ vapor decontamination strategy would further reduce need by 84% to only 1.15 billion respirators. A reusable respirator strategy (with either disposable or decontaminated filters), where one respirator is assigned to each HCW for the duration of the pandemic, would further reduce need to approximately 18 million respirators, for a total reduction in respirator need by over 99%. Using a new surgical mask daily would require 3.29 billion surgical masks.

*Cost estimate*
The estimated costs for each respirator use strategy are summarized in Table 4 and Figure 1B. The use of a new respirator per patient per HCW would cost an average of $6.38 billion ($16.09 thousand (k) per patient). Extended use of one respirator per day would reduce the cost to $2.83 billion ($7.13k per patient), saving approximately $3.55 billion. The $H_2O_2$ vapor decontamination strategy would reduce cost to $1.65 billion ($4.17k per patient), saving approximately 1.18 billion, though sensitivity analyses estimated the cost of the $H_2O_2$ decontamination system could vary between $1.51-$4.98 billion (Supplementary Table 1). The decontamination by UVGI strategy would reduce the cost to $1.41 billion ($3.56k per patient), saving an additional $24 million. A reusable respirator with disposable filters would cost $1.24 billion ($3.13k per patient), though this is almost entirely filter costs ($1.13 billion). A reusable respirator with a decontaminated filter and surgical mask strategies would be the least costly strategies at $831 million dollars and $460 million dollars ($2.10k and $1.16k per patient, respectively), which is a total cost savings of over $5.54 billion (Figure 1B). This is more than the amount of money provided by the CARES Act to support the CDC's pandemic response efforts and programs.[56]

*Waste estimate*
The estimated waste generated by each respirator use strategy is summarized in Table 4 and Figure 1C-D. The use of a new respirator per patient encounter per HCW would generate 84.0 million kg of waste (211.93 kg of waste per patient). Extended use of one respirator per day would reduce waste to 37.22 million kg (93.90 kg per patient). The decontamination by UVGI strategy would reduce waste to 18.61 million kg (46.95 kg per patient). A $H_2O_2$ vapor decontamination (with a 30% discard rate) strategy would reduce waste to 13.03 million kg (32.87 kg per patient). A reusable respirator with disposable filters would generate 15.73 million kg of waste (14.88 million kg from filters, 39.68 kg total per patient). Pairing the reusable respirator with a decontaminated filter would significantly reduce generated waste to 1.58 million kg (3.99 kg per patient), for an overall reduction in waste generation by approximately 82.42 million kg, equivalent to going from a mass of 252 Boeing 747 airplanes to five (Figure 1D). The surgical mask strategy would generate 27.92 million kg of waste (70.45 kg per patient).

*Sensitivity analyses*



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A sensitivity analysis of a larger commonly used disposable respirator (Gerson 1730) did not significantly change the estimated cost of the strategies or relative amounts of waste generation (Supplementary Table 2). An additional sensitivity analysis was conducted looking at a different 3M disposable respirator cost found from the commercial manufacturer 3M to account for variability in market costs ($1.27/respirator). The cost variation did not change the relative rankings of the reuse strategies (Supplementary Table 3).[36 ,57] Cost and waste estimates for commercially available reusable half-facepiece elastomeric respirators (3M 7500 series) with P100 filters (assuming that each HCW uses one pair of filters per week) were also explored (Supplementary Table 4)[58-61]. Low and high cost estimates of $2.02 and $2.26 billion were calculated using sources from the commercial manufacturer 3M,[58] with reusable respirator costs ranging from $25 to $45 per respirator with a single disposable P100 filter cost of $7.00.[59] These cost estimates of $2.02-$2.26 billion were lower than the one respirator per day reuse strategy, but higher than the $H_2O_2$ decontamination, UVGI decontamination, reusable respirator, reusable respirator with decontaminated filters, and surgical mask strategies (Table 4, Supplementary Table 4). Low and high waste estimates of 3.22 million kg and 3.59 million kg were calculated using a respirator weight of 135 grams and filter weight of 4.54 grams (Supplementary Table 4). These waste estimates were lower than the one per day reuse strategy, $H_2O_2$ decontamination, UVGI, reusable respirator, and surgical mask strategies, but higher than the reusable respirator with decontaminated filters strategy (Table 4, Supplementary Table 4).

A sensitivity analysis of the $H_2O_2$ decontamination system costs estimated a range of $1.51-$4.98 billion, with variation in cost driven by differing estimates in the number of decontamination centers required to service all of the hospitals in the United States and in the cost of the decontamination per mask (Supplementary Table 1).

Sensitivity analyses of respirator discard rates and maximum cycles of $H_2O_2$ decontamination found that a 10% discard rate lowered respirator usage, cost, and waste generation by 657 million respirators, $560 million, and 7.45 million kg, respectively. A 50% discard rate would increase respirator usage, cost and waste generation by 660 million respirators, $570 million, and 7.44 million kg, respectively. Lowering maximum decontamination to 10 cycles increased respirator usage, cost and waste generation by 160 million respirators, $150 million, and 1.86 million kg, respectively (Supplementary Tables 5-6).

A sensitivity analysis of the UVGI decontamination system costs estimated a range of $1.41-1.42 billion, even accounting for variations in sophistication of technology installed (Supplementary Table 7). Sensitivity analyses of respirator discard rates and maximum cycles of UVGI decontamination found that a 10% discard rate reduced respirator usage, cost, and waste generation by 654 million respirators, $560 million, and 7.44 million kg, respectively. A 50% discard rate increased respirator usage, cost and waste generation by 660 million respirators, $570 million, and 7.44 million kg, respectively. Lowering maximum decontamination to 2 cycles increased respirator usage, cost, and waste generation by 990 million respirators, $850 million, and 11.17 million kg, respectively (Supplementary Tables 8-9).

**Table 4 Numbers of respirators, cost accumulated, and waste generated per strategy over a duration of 6-months per base, low, and high number of estimated HCWs**

| Respirator strategy | Number of respirators required | Cost accumulated (USD) | Cost accumulated (USD) per patient | Waste generated (kg) | Waste generated (kg) per patient |
|---|---|---|---|---|---|
| 1 per patient encounter | 7.41 (7.22-7.59) billion | $6.38 (6.21-6.52) billion | $16.09 (15.67-16.46) thousand | 84.0 (81.79-85.96) million | 211.94 (206.38-216.88) |
| 1 per day | 3.29 (3.10-3.47) billion | $2.83 (2.67-2.98) billion | $7.13 (6.73-7.52) thousand | 37.22 (35.15-39.29) million | 93.90 (88.69-99.12) |
| UVGI-decontaminated 3M 1860 N95 respirators | 1.64 (1.55-1.73) billion | $1.41 (1.33-1.49) billion | $3.56 (3.37-3.76) thousand | 18.61 (17.58-19.64) million | 46.95(44.34-49.56) |
| $H_2O_2$ decontaminated 3M 1860 N95 respirators | 1.15 (1.09-1.21) billion | $1.65 (1.60-1.71) billion | $4.17 (4.03-4.31) thousand | 13.03 (12.30-13.75) million | 32.87 (31.04-34.69) |
| Reusable TEAL respirator + disposable filters | 0.018 (0.017-0.019) billion | $1.24 (1.17-1.31) billion | $3.13 (2.96-3.30) thousand | 15.73 (14.85-16.60) million | 39.68 (37.47-41.88) |



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|---|---|---|---|---|---|
| Reusable TEAL respirator + decontaminated filters | 0.018 (0.017-0.019) billion | $0.831 (0.822 -0.841) billion | $2.10 (2.07 -2.12) thousand | 1.58 (1.49-1.67) million | 3.99 (3.77-4.21) |
| Surgical mask, 1 per day | 3.29 (3.10-3.47) billion (surgical masks) | $0.460 (0.434-0.485) billion | $1.16 (1.10-1.23) thousand | 27.92 (26.37-29.47) million | 70.45 (66.53 -74.36) |

**Discussion**

*Principal findings*

The COVID-19 pandemic has dramatically increased the demand for respirators across the world, leading to supply shortages, spending in the billions of dollars, and generation of large amounts of medical waste. Even after widespread vaccination efforts, masks will likely continue to be required due to factors such as variable vaccine uptake, incomplete vaccinations, lack of knowledge as to who has received a vaccine, the possibility of reinfection, and unclear duration of vaccination efficacy.[62 ,63] Additionally, even after the pandemic, respirator and mask usage both in healthcare settings and among the general public may persist.[64] The continued use of disposable respirators and masks is unlikely to be sustainable and will have significant environmental consequences.[21] With this in mind, it is critical to understand the best strategy to maximize respirator and mask availability while minimizing costs and waste generation.

Of the strategies compared, we find that all reuse strategies (UVGI decontamination, $H_2O_2$ vapor decontamination, reusable respirators with disposable filters, or reusable respirators with decontaminated filters), could significantly decrease the number of respirators required compared to single- or extended-use mask strategies by at least 1.65 billion respirators in the United States alone. This would greatly increase availability and access of respirators worldwide. In addition, reuse strategies could save at least $1.18 billion dollars in costs nationally over the course of the pandemic. Finally, reuse strategies significantly reduce waste generation in the United States by at least 18.61 million kg. These estimates from our study only capture the economic and environmental impact over the first six months of the COVID-19 pandemic in the US and suggest that the long-term and global impact of reuse strategies are even higher, especially when considering respirators and masks used by the general population.

Our analyses found that UVGI decontamination, $H_2O_2$ vapor decontamination, and reusable respirators with disposable filters were similar in cost and waste generation. Combining the strategies by utilizing a reusable respirator with either $H_2O_2$ vapor-decontaminated filters was the least costly of all strategies compared and generated the least amount of waste. This finding suggests that even with UVGI and $H_2O_2$ vapor decontamination strategies, the adoption of a reusable respirator can have a significant impact in both cost and waste generation, though additional studies are needed to estimate the impact of additional costs, such as shipping to shared decontamination sites, installation costs, and time associated with decontamination or cleaning methods. Additional investigation is needed to capture other potential costs and benefits related to each mask-reuse strategy.

In settings where UVGI or $H_2O_2$ vapor decontamination are not feasible, such as in resource-constrained settings where installation and maintenance of such systems are challenging, reusable respirators with disposable filters may be preferable to disposable respirators. These respirators may also be decontaminated with standard hospital equipment such as alcohol and bleach wipes, which may be more readily available in settings with limited resources.[10 ,12] Anticipatory investment in a reusable respirator may not only provide access to high-quality PPE for COVID-19 in such settings but reduce overall waste and injury to our environment. Development of technologies to facilitate decontamination of respirators and/or filters that do not require special equipment, training, or infrastructure could even further reduce costs and waste as in the reusable respirator with decontaminated filters strategy.

*Limitations*

One potential limitation of our study is the assumption that all respirator strategies discussed are equally effective at protecting the user. The decision to employ decontamination methods for reuse should be weighed against the possibility for greater health risks incurred by incomplete decontamination or lowered respirator efficacy, which may incur additional costs. The CDC recommended extended respirator use and reuse strategies for N95 respirators if respirators maintained their fit and function after decontamination.[65] Several studies have evaluated the effect of extended use and re-use strategies that require multiple donning on the fit and efficacy of N95 respirators independent of decontamination. One study found that 48% of subjects failed a fit test after only one redonning of



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an N95 respirator. Additionally, another study found that among test subjects experienced in respirator donning, consecutively donning the same respirator 5 times was the threshold before mask-fit dropped below 100%.[66] Furthermore, both UVGI and $H_2O_2$ decontamination methods have shown to reduce filtration and mask performance after 3 rounds of decontamination in some studies.[67] Therefore, it is important to note that the efficacy of each reuse strategy may not be not equal and should be considered prior to implementation. Potential costs related to unequal respirator efficiency and protection were not estimated in our analysis.

An additional limitation of our study is that we modelled one strategy for all HCWs, regardless of frequency and type of patient contact. For HCWs at low risk of contact with bodily fluids (including respiratory droplets), it may be possible to deploy alternate strategies such as extended use of disposable respirators or less frequent decontamination. This could potentially further reduce cost and waste and increase respirator availability without sacrificing protection.

We estimated only a few respirator strategies and decontamination methods, and other methods for extended respirator use and reuse across the world were not captured in our analysis. Furthermore, our estimates were performed from a US perspective, and these numbers will be different for other countries depending on parameters such as number of healthcare workers, rates of infection, and number of hospitalized patients, though we suspect that the relative benefit of reuse strategies compared to single- or extended-use respirator strategies will persist. Additionally, the number of COVID-19 hospitalizations were likely underestimated in this study, as only two-thirds of states and territories in the United States have reported this data during the COVID-19 pandemic; however, we suspect that this therefore underestimates the potential impact of mask reuse strategies.[46] Furthermore, our cost estimates did not include installation, maintenance, distribution, or personnel costs associated with various strategies, and additional studies should be performed. In addition, our analysis measured only the waste generated by masks themselves and did not study the environmental impact of manufacturing, packaging or waste generation from decontamination processes, which some studies estimate could generate up to 90% of greenhouse gas emissions.[19 ,68] Furthermore, the environmental impact of single-use plastics generated from packaging related to mask use, estimated to have increased by up to 40% during the pandemic, may contribute a significant amount of additional environmental waste.[69] These aspects were not included in our analyses and require further quantification. Finally, our estimates for the reusable respirator strategy was based on a recently published prototype.[10] Updated analyses should be performed as these and other low-cost reusable respirators and masks become more available.[12 ,70]

*Implications and future research*

While our analysis measured the economic and environmental impact of several mask reuse strategies, there are several areas of investigation that may contribute to further reductions in cost and environmental impact. For example, our analysis highlighted the importance of considering not only reusable respirators, but reusable or decontaminatable filters, as these drove the cost and waste of reusable respirator/disposable filter strategies. Inexpensive, low-tech methods for filter decontamination are needed. Alternatively, redesign of reusable respirators to require smaller filters or development of fully reusable respirators would greatly reduce cost, waste and potentially the need for single-use plastics. Additionally, the development of novel materials for masks to increase durability of these systems after repeated exposures to $H_2O_2$ vapor or other decontamination techniques may increase the lifespan of masks and decrease the volume of masks used. Incorporation of bactericidal or antiviral agents, nanoparticles, or nanotechnology into masks may also increase their reusability and potentially decrease the need for cleaning agents in regions where there may be concomitant shortages of these solutions. Antimicrobial agents derived from natural products (tea tree oil, grapefruit seed extract, etc.) as well as nanoparticles (NPs) from different metals and metal compounds (copper, silver, zinc oxide, etc.) have also been shown to improve filtration and reduce viral load on mask surfaces.[14 ,15] There are a variety of masks now commercially available that use nanotechnology and range from disposable surgical masks, washable masks, and reusable respirators such as Innonix RespoKare (citric acid NPs), Cupron Inc. (copper NPs), and Argaman BioBlockX ™ (silver NPs).[14 ,15 ,18] These strategies may also decrease waste of common hospital-based wipes used to decontaminate masks, which was not included in this analysis. Finally, the development of biodegradable or recyclable materials that provide efficient particle protection may minimize the environmental effects of discarded masks.

Our analysis raises key questions for stakeholders regarding the optimal strategy to both provide sufficient protection for healthcare workers and patients while also assuring equitable access to PPE and reducing environmental harm. Given our findings that reusable respirator strategies greatly reduce the number of respirators



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required and medical waste generated, it is interesting that reusable respirators or decontamination strategies have largely not been adopted in the US prior to the COVID-19 pandemic. We hypothesize that this could be due to a number of reasons including cost and availability of reusable respirators, lack of recognition of the scale of medical waste and its impact on the environment, and individual healthcare systems' lack of accountability with regard to medical waste. We have reason to believe that the first two reasons will be addressed over the course of the pandemic. Given renewed interest in new technologies for PPE, we expect options and availability for reusable respirators to continue to expand.[15] We believe our study as well as others will increase public awareness of the environmental impact of disposable PPE, particularly masks.[38 ,69] In order to improve hospital system accountability over medical waste, however, we may need to turn to policymakers to consider nationwide incentives such as subsidies to transition to reusable PPE, taxes to offset medical waste generation, and other incentives as has been used to promote transition to green technologies in other fields.[71-73]

*Conclusions*

In summary, respirator reuse technologies are critical to meet the supply demands imparted by COVID-19, especially in low-resource settings. This need is emphasized by the likelihood that respirators will continue to be commonly used even after widespread vaccination and post-pandemic in certain scenarios, such as healthcare and crowded transportation areas, and such technologies can enable more sustainable use of respirators moving forward. Furthermore, these technologies can save billions of dollars that can be redistributed toward other efforts for economic and environmental recovery brought on by the pandemic. Further study is needed regarding reuse fit and filtration efficacy to minimize health risks associated with reuse strategies. Additionally, future development of low-cost, low-tech technologies to enable respirator and/or filter decontamination is needed to further minimize the economic and environmental costs of respirators.

**Footnotes**

**Contributors:** JNC, OG, JC, CH, and GT conceived and designed the analysis. JB, AW, PRC, and FD contributed data. JNC, OG, and JC collected data and performed the analysis. JNC, OG, JC, and GT wrote the manuscript. JNC, OG, JC, JB, AW, PRC, FD, CH, and GT interpreted the data and reviewed and approved the manuscript. The corresponding author, GT, provided supervision over the study and is the guarantor. GT confirms that all authors meet the authorship criteria and no contributing authors have been omitted.

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**Competing interests:** The authors declare the following competing financial interest(s): AJW, JDB, and GT have filed multiple patents surrounding the respirator and sensors. In addition, AJW, JDB and GT have a financial interest in TEAL Bio, a biotechnology company focused on developing the next generation of personal protective equipment. JNC, PRC, OG, JC, FD, and CH declare no competing interests.

**Data Sharing:** All data is included in the manuscript and/or supplementary materials, no additional data is available.

GT provides attestation that this study reflects honest and accurate data and transparent disclosure of all relevant information. Nothing has been omitted or withheld from this study.

**Fig. 1** Comparison of the following per respirator reuse strategy: A) number of respirators or surgical masks used, B) costs in billions of USD, C) waste generated in millions of kg, D) waste generated per strategy in the equivalent number of 747 airplanes by mass (mass of one 747 airplane, 333,000 kg).



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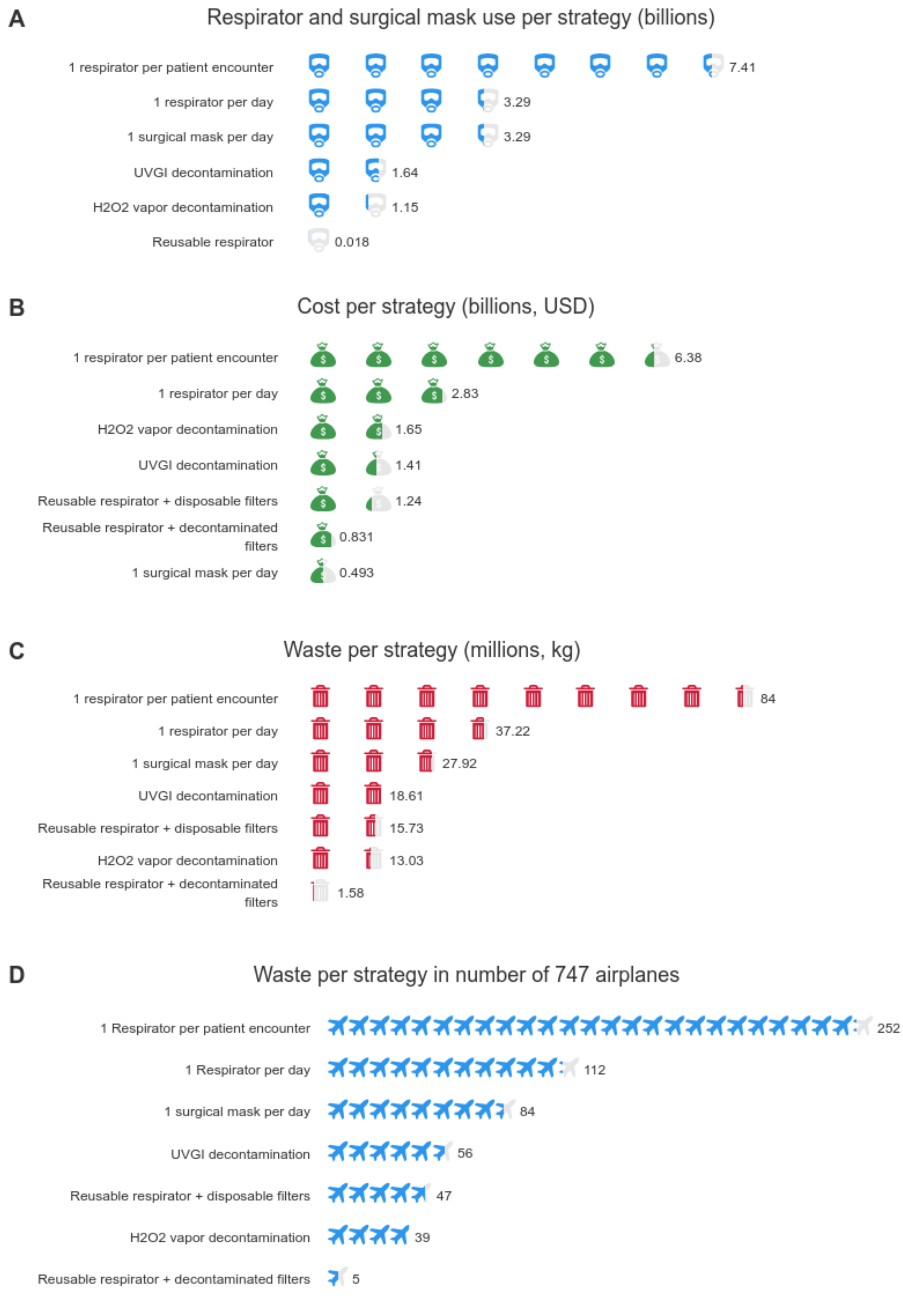


**Fig. 1** Comparison of the following per respirator reuse strategy: A) number of respirators or surgical masks used, B) costs in billions of USD, C) waste generated in millions of kg, D) waste generated per strategy in the equivalent number of 747 airplanes by mass (mass of one 747 airplane, 333,000 kg).

**Supplementary Table 1 Sensitivity analysis: $H_2O_2$ decontamination strategy cost**

| Base system cost | Shipping cost | Respirator cost | Overall cost accumulated (USD) |
|---|---|---|---|
| $268 million | $250 million | $989 million | $1.51 billion |
| $415 million | $250 million | $989 million | $1.65 billion |
| $3.74 billion | $250 million | $989 million | $4.98 billion |

**Supplementary Table 2 Sensitivity analysis: Disposable Gerson 1730 respirator***

| Respirator strategy | Number of respirators required | Cost accumulated (USD) | Waste generated (kg) |
|---|---|---|---|
| 1 per patient (all hospitalized patients) | 7.41 (7.22-7.59) billion | $6.52 (6.35-6.68) billion | 126.0 (122.7-129.0) million |
| 1 per day | 3.29 (3.10-3.47) billion | $2.89 (2.73-3.05) billion | 55.85 (52.74-58.95) million |
| UVGI-decontaminated N95 respirators | 1.64 (1.55-1.73) billion | $1.45 (1.37-1.53) billion | 27.92 (26.37-29.47) million |
| $H_2O_2$-decontaminated N95 respirators | 1.15 (1.09-1.21) billion | $1.68 (1.62-1.73) billion | 19.55 (18.46-20.63) million |
| Reusable respirator + disposable filters | 0.018 (0.017-0.019) billion | $1.27 (1.20-1.34) billion | 23.18 (21.93-24.42) million |
| Reusable respirator + decontaminated filters | 0.018 (0.017-0.019) billion | $0.833 (0.824-0.842) billion | 1.955 (1.893-2.017) million |

**The weight of one Gerson 1730 N95 Respirator is equal to 17g*

**Supplementary Table 3 Sensitivity Analysis: Variable Market Costs for Disposable Respirators**

| Cost of one 3M 1860 N95 respirator | $0.86 (base case) | | $1.27 | |
|---|---|---|---|---|
| Respirator strategy | Cost accumulated (USD) | Cost accumulated (USD) per patient | Cost accumulated (USD) | Cost accumulated (USD) per patient |
| 1 per patient encounter | $6.38 (6.21-6.52) billion | $16.09 (15.67-16.46) thousand | $9.42 (9.17-9.64) billion | $23.76 (23.13-24.31) thousand |
| 1 per day | $2.83 (2.67-2.98) billion | $7.13 (6.73-7.52) thousand | $4.17 (3.94-4.40) billion | $10.53 (9.94-11.11) thousand |
| UVGI-decontaminated 3M 1860 N95 respirators | $1.41 (1.33-1.49) billion | $3.56 (3.37-3.76) thousand | $2.09 (1.97-2.20) billion | $5.26 (4.97-5.56) thousand |
| $H_2O_2$-decontaminated 3M 1860 N95 respirators | $1.65 (1.60-1.71) billion | $4.17 (4.03-4.31) thousand | $2.13 (2.04-2.21) billion | $5.36 (5.16-5.57) thousand |
| Reusable TEAL respirator + disposable filters | $1.24 (1.17-1.31) billion | $3.13 (2.96-3.30) thousand | $1.78 (1.68-1.88) billion | $4.49 (4.24-4.74) thousand |
| Reusable TEAL respirator + decontaminated filters | $0.831 (0.822 -0.841) billion | $2.10 (2.07 -2.12) thousand | $0.858 (0.848 -0.869) billion | $2.17 (2.14 -2.19) thousand |
| Surgical mask, 1 per day | $0.460 (0.434-0.485) billion | $1.16 (1.10-1.23) thousand | $0.460 (0.434-0.485) billion | $1.16 (1.10-1.23) thousand |

**Supplementary Table 4 Sensitivity analysis: Reusable elastomeric respirator + disposable p100 filter**

| Parameter | Value |
|---|---|
| Number of respirators required | 18 (17-19) million |
| Number of filters required (by pair) | 108 (102-114) million |
| | |
| **Results** | |
| Reusable respirator + filter cost (USD) | $2.14 (2.02-2.26) billion |
| Reusable respirator + filter waste (kg) | 3.41 (3.22-3.59) million |

**Supplementary Table 5 Sensitivity analysis: $H_2O_2$ decontamination system respirator discard rate**

| Discard rate | Number of respirators required | Cost accumulated (USD) | Waste generated (kg) |
|---|---|---|---|
| 10% | 493 (465-520) million | $1.09 (1.07-1.11) billion | 5.58 (5.27-5.89) million |

| | | | |
|---|---|---|---|
| 30% | 1.15 (1.09-1.21) billion | $1.65 (1.60-1.71) billion | 13.03 (12.30-13.75) million |
| 50% | 1.81 (1.71-1.91) billion | $2.22 (2.13 -2.31) billion | 20.47 (19.33-21.61) million |

**Supplementary Table 6 Sensitivity analysis: Maximum cycles of decontamination per respirator for $H_2O_2$ decontamination system**

| Number cycles | Number of respirators required | Cost accumulated (USD) | Waste generated (kg) |
|---|---|---|---|
| 10 | 1.31 (1.24-1.39) billion | $1.80 (1.73-1.86) billion | 14.89 (14.06-15.71) million |
| 20 | 1.15 (1.09-1.21) billion | $1.65 (1.60-1.71) billion | 13.03 (12.30-13.75) million |

**Supplementary Table 7 Sensitivity analysis: UVGI decontamination strategy cost***

| Parameter | Value |
|---|---|
| Cost of 2 surgical suite UVGI system | $40,000.00 |
| Cost of repurposed or low tech UVGI lamp system | $50.00 |
| | |
| **Results** | |
| Base cost | $1.41 (1.33-1.49) billion |
| Base cost + cost of 2 surgical suite UVGI systems | $1.42 (1.34-1.49) billion |
| Base cost + cost of repurposed or low tech UVGI lamp system | $1.41 (1.33-1.49) billion |
| *Assuming distribution across hypothetical 60 sites across U.S. | |

**Supplementary Table 8 Sensitivity analysis: UVGI decontamination system discard rate**

| Discard rate | Number of respirators required | Cost accumulated (USD) | Waste generated (kg) |
|---|---|---|---|
| 10% | 986 (931-1040) million | $848 (800-895) million | 11.17 (10.55-11.79) million |
| 30% | 1.64 (1.55-1.73) billion | $1.41 (1.33-1.49) billion | 18.61 (17.58-19.64) million |
| 50% | 2.30 (2.17-2.43) billion | $1.98 (1.87-2.09) billion | 26.05 (24.61-27.50) million |

**Supplementary Table 9 Sensitivity analysis: Maximum cycles of decontamination per respirator for UVGI decontamination system**

| Number cycles | Number of respirators required | Cost accumulated (USD) | Waste generated (kg) |
|---|---|---|---|
| 2 | 2.63 (2.48-2.77) billion | $2.26 (2.13-2.39) billion | 29.78 (28.12-31.43) million |
| 5 | 1.64 (1.55-1.73) billion | $1.41 (1.33-1.49) billion | 18.61 (17.58-19.64) million |

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