


BMJ Open Thinking green: modelling respirator reuse strategies to reduce cost and waste

Jacqueline Chu,^{1,2} Omkar Ghenand,³ Joy Collins,⁴ James Byrne,^{2,4,5} Adam Wentworth,^{2,4,6} Peter R. Chai,^{2,7} Farah Dadabhoy,^{6,7} Chin Hur,^{8,9} Giovanni Traverso ^{4,6}

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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 USA.

Participants All healthcare workers within the USA.

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 USA. 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 USA over 6 months. One respirator per day per healthcare worker would require 3.29 billion respirators, cost \$2.83 billion and generate 37.22 million kg of waste. Decontamination by ultraviolet germicidal irradiation would require 1.64 billion respirators, cost \$1.41 billion and accumulate 18.61 million kg of waste. H₂O₂ vapour decontamination would require 1.15 billion respirators, cost \$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 H₂O₂ vapour-decontaminated 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 with single-use or daily extended-use of disposable respirators. Future development of low-cost, simple technologies to enable respirator and/or filter decontamination is needed to further minimise the economic and environmental costs of masks.

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 maximise

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.

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 vapour (H₂O₂) 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 US government awarded a \$415 million contract to Battelle in April 2020 to deploy 60 hydrogen peroxide vapour 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



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For numbered affiliations see end of article.

Correspondence to
Dr Giovanni Traverso;
cgt20@mit.edu

thus far been shown to compromise mask integrity.^{3 5} Nebraska Medicine piloted a UVGI system that has been approved by the US 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 sterilisation, 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 MI mask¹⁶ and ClearMask, have recently been developed.¹⁷ Potential benefits of reusable respirators compared with disposable respirators could include reduced cost and waste. The use of innovative filtration techniques and antimicrobial nanoparticles (NPs) 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 7200 tons a day in medical waste, a sizeable 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 maximises supply, minimises cost and minimises waste is unknown. This analysis estimates respirator use, cost and waste generation in the USA over the course of the first 6 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 for 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 were sourced and adapted from the scientific literature or USA 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}

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 H₂O₂ vapour decontamination, one reusable respirator with disposable filters per HCW, one reusable respirator with H₂O₂ vapour-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.^{30–32} For the H₂O₂ and UVGI decontamination strategies, we accounted for a 30% respirator discard rate due to soiled or damaged respirators as has previously been reported.³³ 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.^{34–36}

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 hospitalised patients (COVID-19 and non-COVID-19), average length of stay (LOS) and average number of visits from HCWs per day ([table 2](#)).³⁴ Data for the number of respirators required per patient per day, LOS per patient and the number of ICU and hospital admissions were extracted from the recent COVID-19 literature, government reports and a previous influenza study estimating respirator usage to prevent aerosol transmission.^{34 37–40} To estimate the number of overall hospitalised 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 2020.⁴¹ In addition, HCWs with patient contact were estimated to be using four respirators per day in between direct patient care.^{34 42} HCWs without patient contact were assumed to be using one respirator per day given universal masking ([table 3](#)).

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

Parameter	Value	Reference
US population as of 2019	328.2 million	73
Total number of healthcare and frontline workers in the USA as of 2020	18 (17–19) million	34–36
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	54
Total cost of assembled reusable transparent elastomeric adaptable long-lasting (TEAL) respirator, minus filters	US\$6.11 (\$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	US\$0.34 (\$0.25 GBP; \$0.29 Euro)	10
Cost of one 3-ply surgical mask (Fluidshield Level 1)	US\$0.14 (\$0.10 GBP; \$0.12 Euro)	47
Cost of one 3M 1860 N95 respirator	US\$0.86 (\$0.62 GBP; \$0.73 Euro)	46
Cost of the National Battelle System funded by the US Food and Drug Administration (FDA)	US\$415 million (\$300.23 million GBP; \$352.93 Euro)	6
Reduction in the number of respirators required for HCW population in the USA by the use of H ₂ O ₂ vapour decontamination	20-fold	6
Reduction in the number of respirators required for HCW population in the USA by the use of UVGI	5-fold	11

HCW, healthcare worker; UVGI, ultraviolet germicidal irradiation.

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 H₂O₂ vapour decontamination strategy, using currently available data on respirator integrity and efficiency after multiple cycles of H₂O₂ vapour 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.³³ Therefore, to form

our estimates for H₂O₂ vapour 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 decontamination nationally, we performed sensitivity analyses using 10% and 50% discard rates, as well as a maximum of 10 cycles of H₂O₂ decontamination per respirator.

To model usage estimates for reuse of respirators enabled by daily UVGI decontamination, we used

Table 2 Hospitalisation-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	49
Number of patients admitted to the general ward	12 583 927	37 49
Number of patients admitted to the Intensive Care Unit (ICU)	1 643 846	37 49
Number of hospitalisations due to COVID-19	396 355	41
Average length of stay for general ward patients	4.6 days	38
Average length of stay for patients admitted to the ICU	3.3 days	38
Median length of stay for non-ICU COVID-19 patients	10.1 days	40
Median length of stay for COVID-19 patients admitted to the ICU	10.5 days	40
Number of respirators required per day for interactions with general ward patients	8	34
Number of respirators required per day for interactions with ICU patients	14 (12–16)	34

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 with patient contact	Number of workers without patient contact	Reference
Number of nursing home workers	3 427 000	856 750	2 570 250	34
Number of emergency medicine service workers	297 000	267 300	29 700	34
Number of emergency department workers	132 000	132 000	0	34
Number of hospital workers	6 053 000	1 997 490	4 055 510	34
Number of outpatient workers	3 206 000	2 148 020	1 057 980	34
Number of other healthcare workers in other occupations	6 000 000	0	6 000 000	34 35

HCW, healthcare worker.

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 five cycles.⁴³ Therefore, to form our estimates for UVGI-enabled reuse of respirators, we divided the one respirator per HCW 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.^{33 44 45} 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 H₂O₂ vapour-decontaminated filter strategies, we assumed that every HCW in the USA 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 2/5 of the cost and waste generated from an N95 respirator.¹⁰ If filters were to be decontaminated using H₂O₂ vapour, 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 USD 2020), multiplied by the number of respirators required⁴⁶; one surgical mask, \$0.14, multiplied by the number of surgical masks required⁴⁷; reusable respirator, \$6.11, multiplied by the number of reusable respirators required¹⁰; a pair of filters for reusable respirators, \$0.34, multiplied by the number of pairs of filters required; and nationally distributed H₂O₂ vapour decontamination systems across 60 sites, \$415 million.⁶ Due to variation in implementation and maintenance costs for Battelle H₂O₂ vapour decontamination systems across sites, it was difficult to estimate exact costs.⁴⁸ We performed a sensitivity analysis to estimate lower and upper-bound costs based on data from the

Battelle decontamination centre in Somerville, Massachusetts, and added them to the total cost of the respirators themselves. This decontamination centre is capable of decontaminating 80 000 respirators per day and servicing up to roughly 157 hospitals. There are currently 6090 hospitals across the USA.⁴⁹ For the lower bound, we estimated that if each site were able to service 157 hospitals, this would require approximately 39 decontamination centres and only 65% of the 415 million dollars to fund 60 sites across the USA. 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.⁵⁰ We performed the sensitivity analysis varying different parameters for the lower and upper bounds in order to test the widest range for the cost of the H₂O₂ decontamination strategy. In addition, we estimated the shipping costs from a large academic hospital in Boston, Massachusetts (Massachusetts General Hospital) to the local Battelle decontamination centre in Somerville, Massachusetts. The shipping costs for 1 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 11.33 kg for shipping 1000 masks over a distance of roughly 5632.7 meters).⁵¹ We scaled this cost by the number of hospitals and Battelle sites across the USA over the course of the first 6 months of the pandemic and arrived at a total nationwide 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 H₂O₂ vapour decontamination systems.³² This may be because UV systems require significantly less space and personnel than H₂O₂ vapour decontamination systems.³³ 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 system¹¹ to a less expensive, lower volume system that uses repurposed materials.^{9 52} In

addition, we explored a range of UVGI system costs which do not include installation, maintenance, distribution, energy or personnel costs.^{9 11 43 52 53} We also estimated the average cost generated per patient for each strategy by dividing the total cost by the total number of hospitalised patients with COVID-19 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, 8.5 and 46.5 g, respectively.^{10 29 54} Single filters for reusable respirators were estimated using 1/5 of a respirator (2.26 g per a single filter, 4.53 g 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 hospitalised patients with COVID-19 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 USA for each strategy are shown in [figure 1A](#), [table 4](#). The use of a new respirator per patient encounter in the USA 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 H₂O₂ vapour 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 summarised in [figure 1B](#), [table 4](#). 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 H₂O₂ vapour decontamination strategy would reduce cost to \$1.65 billion (\$4.17k per patient), saving approximately \$1.18 billion, although sensitivity analyses estimated the cost of the H₂O₂ decontamination system could vary between \$1.51 and \$4.98 billion (online supplemental 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), although 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 programmes.⁵⁵

Waste estimate

The estimated waste generated by each respirator use strategy is summarised in [figure 1C,D](#), [table 4](#). The use of a new respirator per patient encounter per HCW would generate 84.0 million kg of waste (211.94 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 H₂O₂ vapour 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 (14.89 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 (online supplemental 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 (online supplemental table 3).^{46 56} Cost and waste estimates for commercially available reusable half-facepiece elastomeric respirators (3M 7500 series) with P100 filters (assuming that each HCW uses one

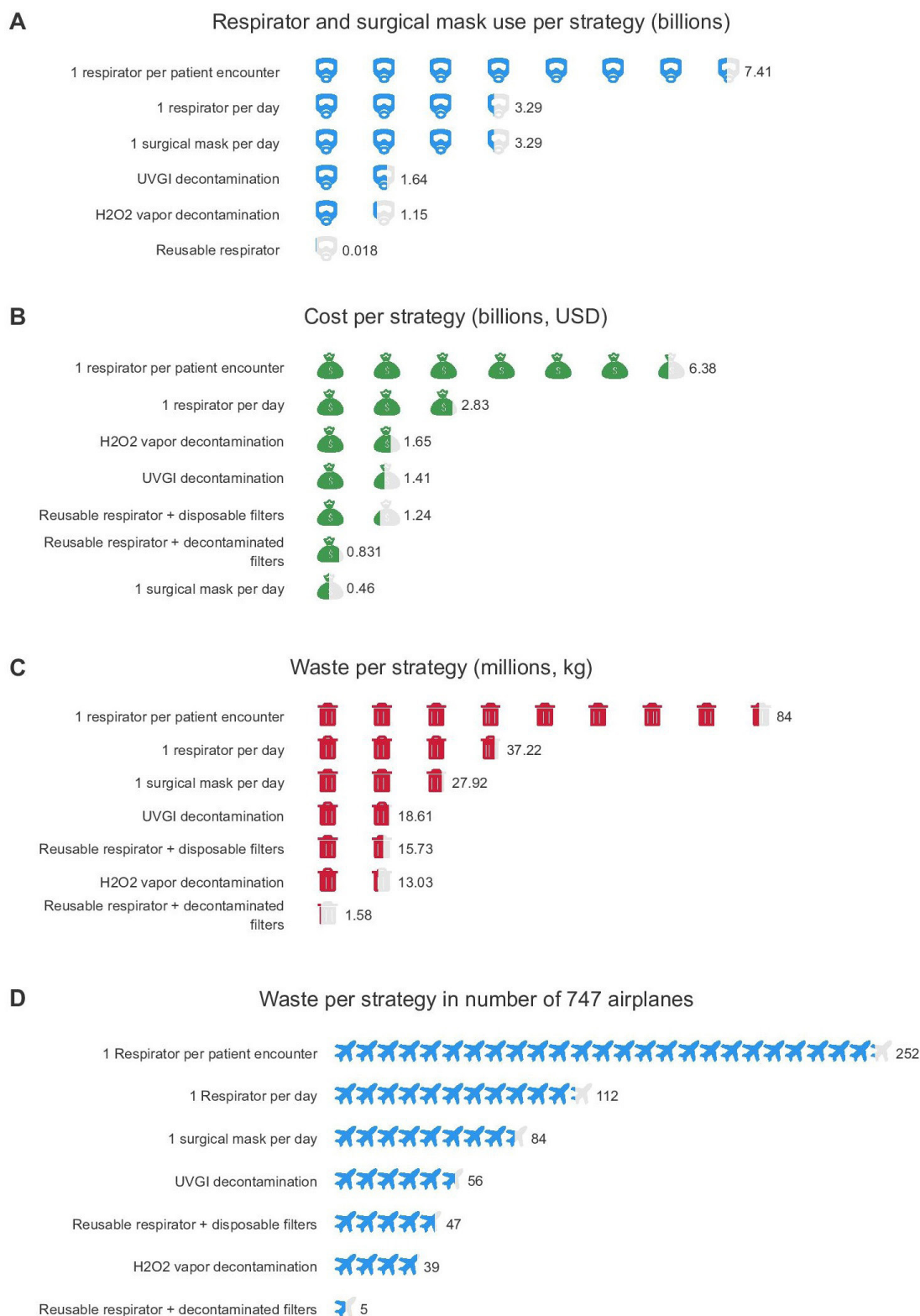


Figure 1 Comparison of the following per respirator reuse strategies: (A) number of respirators or surgical masks used, (B) costs in billions of USD, (C) waste generated in millions of kg, (D) waste generated per strategy in the equivalent number of 747 airplanes by mass (mass of one 747 aeroplane, 333 000 kg). Values are estimated for the first 6 months of the pandemic. UVGI, ultraviolet germicidal irradiation.

pair of filters per week) were also explored (online supplemental table 4).^{57–60} Low and high cost estimates of \$2.02 and \$2.26 billion were calculated using sources from the

commercial manufacturer 3M,⁵⁷ with reusable respirator costs ranging from \$25 to \$45 per respirator with a single disposable P100 filter cost of \$7.00.⁵⁸ These cost estimates of

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 (US\$)	Cost accumulated (US\$) 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 ₂ O 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)	\$0.460 (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)

HCW, healthcare worker; TEAL, transparent elastomeric adaptable long-lasting; UVGI, ultraviolet germicidal irradiation.

\$2.02–\$2.26 billion were lower than the one respirator per day reuse strategy, but higher than the H₂O₂ decontamination, UVGI decontamination, reusable respirator, reusable respirator with decontaminated filters and surgical mask strategies (table 4, online supplemental 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 g and filter weight of 4.54 g (online supplemental table 4). These waste estimates were lower than the one per day reuse strategy, H₂O₂ decontamination, UVGI, reusable respirator and surgical mask strategies, but higher than the reusable respirator with decontaminated filters strategy (table 4, online supplemental table 4).

A sensitivity analysis of the H₂O₂ 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 centres required to service all of the hospitals in the USA and in the cost of the decontamination per mask (online supplemental table 1).

Sensitivity analyses of respirator discard rates and maximum cycles of H₂O₂ 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 (online supplemental tables 5 and 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 (online supplemental 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, \$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 two cycles increased respirator usage, cost and waste generation by 990 million respirators, \$850 million and 11.17 million kg, respectively (online supplemental tables 8 and 9).

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.^{61 62} Additionally,

even after the pandemic, respirator and mask usage both in healthcare settings and among the general public may persist.⁶³ 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 maximise respirator and mask availability while minimising costs and waste generation.

Of the strategies compared, we find that all reuse strategies (UVGI decontamination, H₂O₂ vapour decontamination, reusable respirators with disposable filters or reusable respirators with decontaminated filters) could significantly decrease the number of respirators required compared with single-use or extended-use mask strategies by at least 1.65 billion respirators in the USA 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 USA by at least 18.61 million kg. These estimates from our study only capture the economic and environmental impact over the first 6 months of the COVID-19 pandemic in the USA 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, H₂O₂ vapour decontamination and reusable respirators with disposable filters were similar in cost and waste generation. Combining the strategies by using a reusable respirator with H₂O₂ vapour-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 H₂O₂ vapour decontamination strategies, the adoption of a reusable respirator can have a significant impact in both cost and waste generation, although 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 H₂O₂ vapour decontamination is 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 also 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.⁶⁴ Several studies have evaluated the effect of extended use and reuse 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 five times was the threshold before mask-fit dropped below 100%.⁶⁵ Furthermore, both UVGI and H₂O₂ decontamination methods have shown to reduce filtration and mask performance after three rounds of decontamination in some studies.⁶⁶ Therefore, it is important to note that the efficacy of each reuse strategy may not be 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 hospitalised patients, although we suspect that the relative benefit of reuse strategies compared with single-use or extended-use respirator strategies will persist. Additionally, the number of COVID-19 hospitalisations was likely underestimated in this study, as only two-thirds of states and territories in the USA have reported this data during the COVID-19 pandemic; however, we suspect that this therefore underestimates the potential impact of mask reuse strategies.⁴² 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 67} 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.⁶⁸ These aspects were not included in our analyses and require further quantification. Finally, our estimates for the reusable respirator strategy were 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 69}

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 also reusable or decontaminatable filters, as these drove the cost and waste of reusable respirator/disposable filter strategies. Inexpensive, simple 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 H₂O₂ vapour 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 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 Innox RespoKare (citric acid NPs), Cupron (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 minimise 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 ensuring 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 USA prior to the COVID-19 pandemic. We hypothesise 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 are hopeful 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.^{31 68} 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.⁷⁰⁻⁷²

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 emphasised 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 towards other efforts for economic and environmental recovery brought on by the pandemic. Further study is needed regarding reuse fit and filtration efficacy to minimise health risks associated with reuse strategies. Additionally, future development of low-cost, simple technologies to enable respirator and/or filter decontamination is needed to further minimise the economic and environmental costs of respirators.

Author affiliations

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

²Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

³Department of Biological Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

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

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

⁶Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

⁷Department of Emergency Medicine, Brigham and Women's Hospital, Boston, Massachusetts, USA

⁸Department of Medicine, Columbia University Medical Center, New York, New York, USA

⁹Department of Epidemiology, Columbia University Medical Center, New York, New York, USA

Contributors J Chu, OG, J Collins, CH and GT conceived and designed the analysis. JB, AW, PRC and FD contributed data. J Chu, OG and J Collins collected data and performed the analysis. J Chu, OG, J Collins and GT wrote the manuscript. J Chu, OG, J Collins, 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 AW, JB and GT have filed multiple patent applications surrounding a reusable respirator and sensors that can be integrated into a respirator. In addition, AW, JB and GT have a financial interest in TEAL Bio, Inc., a biotechnology company focused on developing the next generation of personal protective equipment.

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ORCID iD

Giovanni Traverso <http://orcid.org/0000-0002-9232-4517>

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