UV Sterilization of Personal Protective Equipment with Idle Laboratory Biosafety Cabinets During the COVID-19 Pandemic

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ABSTRACT

DISCLAIMER: This article does not represent the official recommendation of the Cleveland Clinic or Case Western Reserve University School of Medicine, nor has it yet been peer reviewed. We are releasing it early, pre-peer review, to allow for quick dissemination/vetting by the scientific/clinical community given the necessity for rapid conservation of personal protective equipment (PPE) during this dire global situation. We welcome feedback from the community.

Personal protective equipment (PPE), including face shields, surgical masks, and N95 respirators, is crucially important to the safety of both patients and medical personnel, particularly in the event of an infectious pandemic. As the incidence of Coronavirus Disease (COVID-19) increases exponentially in the United States and worldwide, healthcare provider demand for these necessities is currently outpacing supply. As such, strategies to extend the lifespan of the supply of medical equipment as safely as possible are critically important. In the midst of the current pandemic, there has been a concerted effort to identify viable ways to conserve PPE, including decontamination after use. Some hospitals have already begun using UV-C light to decontaminate N95 respirators and other PPE, but many lack the space or equipment to implement existing protocols. In this study, we outline a procedure by which PPE may be decontaminated using ultraviolet (UV) radiation in biosafety cabinets (BSCs), a common element of many academic, public health, and hospital laboratories, and discuss the dose ranges needed for effective decontamination of critical PPE. We further discuss obstacles to this approach including the possibility that the UV radiation levels vary within BSCs. Effective decontamination of N95 respirator masks or surgical masks requires UV-C doses of greater than 1 Jcm^{-2}, which would take a minimum of 4.3 hours per side when placing the N95 at the bottom of the BSCs tested in this study. Elevating the N95 mask by 48 cm (so that it lies 19 cm from the top of the BSC) would enable the delivery of germicidal doses of UV-C in 62 minutes per side. Effective decontamination of face shields likely requires a much lower UV-C dose, and may be achieved by placing the face shields at the bottom of the BSC for 20 minutes per side. Our results are intended to provide support to healthcare organizations looking for alternative methods to extend their reserves of PPE. We recognize that institutions will require robust quality control processes to guarantee the efficacy of any implemented decontamination protocol. We also recognize that in certain situations such institutional resources may not be available; while we subscribe to the general principle that some degree of decontamination is preferable to re-use without decontamination, we would strongly advise that in such cases at least some degree of on-site verification of UV dose delivery be performed.

Introduction

Personal protective equipment (PPE) is essential for protecting medical personnel and patients during outbreaks of airborne or droplet borne infectious diseases. In particular, the use of face shields, surgical masks and N95 respirators are recommended for infections that may be transmitted by respiratory droplets or airborne particles.[1] Due to the rapidly emergent nature of the novel Coronavirus Disease (COVID-19) and stringent requirements of proper PPE protocol, many hospitals are running dangerously low on these protective devices. As a result, both patients and their healthcare providers are at increased risk of contracting and spreading COVID-19.

As previously suggested, one method of preserving our current supply of PPE is through cycles of decontamination and reuse with ultraviolet germicidal irradiation (UVGI). Substantial work has been done evaluating the efficacy of UVGI for decontamination of N95 filtering faceplate respirators (FFRs).[2–6] Recently, UVGI has also been used to facilitate decontamination and re-use of plastic face shields.[7] Ultraviolet (UV) light is a form of electromagnetic radiation with more energy than visible light, but less energy than x-rays. It can be categorized into UV-A (315-400 nm), UV-B (280-315 nm), and UV-C (100-280 nm). The germicidal effectiveness of UV radiation is in the 180-320 nm range, with a peak at 265 nm.[8] The higher-energy UV-C rays can damage DNA and RNA via cross-linking of thymidine and uracil nucleotides, respectively, thus preventing the replication of microbes such as bacteria and viruses.[9] At these wavelengths, the amount of surface pathogen inactivation is directly proportional to the dose of UV radiation, with dosage being defined as the product of intensity (W/m^2) and exposure duration(s).[10,11] Therefore, UVGI is a relatively simple method of decontamination that causes minimal damage to the respirator and avoids the use of irritating chemicals.

One potential concern with using UVGI decontamination is the possibility that it may cause N95 masks to lose their efficacy due to degradation. Fortunately, multiple studies have addressed this question.[4,5,12,13] Their results are summarized in table 1.

There are two primary types of damage that can happen to an N95 mask: 1) structural damage that affects fit, and 2) damage to the filter. Structural damage can be readily detected by performing regular respirator fit tests. Thus, assuming fit tests are performed regularly, the possibility of damage to the filter is the greater concern because it cannot be detected as easily. The only study to observe either type of damage used a range of very high doses of UVGI.[4] At their lowest dose (120 Jcm^{-2}), the only significant damage was that, for one model of mask, one layer of the filter became significantly more susceptible to being punctured by a steel ball (decreased burst strength). At higher doses damage gradually became more significant.

Based on these studies, UV radiation appears to be safe for N95 masks at the levels necessary to achieve

Table 1. **Key findings from research on UV-mediated mask degradation.**

Study	Total dose of UV radiation used	Results	Masks tested
Lore et al., 2012	1.8 Jcm^{-2}	"No significant degradation in filter performance at 300-nm particle size."	3M 1860s and 3M 1870
Lindsley et al., 2015	Multiple ranging from 120 Jcm^{-2} - 950 Jcm^{-2}	Essentially no effect on flow resistance. Some mask types showed increased particle penetration at higher doses. Bursting strength of some filter layers decreased with higher doses. Strap breaking strength decreased substantially at high doses. At 120 Jcm^{-2} the only significant degradation was decreased bursting strength on one filter layer of one mask.	3M 1860, 3M 9210, Gerson 1730, and Kimberly-Clark 46747
Viscusi et al., 2009	3.24 Jcm^{-2} (half to each side of the mask)	No effect on filter penetration, airflow resistance, or physical appearance.	Three N95 FFR models, three surgical N95 respirator models, and three P100 models. The N95s were randomly selected from the US Strategic National Stockpile and the P100s were randomly selected from commercially available models.
Bergmann et al., 2010	4.68 Jcm^{-2}	"[No] observable physical changes"	Same as Viscusi et al., 2009
Heimbuch, 2019	Multiple ranging from 1 Jcm^{-2} to 20 Jcm^{-2} applied in cycles of 1 Jcm^{-2}	Fit test performance not significantly affected by UVGI but is affected by repeated doffing and donning. Minor effect on filtration efficiency for one mask after 10 Jcm^{-2} of UV radiation, but still within safe limits. Overall, no "meaningful" effect.	3M 1860, 3M 1870, 3M VFlex 1805, Alpha Protech 695, Gerson 1730, Kimberly-Clark PFR, Moldex 1512, Moldex 1712, Moldex EZ-22, Precept 65-3395, Prestige Ameritech RP88020, Sperian HC-NB095, Sperian HC-NB295, U.S. Safety AD2N95A, and U.S.Safety ADN95

decontamination. The decision-making challenge is to determine a safe upper limit on the number of decontamination cycles an individual mask experiences, as damage from UV radiation is cumulative. 4.68 Jcm^{-2} is the highest total amount of UV radiation for which absolutely no physical degradation was observed. In a desperate situation (e.g. where the alternative is not decontaminating or using no PPE), up to 20 Jcm^{-2} or perhaps even 120 Jcm^{-2} may be safe. Note that repeated donning and doffing of masks also leads to structural damage.[14] It is likely that masks would need to be replaced for this reason well before they experienced enough decontamination cycles to experience a cumulative UV dose of 20 Jcm^{-2}.

Although there is no current consensus on the amount of UV radiation required to inactivate SARS-CoV-2, the UV dose required to inactivate 90% of single-stranded RNA viruses on gel media is an estimated 1.32 - 3.20 $mJcm^{-2}$.[2] These estimates represent the likely dose needed to inactivate COVID-19 on face shields, while porous materials like N95 masks or surgical masks present a different challenge. Several studies have been conducted to identify the required dose to inactivate other single-stranded RNA viral contaminants on N95 masks. For example, for a 3 log reduction in recovered MS2 phage particles placed on soiled FFR masks, Vo et al. found a necessary UVGI dose of 4.32 Jcm^{-2}.[15] Comparably, for a variety of mask models, Mills et al. found that a 1 Jcm^{-2} UVGI dose conferred a range of 1.42 to 4.84 log reduction of H1N1 influenza viral load.[3] While more *in vitro* studies are likely needed to identify the dose required for safe decontamination, literature suggests that a dose of at least 1Jcm^{-2} is required to decontaminate soiled FFR masks prior to re-use. These data are summarized in a recently released CDC report.[16] UVGI and other decontamination methods are also summarized online at `https://www.n95decon.org`.

Many university-affiliated hospitals and higher academic laboratories have access to biosafety cabinets (BSCs) that are regularly used in research to decontaminate laboratory equipment via UV-C light. Due to current social distancing and quarantine measures, there likely exist a substantial number of BSCs that are not currently in use and therefore may be available to be temporarily repurposed for N95 respirator, or other PPE decontamination. While this paper focuses on BSCs, many other promising approaches to UVGI decontamination are being designed by other groups.[7,17]

Given the urgency of the ongoing COVID-19 pandemic, we sought to determine if BSCs could be temporarily repurposed for UVGI decontamination to preserve a dwindling supply of PPE. To do this, we measured the minimum light intensity output by a standard BSC, as well as the variability of light intensity between and within several BSCs. From these measurements, we calculate a recommended time of 4.3 hours per side (62 minutes per side if the masks can be elevated to 19 cm from the UV-C source) to irradiate FFRs in a BSC to inactivate potential SARS-CoV-2 virus, or 20 minutes per side to irradiate solid PPE, like face shields.

Methods

Two different BSCs were used in this experiment, the LabGard ES NU-540-400 Class II, Type A2 model (NuAire, Plymouth, MN), and the the Labgard ES ENergy Saver Class II, Type A2 model (NuAire, Plymouth, MN). Both

BSCs were equipped with a General Electric Germicidal Lamp model G30T8, which is reported to use 253.7 nm UV-C radiation and provide an average intensity of 100 $\mu W \mathrm{cm}^{-2}$ to the cabinet floor. We measured UV fluence using a UV meter (to obtain absolute measurements) and measured variance due to mask geometry using an array of three photodiodes (see supplemental materials). Experiments were performed on N95 3M 1860S respirators.

UV meter measurements

These measurements were conducted by placing a UV fluence meter (General Tools UV512C) at each of nine positions in each BSC (see Fig S1. Measurements were also taken in each of the 9 positions at elevations of 33 cm and 48.3 cm above the BSC floor. The UV meter was left in place until the reported value stabilized, at which point that value was recorded as the quantity of UV radiation reaching that position in the BSC. An array of measurements were also taken using photodiodes to assay heterogeneity within a given position. These data are presented in the supplemental materials).

Results

UV-C measurements in multiple BSCs

Our measurements of absolute UV-C radiation across BSC floors, as made with UV meters, show a clear pattern of spatial variation in UV intensity (see Fig. 1). Interestingly, many of the measured values substantially exceed the manufacturer's specified fluence (100 $\mu W \mathrm{cm}^{-2}$). In BSC 1, all of the measurements were greater than 100 $\mu W \mathrm{cm}^{-2}$. Because the UV meter cannot be attached to a mask, these measurements do not take into account variation produced by mask geometry.

Importantly, the minimum observed value differed substantially between BSCs: 111 $\mu W \mathrm{cm}^{-2}$ vs. 64 $\mu W \mathrm{cm}^{-2}$. This finding is consistent with the fact that the amount of UV-C light emitted is known to decay as bulbs age, and highlights the importance of either using new bulbs or measuring UV-C output to verify that it is sufficient. Note that annual BSC certification (NSF Standard 49) does not include measuring UV output, although many certification agencies offer it as an optional add-on test.

Elevated measurements

Given a cylindrical UV source with length roughly on the same order of magnitude as the distances from which in intensity is measured, we expect that time for desired dose will increase at least faster than linearly with respect to distance from UV lamp.[18] To assess the possibility of raising masks within the BSC to reduce decontamination time based this relationship, we also took measurements of UV intensity at 33 cm and 48.3 cm above the BSC floor (Fig 2). The total height of the BSC was 67.3 cm.

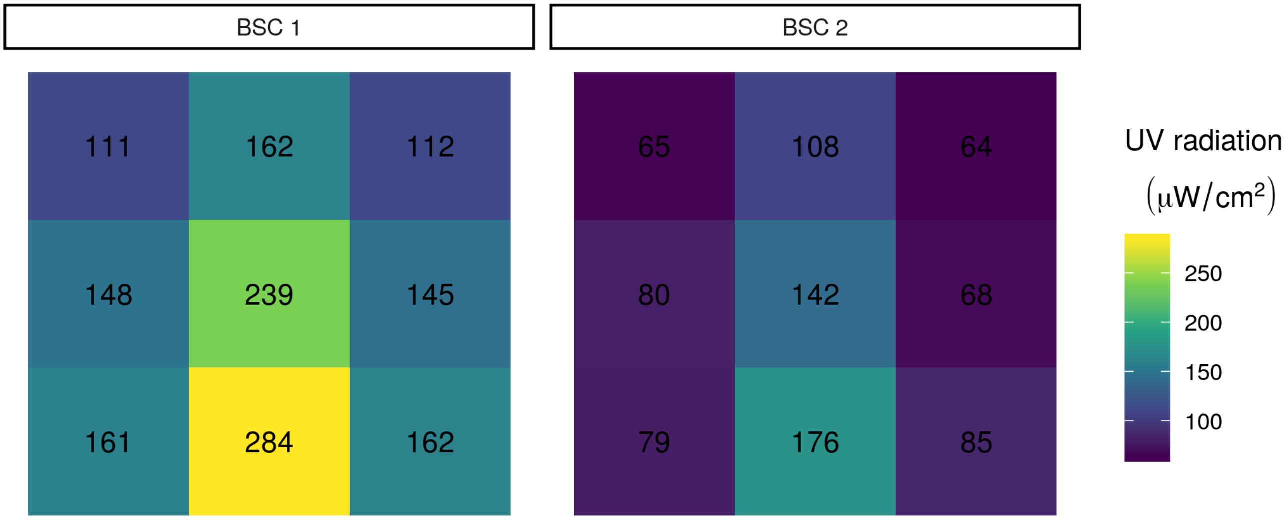

Figure 1. UV radiation in each sector of each BSC as measured with a UV meter. Each of the nine sections per BSC shows the UV radiation measured in the section. Numbers indicate UV radiation measured in each section.

Indeed, our UV intensity data with respect to the nearest distance to the UV bulb, stratified by position relative to the length of the UV lamp, reveals a close fit to an inverse square function function. These data suggest that this principle can be used to deliver much higher doses than those achieved on the floor of the BSC by raising the object to be decontaminated.(Fig 3).

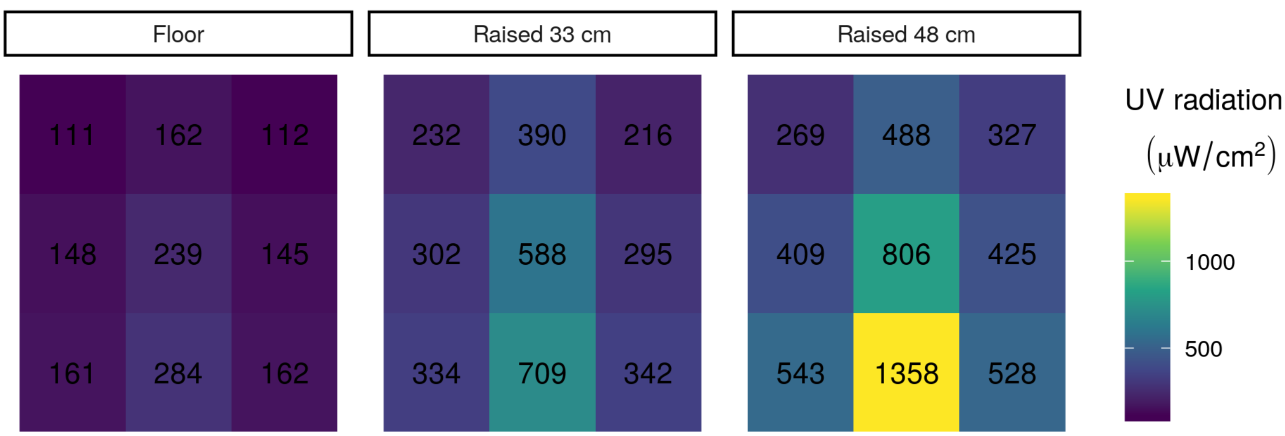

Figure 2. UV radiation in each sector of BSC 1 at three different heights. Each of the nine sections per elevation shows the UV radiation measured in the section. Numbers indicate UV radiation measured in each location with the UV meter.

The literature on this subject, including a recent CDC summary, suggests that a dose of *at least* 1 Jcm^{-2} of UV-C is required to decontaminate FFRs.[3,14–16] Hospitals can, of course, choose a different target dose based on their internal risk analysis. To estimate the time (per side of the mask) required for decontamination in a BSC, we can use the following equation:

$$\frac{\text{target dose mJ}}{\text{cm}^2} \times \frac{\text{cm}^2}{\text{min intensity}\mu W} \times \frac{1000\mu W \text{ seconds}}{1 \text{ mJ}} \times \frac{1 \text{ minutes}}{60 \text{ seconds}} = \text{ recommended time.} \quad (1)$$

For explanations of all terms in this equation, see table 2. Selecting 1 J cm^{-2} as our target dose, this equation reduces to:

$$\frac{1000 \text{ minutes}}{\text{min intensity}} = \text{ recommended time (minutes).} \quad (2)$$

Table 2. **Description of equation terms**

Value	Description
target dose	UV dose required to achieve desired level of decontamination (using 1 J cm^{-2})
min intensity	The lowest UV-C intensity anywhere in the BSC in μWcm^{-2}
recommended time	Estimated time (in minutes) to decontaminate one side of an FFR

Now we must choose a value for intensity. To ensure that all masks in the BSC achieve the target UV radiation dose, we must select the minimum level of UV-C radiation anywhere in the BSC. Based on the UV meter data, the lowest UV-C radiation level we observed across both hoods is 64 μWcm^{-2}. Plugging these values into equation 2, we find that the minimum time required to decontaminate FFRs in a standard BSC, assuming the variance we measured above, is 4.3 hours per side. As that may be a prohibitively long time to wait, we also consider the possibility of elevating PPE within a BSC to reduce the decontamination time. Based on our measurements in Fig 2, we estimate that raising PPE 48.1 cm off the floor of a 67.3 cm tall BSC with a specified fluence of 100μW should reduce the needed decontamination time to a minimum of 62 minutes per side, given the lowest UV measurement made at that height.

Estimating time to decontaminate face-shields in a BSC

In order to decontaminate face-shields in a BSC, much lower UV doses must be achieved. 2-5 mJ cm^{-2} of UV radiation is estimated to kill most single-stranded RNA viruses on gel media (similar to the hard plastic face-shield). To err on the side of caution and ensure that other pathogens were also deactivated, we will base our recommendation for face-shield decontamination on a target dose of 60 mJ cm^{-2}. Because of the flat, uniform nature of face-shields, we also do not need to account for UV dose variation due to mask geometry. As a result, we can use the following equation to calculate our recommended decontamination time:

$$\frac{\text{target dose mJ}}{\text{cm}^2} \times \frac{\text{cm}^2}{\text{min intensity}\mu W} \times \frac{1000\mu W \text{ seconds}}{1 \text{ mJ}} \times \frac{1 \text{ minutes}}{60 \text{ seconds}} = \text{recommended time (minutes)}. \quad (3)$$

Plugging in 60 mJ cm^{-2} as our target dose, and 64 $\mu W\text{cm}^{-2}$ as the minimum intensity, we calculate a recommended time in the bottom of our BSC of 15.6 minutes per side for plastic face-shield decontamination.

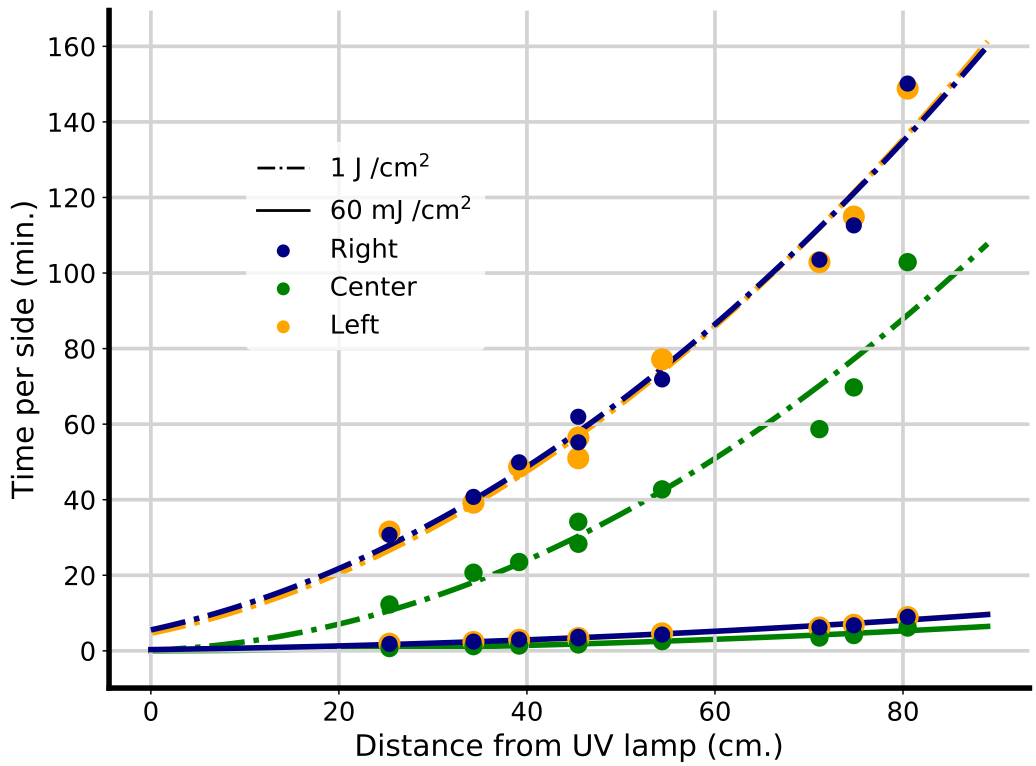

Figure 3. Time to decontaminating dose with respect to distance from UV lamp for face-shield and FFR decontaminating doses. An inverse square function was fit to UV fluence data from hood 1 at various heights for the left, center, and right-hand sections of the BSC, as visualized in Fig 2, and used to calculate time for decontaminating dose per side at target doses of 1 J cm^{-2} and 60 mJ cm^{-2} This approximate inverse square relation can be exploited to deliver high doses of UV within a BSC in a reasonable amount of time by positioning PPE close to the UV lamp.

Discussion

Ideally, a new mask or respirator would be used for each individual to minimize the transmission of infectious diseases that are airborne or transmitted via respiratory droplets. However, crises such as the current COVID-19 pandemic can create shortages that necessitate measures to conserve PPE. Among potential methods for decontamination, previous work has suggested UVGI results in less physical deformation than bleach, microwave irradiatin, and vaporized hydrogen peroxide. [5]

Additionally, this and other investigations of UVGI for the purpose of PPE decontamination was motivated by the ubiquity of UV lamp equipped biosafety cabinets, especially at large biomedical research institutions. Various groups have therefore begun decontaminating respiratory protective equipment themselves using UVGI and "homebrew" setups. For example, enterprising clinicians at the University of Nebraska Medical Center are stringing N95 respirators between two towers of UVGI bulbs placed on either side of a room in order to inactivate potential SARS-CoV-2 viral contaminants on the masks.[17]

From our measurements, normalized to the technical specifications of the manufacturer using a typical BSC, we estimate the minimum time to decontaminate FFR is 4.3 hours per side. We estimate the minimum time to decontaminate face-shields is 15.6 minutes per side We invite other scientists to add measurements from their own BSCs to our github repository to allow continued updating of this recommendation.[19] Ideally, clinical sites interested in using this protocol should take measurements using calibrated UV fluence detectors of their specific BSCs prior to implementation of this protocol. If a calibrated UV detector is unavailable, UV test strips could provide an affordable way to ensure an appropriate UV dose is achieved in a given BSC. To calculate a time for an arbitrary BSC model, we recommend using Equation 2. In the future, it may be possible to design a technique that avoids the need to flip masks over and irradiate each side separately. By elevating masks off the surface of the BSC and, if necessary, placing reflective material underneath them, it should be possible to ensure that UV radiation reaches the entire mask surface simultaneously and would reduce the manual labor and time required for this protocol.

Inspired by the protocol developed by Lowe et al., we propose a workflow to optimize the utilization of institutional resources:[17]

1. Prior to use, PPE should be directly labeled to identify the original owner by both name and department.
2. After use, place in sealed packaging and distribute to BSC locations.
3. Using sterile technique, remove PPE from packaging and place on working surface of cabinet.
4. Ensure that there is no overlap of adjacent masks, as any unexposed areas will not be decontaminated.
5. After transfer, adequately decontaminate any external surface that came in contact with the used masks or packaging and destroy the packaging via biological waste.
6. For FFR: Close the hood and power on the UV light for 62 minutes on an elevated platform or 4.3 hours if the FFR is placed on the floor of the BSC.

7. For face-shields: Close the hood and power on the UV light for 15.6 minutes
8. After this duration, power off the UV light, open the cabinet, and carefully flip the masks to expose the opposite side, ensuring no overlap of adjacent masks.
9. Close the hood and power on the UV light again for the recommended time for your PPE type.
10. Again, adequately decontaminate or dispose of any external surface that comes in contact with the masks.
11. Once the full duration has elapsed, power off the UV light and open the hood.
12. While maintaining sterility of the cabinet, add a tally to each mask indicating the number of UVGI cycles it has experienced and individually place in sterile, sealed packaging.
13. Remove packages from cabinet and redistribute to original owner.

Limitations

Despite the measures taken here to ensure adequate decontamination of PPE, following this protocol by no means guarantees complete sterilization or decontamination. This method should be implemented *only if* PPE *must be reused*. FFRs contain multiple layers of filtration, and respiratory droplets may penetrate into the inner layers. Though UV-C light has been shown to transmit into and through FFR materials, the transmittance of light ranges from 23-50% through the outer layer depending on the model of the FFR.[6] Therefore, the ability for UVGI to thoroughly sanitize FFRs may vary based on the ability for UV-C light to penetrate through to the internal filtering medium, which contributes the most filtration ability. Virologic testing to determine the degree of decontamination of the inner mask layers is ongoing.

Previous *in vitro* studies imply that the shape of the inactivation-curve is modulated by the surface being decontaminated. Generally, studies find a much lower dose needed to inactivate virus on gel or plate-based media compared to FFRs such as the N95 mask.[2,3] The feasibility of our approach for decontaminating FFRs is therefore limited by the long-time duration (at least 4.3 hours per side) needed to achieve a germicidal UV-C dose on the floor of a BSC.

Variance in received dose due to the shape of the FFRs may also contribute to incomplete decontamination. We considered this possibility using an array of photo-diodes affixed to different positions on each mask throughout our 3 X 3 grid. In the areas of the grid receiving the lowest intensity (the front corners), the median observed proportional variance (max intensity/min intensity) across the masks was 2.17. Scaling our recommendation by this value, 9.4 hours per side would be required to decontaminate each mask. We did not incorporate this into our main recommendation due to concerns about the our use of directional sensors to measure received dose (i.e. the measured intensity varied substantially with direction of the sensor in addition to sensor position). We believe that our measurements with a UV fluence meter are more reliable and repeatable. We present the photo-diode measurements here as an important potential limitation and something that hospital systems should consider when calibrating their own BSCs. The full photo-diode data and results can be found in the supplemental materials.

Additionally, without measuring the absolute UV-C levels in a given BSC, it is not possible to be sure that it is outputting the specified amount of radiation. For instance UV-C lamps can produce visible light without a significant loss of intensity while UV intensity has fallen below the germicidal threshold. Ideally, UV-C fluence in each BSC should be measured and verified before using this protocol. Given the scarcity of UV-C fluence meters, however, this may not be possible in all cases. The next best solution is to use the newest UV-C bulbs available. Bulbs should be inspected and cleaned regularly to ensure that debris is not blocking UV radiation.[20,21] With only three BSCs measured, we cannot fully quantify the amount of variation we expect to see across the set of all BSCs. There almost certainly exist BSCs with locations where the UV radiation received is lower than the lowest value we measured. In the future we hope to collect enough data to perform more robust statistics.

As discussed in the background, UV-C-mediated degradation of polymers within the respirator is another possible concern. Fit and filtration testing of the N95 respirators used in this experiment did not reveal any decline in filtration efficiency following UV-C exposure (Fig S4). While we do not anticipate such degradation being the limiting factor, we recommend that hospitals employing this approach take additional precautions such as: 1) labeling N95 respirators so that they can be reused by the same individual, 2) marking the number of times the same mask has undergone decontamination, as was recommended by Lowe et al.[17], and ensuring this number does not exceed 40, and 3) regularly fit-testing respirators. Virologic validation of N95 masks radiated in our BSCs using the protocol presented herein is ongoing, and we will update this document as data become available.

Code and Data Availability

All data used in this paper and code written to analyze it are open source and publicly available.[19]

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Author contributions statement

This was a massive team effort with everyone contributing their specific expertise (Fig 4):

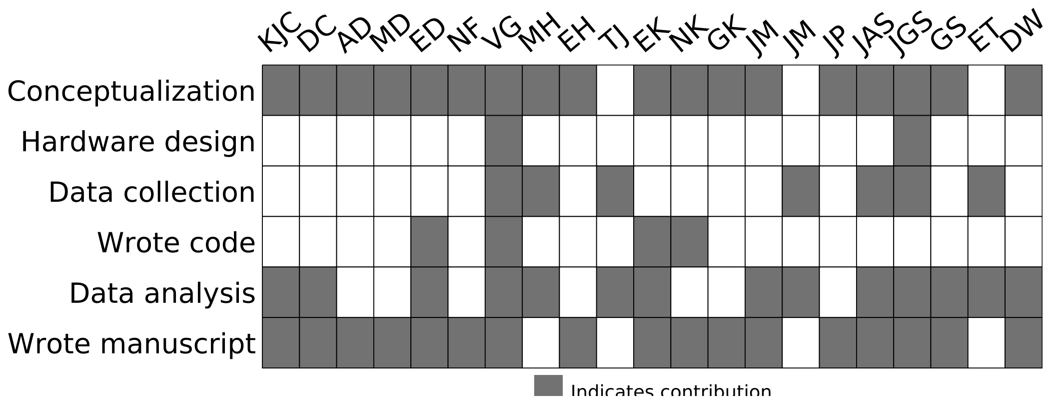

Figure 4. **Author contributions**

Repeat Disclaimer

This article does not represent the official recommendation of the Cleveland Clinic or Case Western Reserve University School of Medicine, nor has it yet been peer reviewed. We are releasing it early, pre-peer review, to allow for quick dissemination/vetting by the scientific/clinic community given the necessity for rapid conservation of PPE during this dire global situation. We welcome feedback from the community.

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Supplemental Materials

Supplemental Methods

Photodiode measurements

We affixed three photodiodes (MTPD4400D-1.4) to a standard N95 respirator (3M) and measured UV fluence from nine positions (across a 3x3 grid) equally spaced on the counter of each BSC (Fig S1).

Photodiodes were operated in zero-bias photovoltaic mode. While the photodiodes had a wide UV spectral range, we did not utilize filters since the diodes were only used to measure relative irradiance and we expected UVC output to be a stable fraction of total UV output from the bulbs.

Since voltage measured (less than 1V) was substantially less than the saturating voltage of approximately 4.8V, we expect to be operating within the linear dynamic range of the photodiodes. The photodiodes used in measurements were of the same model number and from the same lot and were therefore expected to have the same operating characteristics. Measurements of light intensity from the photodiodes were recorded by a Raspberry Pi at 40ms intervals for a total period of 4 seconds. A circuit board with an LM324N operational amplifier (for signal amplification) and an ADS1015 analog-to-digital converter were used to interface the photodiodes and the Pi (Fig S2.

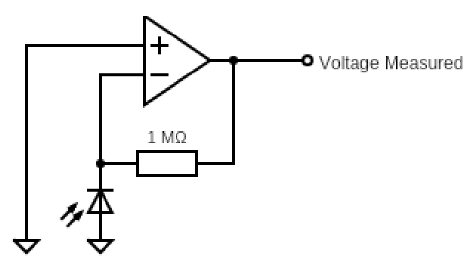

Figure S2. Schematic of part of the circuit containing the photodiode. A 1 megaohm resistor was chosen to sufficiently amplify the signal from the photodiode. The resulting voltage (less than 1V) was substantially less than the saturating voltage of approximately 4.8V. Voltage measurements were made with an analog-to-digital converter connected to a Raspberry Pi but could also be read through an oscilloscope.

Resulting data were used to generate heatmaps of the values

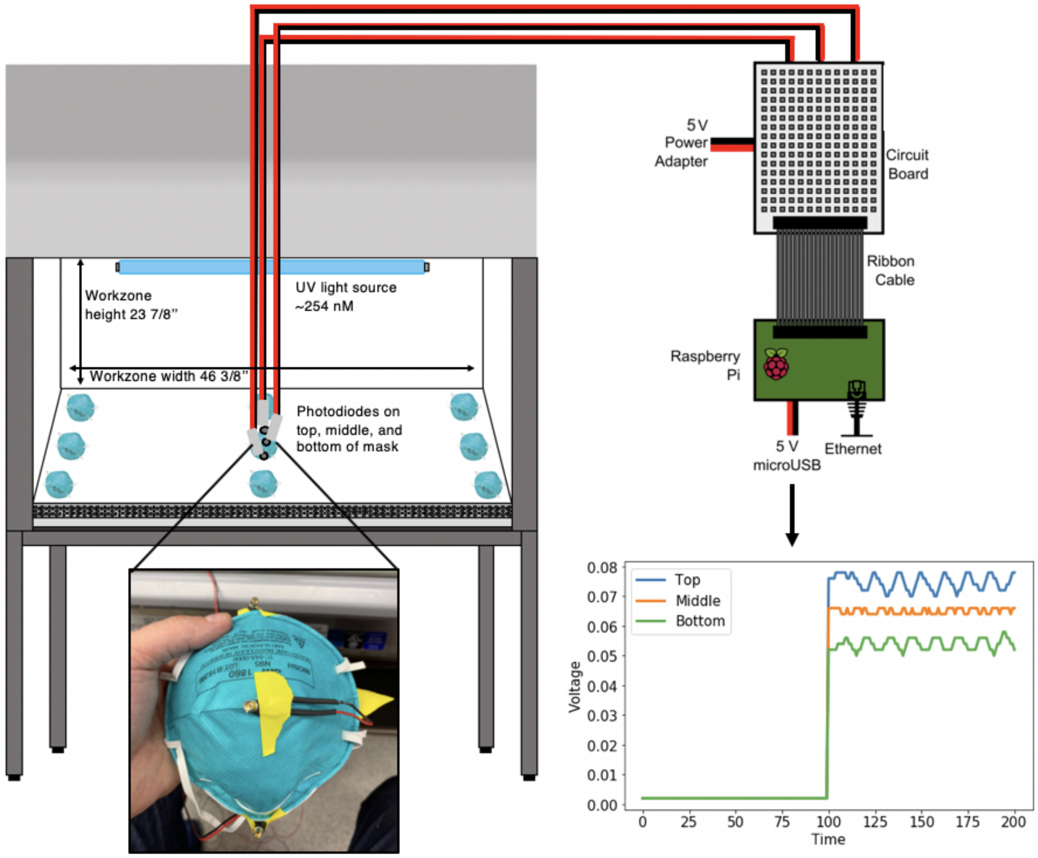

Figure S1. Schematic of our process for measuring light intensity across the base of a BSC with photodiodes. A photodiode was attached to the top (north), middle, and bottom (south) of an N95 mask, and the voltage of light that reached diodes was measured both with the UV light turned off and then on. This measurement was performed within each sector of a 3x3 grid at the base of the BSC workzone as illustrated.

from all three photodiodes and the UV meter at each position of the 3x3 grid at the base of the BSCs. Analysis was performed in the R programming language[22] using the ggplot2[23] and dplyr[24] packages (all code and data may be viewed in the github repository[19]).

Fit and filtration testing

The N95 respirators were cut into 70 mm $\times$ 70 mm pieces and tested in a circular acrylic air duct with an inner diameter of 50 mm. Ambient aerosols were loaded as the pollutant source. The number concentrations of 0.3 - 1 μm particles were measured by an optical particle counter (Aerotrak 9306, TSI Inc., USA). The concentrations were record every 1 min for 2 times upstream the respirator filter and then 2 times downstream. The single-pass filtration efficiency η, which is a function of particle size diameter, d_p, was calculated by:

$$\eta(d_p) = \left(1 - \frac{C_{down}(d_p)}{C_{up}(d_p)}\right) \times 100\% \tag{4}$$

where C_{up} and C_{down} are the particle number concentrations (pcs/L) at upstream and downstream of the respirator filter, respectively, and each a function of (d_p). The pressure drop across the respirator filter was measured by a differential gauge. The air temperature, relative humidity, and filtration velocity were measured by an airflow/temperature meter at the air duct exhaust.

Supplemental Results

Using an array of photodiodes attached to a standard N95 mask (see Fig S1), we assayed the heterogeneity due to mask geometry at different positions along the bottom of the cabinet (Fig S3). The median proportional variance across each mask was 1.42 between the highest and lowest intensities. If we limit our consideration to the front corners of the array (the areas that receive the lowest irradiance), the median proportional variance across each mask was 2.17 (indicating a higher variance due to mask geometry in these areas).

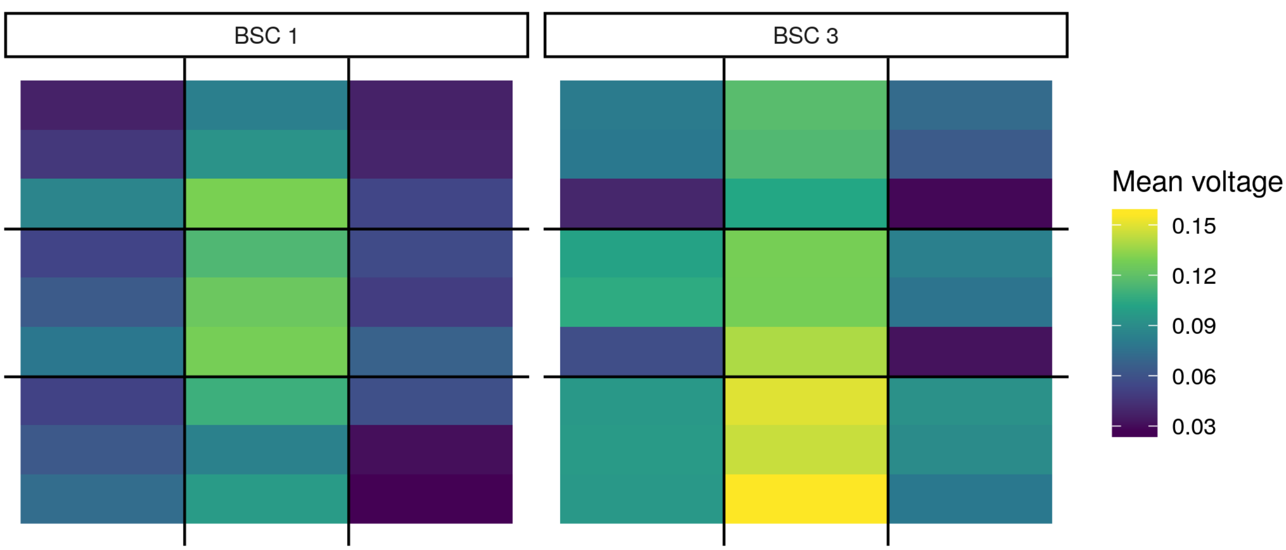

Figure S3. Relative UV intensity as a function of position across the base of two BSCs. Each of the nine sections per BSC shows the voltage from three photodiodes attached to the surface of an N95 mask (top, middle, and bottom). The three photodiodes were attached to different positions on the mask (Fig S1) to demonstrate UV differences across mask surface. To account for ambient light, voltages recorded with the UV lights off were subtracted from the voltages recorded with the UV lights on.

No	Mask	Effi-0.3µm	Effi-0.5µm	Effi-1µm	ΔP (pa)	V_{air} (m/s)	T (°C)	RH (%)
#1	3M1860S-0	90.2%	90.0%	95.6%	185.8	< 0.1	23.7	21.5
#2	3M1860S-15min	92.1%	92.9%	95.6%	186.1	< 0.1	23.6	22.1
#3	3M1860S-30min	93.2%	93.7%	94.6%	186.3	< 0.1	23.6	22.7
#4	3M1860S-1h	92.9%	92.7%	94.8%	184.8	< 0.1	23.6	22.5
#5	3M1860S-2h	93.0%	93.5%	95.6%	187.2	< 0.1	23.7	22.0
#6	3M1860S-6h	89.6%	90.5%	92.9%	186.6	< 0.1	23.7	21.7
#7	3M1860S-days on/off	93.1%	93.9%	94.3%	186.3	< 0.1	23.6	22.1

Figure S4. UV irradiation at the doses discussed does not adversely affect mask filtration efficiency for particles of size 0.3, 0.5, or 1 micron.