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

Theory Division[1,*,+,†]

[1]Cleveland Clinic Lerner Research Institute and Case Western Reserve University School of Medicine, Cleveland, OH, USA
[*]scottj10@ccf.org
[+]all authors contributed meaningfully to this multidisciplinary work
[†]authors in alphabetical order: Kyle J. Card, Dena Crozier, Andrew Dhawan, Mina Dinh, Emily Dolson, Nathan Farrokhian, Vishhvaan Gopalakrishnan, Masahiro Hitomi, Emily Ho, Tanush Jagdish, Eshan S. King, Nikhil Krishnan, Gleb Kuzmin, Jeff Maltas, Julia Pelesko, Jessica A. Scarborough, Jacob G. Scott, Geoff Sedor, Davis T. Weaver

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 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 safely expand the lifespan of the supply of medical equipment are critically important. In the midst of the current pandemic, there has been a concerted effort to identify viable ways to conserve Personal Protective Equipment, including decontamination after use. Some hospitals have already begun using UV-C light to sterilize N95 respirators, but many lack the space or equipment to implement existing protocols. In this study, we outline a procedure by which N95 respirators may be decontaminated using ultraviolet (UV) radiation in biosafety cabinets (BSCs), a common element of many academic, public health, and hospital laboratories. The primary obstacle to this approach is the possibility that the UV radiation levels vary within BSCs. To account for this potential variation in dosing across the base of the BSC, we tested the UV-C radiation in two randomly chosen idle BSCs in our research institute and observed a maximum ratio between the minimum and maximum recorded intensities within a given BSC to be 1.98. Based on these values, we calculated that the surface of an N95 mask placed within a BSC with a manufacturer's reported fluence of 100 $\mu W \mathrm{cm}^{-2}$ should be effectively decontaminated for reuse after approximately 15-20 minutes per side. The degree of decontamination achieved at these doses for the inner filtration layers of an N95 is under investigation. Our results provide support to healthcare organizations looking for alternative methods to extend their reserves of PPE. It is our hope that with an easily implemented strategy, as we have presented here, idle BSCs can be utilized to alleviate the PPE shortage by providing a way to decontaminate PPE to allow safe daily re-use. This should be tested on a larger scale, and confirmed in a virology laboratory before adoption, though we contend that in extremis, this method would be preferred compared to re-use without decontamination.

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 surgical masks and N95 respirators is

recommended for infections that may be transmitted by respiratory droplets and airborne particles, respectively.[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 N95 filtering face-piece respirators (FFRs) is through cycles of decontamination and reuse with ultraviolet germicidal irradiation (UVGI).[2–6] 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). UVGI uses UV-C within 200-300 *nm*.[7] 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.[8] At these wavelengths, the amount of 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).[9,10] 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[4,5,11,12]. 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 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.[13] It is likely that masks would need to be replaced for this reason well before they experienced enough decontamination cycles to experience

Table 1. Key findings from research on UV-mediated mask degradation. For comparison, the target dose we recommend in this paper is 0.06 Jcm^{-2}.

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

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 single-stranded RNA (ssRNA) virus that causes COVID-19, the UV dose required to inactivate 90% of ssRNA viruses is an estimated $1.32 - 3.20$ mJ cm^{-2}.[2] Similar methods using 254 nm UV-C light have been investigated with

SARS-CoV-1.[14] A group at the University of Nebraska Medical Center recently developed a protocol to sterilize N95 respirators using UVGI.[15] Specifically, they subjected used N95s to 60 mJ cm^{-2} of UV-C radiation (254 nm)—which exceeded the estimated sterilization dose of 2-5 mJ cm^{-2} for single-stranded RNA by several-fold—by stringing them across a room containing two UVGI towers on either side. The UVGI doses were remotely monitored using a UV meter to ensure proper sterilization.[15]

Unfortunately, not all hospitals are equipped to set up dedicated rooms for decontamination or possess the specialized UVGI towers that are outlined by Lowe et al.[15] However, 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.

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 FFRs. 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 calculated a recommended time of 15-20 minutes per side to irradiate FFRs in a BSC to inactivate potential SARS-CoV-2 virus contaminants. Due to the large number of idle BSCs nationwide, we estimate FFR requirements can be reduced by up to 75%, significantly easing hospital burden due to a significant lack of PPE.

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 are reported to use 253.7 nm UV-C radiation and provide an average intensity of 100 $\mu W cm^{-2}$ to the cabinet floor. We measured UV fluence in two ways: using a UV meter (to obtain absolute measurements) and using an array of three photodiodes (to calculate variance due to mask geometry).

Photodiode measurements

For the 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 1). 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

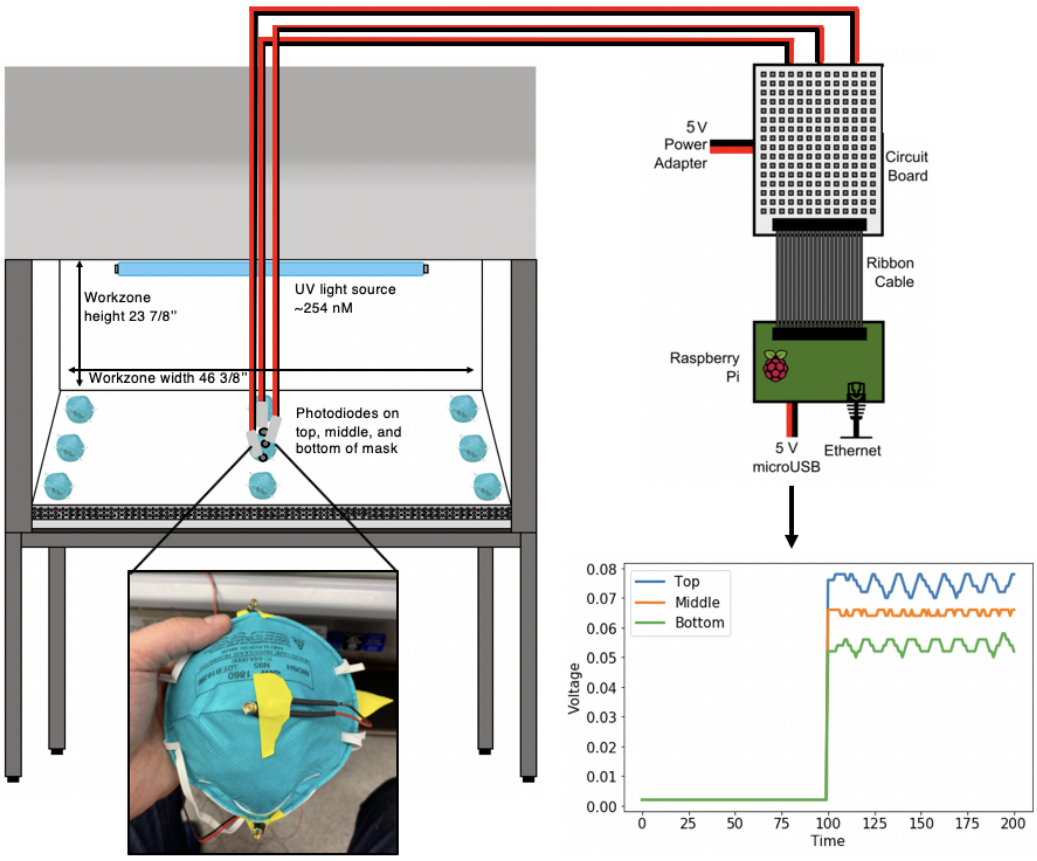

Figure 1. Schematic of our process for measuring light intensity across the base of a BSC with photodiodes. A photodiode was attached to the top (north), middle, and bottom (south) of an N95 mask, and the voltage of light that reached diodes was measured both with the UV light turned off and then on. This measurement was performed within each sector of a 3x3 grid at the base of the BSC workzone as illustrated.

ADS1015 analog-to-digital converter were used to interface the photodiodes and the Pi.

Resulting data were used to generate heatmaps of the values from all three photodiodes at each position of the 3x3 grid at the base of the BSCs. Analysis was performed in the R programming language[16] using the ggplot2[17] and dplyr[18] packages (all code and data may be viewed in the github repository[19]).

UV meter measurements

While the photodiodes can provide information about variation in UV intensity at different mask angles, they cannot tell us the absolute level of UV-C radiation in the BSC. Measuring the absolute quantity of UV radiation hitting each spot in the BSC allowed us to validate our calculations and reduce the uncertainty associated with our recommendations. These measurements were conducted by placing a UV fluence meter (General Tools UV512C) at each of the same nine positions in each BSC that the mask with the photodiodes was placed. 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

hitting that position in the BSC.

Results

As some hospitals attempting to implement this protocol may not have access to both photodiodes and a UV meter, we start by analyzing each of these sets of measurements separately. This way, hospitals with the capacity to do so can perform this analysis on their own BSCs to obtain a protocol that is optimized to their equipment. Any hospitals that do so are invited to deposit their data in our GitHub repository[19] to provide improved recommendations for hospitals that are unable to make their own measurements. Subsequently, we will provide recommendations based on the photodiode measurements in combination with the UV meter measurements.

Photodiode measurements

UV intensity among existing BSCs

The technical specifications of the BSC suggest that approximately 100 $\mu W \text{cm}^{-2}$ of 254 nm UV-C radiation is received along the floor of the cabinet. From the reported UV intensity of a BSC (or any UV-C source) and measured lethal doses for ssRNA viruses and other microbial pathogens in the literature, one can estimate the time to decontamination, assuming insignificant decay in intensity due to equipment wear over time, homogeneous UV irradiance across the source, homogeneous radiant flux over the area of the mask, and comparable pathogen survival between media tested in literature and colonized N95 mask (Fig 4).

However, given the geometry of the mask, we were concerned about spatial heterogeneities in this delivery and hypothesized that masks in different positions could receive different doses. To understand the magnitude of this heterogeneity, we designed an experiment to explore the spatial heterogeneity across a BSC workzone base and over different parts of the mask. Using an array of photodiodes attached to a standard N95 mask (see Fig 1), we assayed the heterogeneity along the bottom of the cabinet. From these measurements, we derived an upper and lower bound estimate for each 3x3 grid at the bottom of the BSCs (Fig 2). To do this we took the median of the three photodiodes per array (we used the median because we consider the photodiodes to be technical replicates with positional variation). Using the upper bound (the *highest* measured UV fluence in the 9 sections), we assumed that this value corresponded to the manufacturer's reported dose. Then, to be conservative, we made our estimate of time needed for decontamination based on the *lowest* measured dose in the 9 sectors.

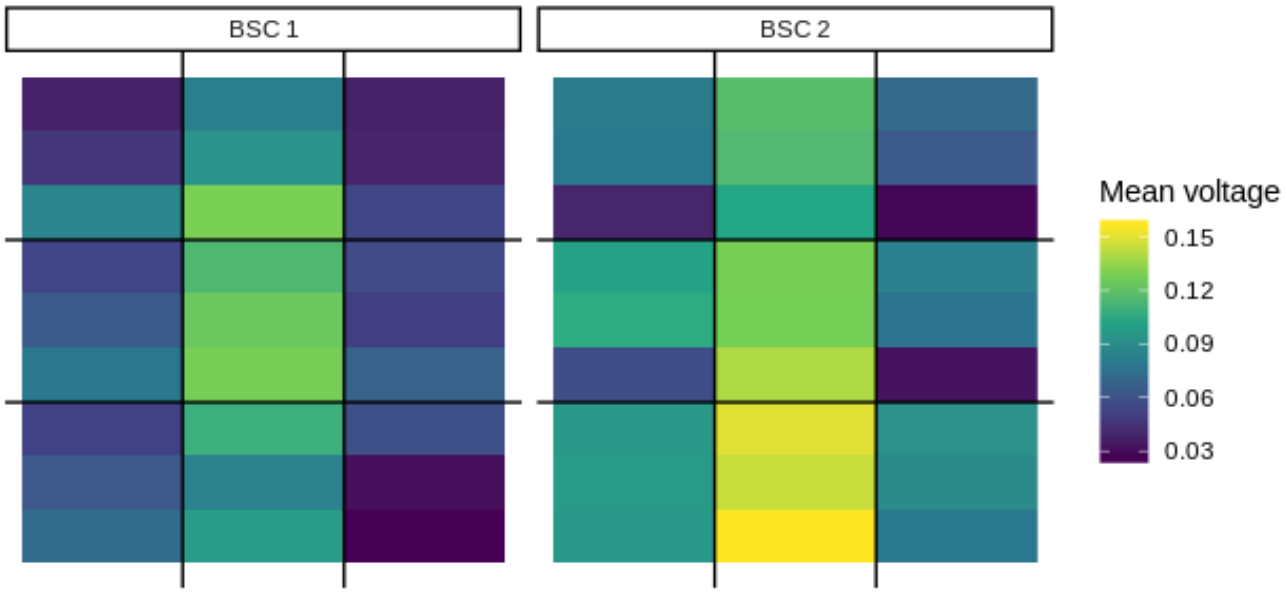

Figure 2. Relative UV intensity as a function of position across the base of two BSCs. Each of the nine sections per BSC shows the voltage from three photodiodes attached to the surface of an N95 mask (top, middle, and bottom). The three photodiodes were attached to different positions on the mask (Fig 1) 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. The median of each grid sector was calculated and used in calculations to determine minimum time of mask exposure for sterilization.

Calculating a time to sterilization scaling factor using relative UV intensity as a function of spatial position at the base of two BSCs

Each of the nine BSC workzone positions contain data from three photodiodes attached to the surface of an N95 mask. The mean intensity across all measurements with the UV lights on was 0.11, with range 0.08 - 0.16, and standard deviation 0.02. To be conservative, we assume the largest measured intensity matches the manufacturer's reported value. Using this value, we then calculate UV received by the mask in the position of least intensity. The minimum measured intensities were a factor of 1.71 and 1.98 lower than the BSC 1 and BSC 2 maximums, respectively (see Table 2). To provide less conservative scaling factor estimates, we also calculate the median voltage for each section of the BSC 3x3 grid. The ratio between the maximum median intensity and minimum median intensity for each BSC are reported in Table 2.

UV meter measurements

Our measurements of absolute UV radiation across BSC floors, as made with UV meters, show a similar pattern of spatial variation in UV intensity (see Fig. 3). Interestingly, many of these values substantially exceed the manufacturer's specified fluence (100 $\mu W \text{cm}^{-2}$). Indeed, in one of the BSCs all of the measurements were greater

Table 2. Range of scaling factors calculated to account for spatial intensity heterogeneity across individual masks and throughout BSC workzone. The scaling factor required to estimate the minimum sterilization time using the BSC while accounting for heterogeneity of UV intensity each mask may receive. The greatest factor difference between the highest and lowest measured UV intensity was 1.98.

Method	BSC 1	BSC 2
Median max:min intensity	1.54	1.83
Absolute max:min intensity	1.71	1.98

than this value. This result implies that our photodiode-based calculations are indeed conservative, as we intended. Note that, because the UV meter cannot be attached to a mask, these measurements do not take into account variation produced by mask geometry.

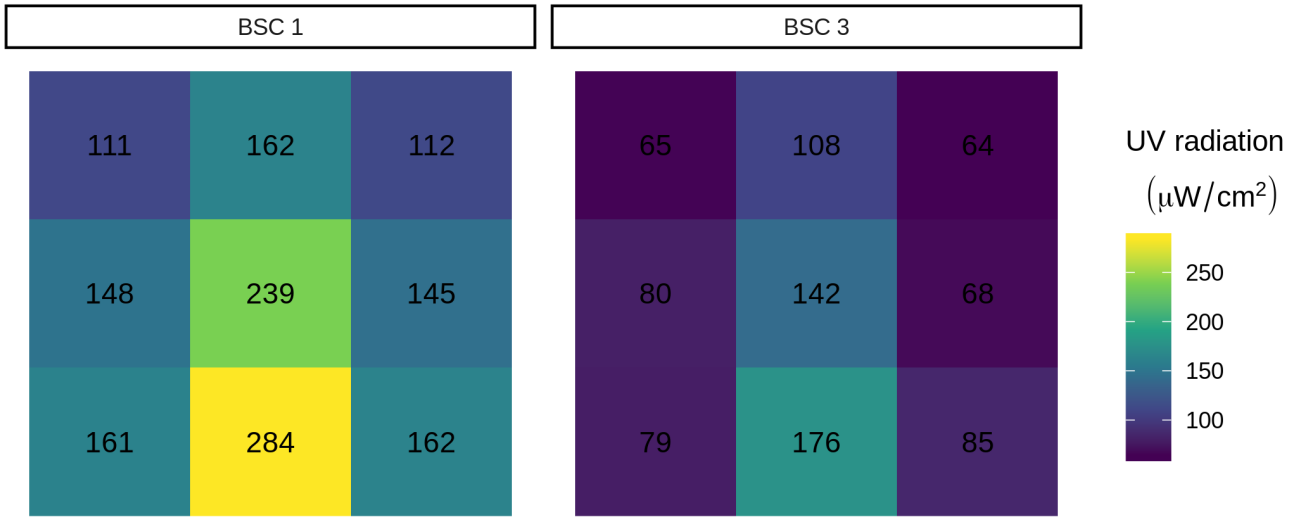

Figure 3. UV radiation in each sector of each BSC as measured with a UV meter. Each of the nine sections per BSC shows the UV radiation measured in the section. Note that BSC 1 here is the same BSC as BSC 1 in Figure 2, but BSC 3 is a new BSC that was not measured with photodiodes. Numbers indicate UV radiation measured in each section.

Because these measurements give us an absolute value for UV radiation at each position in each BSC, we do not need to calculate a scaling factor from these data. Instead we can simply use the lowest observed value as a worst-case estimate. Note that if we were to calculate a scaling factor it would be larger than those observed in the photodiode data: 2.56 for BSC 1 or 2.75 for BSC 3 (based on max:min intensity). However, as discussed in the next section, this inconsistency is balanced out by the fact that many of the UV meter measurements were higher than we assumed in the calculations for the photodiode data.

Importantly, the minimum observed value differed substantially between BSCs: 111 $\mu W \text{cm}^{-2}$ vs. 64 $\mu W \text{cm}^{-2}$.

Some of this variation is likely due to BSC age; BSC 1 was manufactured in 2017 whereas BSC 3 was manufactured in 2006. 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.

Estimating time to sterilize FFRs in a BSC

In order to give a recommendation for how long to leave a mask in a BSC to sterilize it, we must determine the total quantity of UV radiation we want the mask to receive. 2-5 mJ cm^{-2} of UV radiation is estimated to kill most single-stranded RNA viruses. To err on the side of caution and ensure that other pathogens were also deactivated (see Figure 4) Lowe et al. considered both 60 mJ cm^{-2} and 300 mJ cm^{-2} as their target UV radiation level, ultimately selecting 300 mJ cm^{-2}. Here, we will base calculations on a target dose of 60 mJ cm^{-2}. 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 to sterilize a mask in a BSC, we can use the following equation:

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

For explanations of all terms in this equation, see table 3. Selecting 60 mJ cm^{-2} as our target dose, this equation reduces to:

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

Table 3. Description of equation terms

Value	Description
target dose	Dose of radiation necessary to achieve desired level of decontamination (here, we use 60 mJ cm^{-2})
1.98	Most conservative spacial intensity scaling factor, per Table 2
min intensity	The lowest UV-C intensity anywhere in the BSC in $\mu W cm^{-2}$
intensity	Manufacturer-specified UV-C intensity at the surface of the BSC in $\mu W cm^{-2}$ [20]
recommended time	Estimated time 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 radiation dose, we must select the minimum level of UV radiation anywhere in the BSC. Based on the UV meter data, the lowest UV radiation level we observed across both hoods is 64 $\mu W \mathrm{cm}^{-2}$. Plugging this into equation 2 we get a suggested decontamination time of 15.63 minutes per side of the mask.

In the case of the photodiode data, we do not know the minimum intensity. In the interest of being as conservative as possible with our recommendations, we assume for each hood that the maximum observed voltage corresponds to the manufacturer's specified fluence. To estimate the minimum UV radiation level, we can multiply by a ratio from table 2. Consistent with our goal of producing a conservative recommendation, we select the worst-case ratio from the table (1.98):

$$\frac{1000 \text{ minutes}}{\text{intensity}} \times 1.98 = \text{ recommended time (minutes)}. \tag{3}$$

Plugging the manufacturer's specified fluence for our BSCs (100 $\mu W \mathrm{cm}^{-2}$) into this equation, we get 19.8 minutes as the recommended decontamination time per side. Unlike the UV-meter-based recommendation, this calculation takes into account variation due to mask geometry. Note that this value is definitely overly conservative. It is based on an assumption that we know to be wrong for both BSCs we measured (that the maximum level of UV radiation observed anywhere is the amount specified by the manufacturer). However, until more data is available, we prefer to err on the side of being overly conservative. 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. For now we recommend placing PPE into a BSC for 19.8 minutes per side on the assumption that the multiple places in which this value errs on the side of being conservative compensates for the unobserved variation.

Estimating the impact of using UVGI to decontaminate FFRs in the United States

Due to the lack of concrete data on the number of currently available BSCs in the United States, we implemented the "Fermi method" to estimate the number of FFRs that can be decontaminated using the method outlined above. The Fermi method, named after the renowned physicist Enrico Fermi, uses a sequence of "best guess" estimates that are combined together to reach an overall approximation. Given these considerations, our estimates are outlined below.

At the present time there are roughly 83,000 biological scientists in the United States (https://datausa.

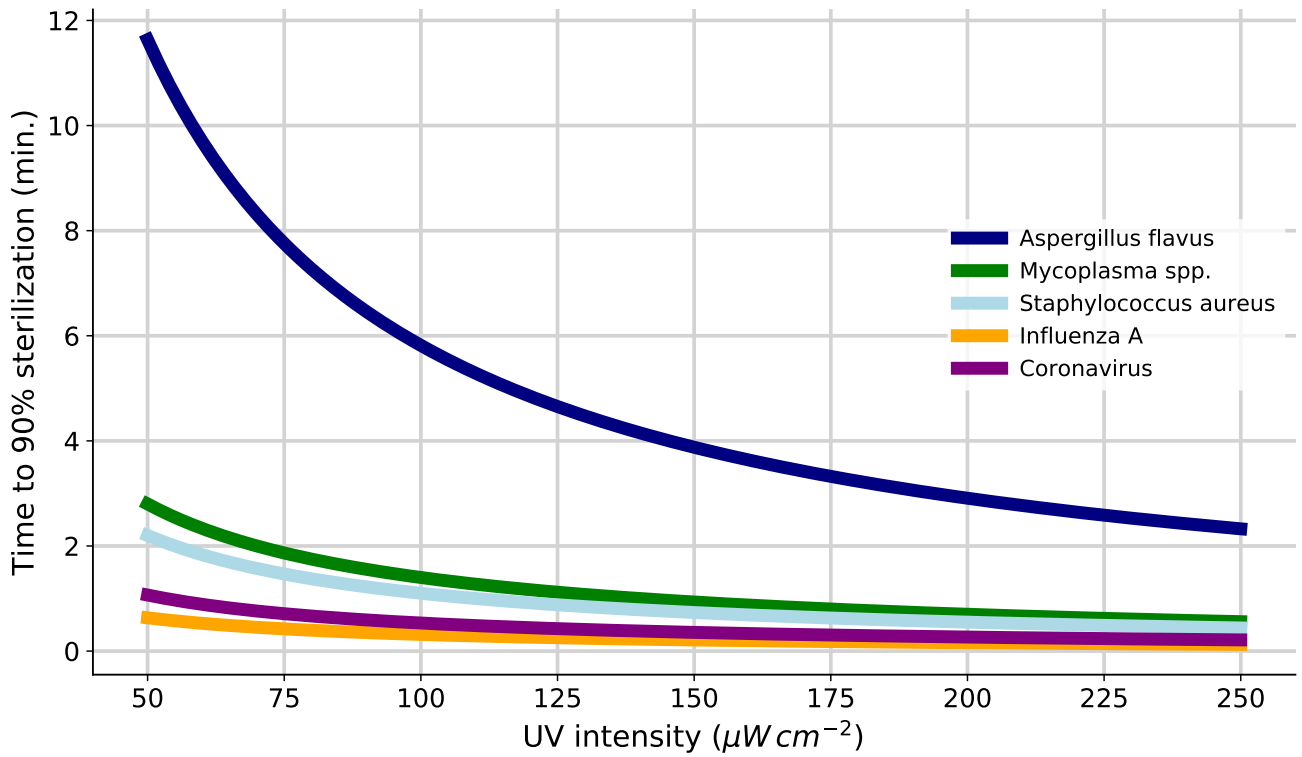

Figure 4. Time in minutes to reach 90% sterilization for a given UV intensity, shown for various representative pathogens. Using previously reported doses for 90% sterilization for key pathogens potentially, transmitted via respiratory droplets, time in minutes for 90% sterilization is shown for a range of UV intensities. [2,21]

io/profile/soc/biological-scientists). If roughly half of these scientists have access to BSCs, and the ratio of cabinets to scientists is estimated at 1 : 10, then this suggests that roughly 4,000 BSCs are available in the United States. Most of these BSCs are idle at this time, given the restrictions on laboratory work in place to limit the spread of COVID-19.

As discussed in the background section, 4.68 Jcm^{-2} is a (very) conservative upper bound on the total quantity of UV radiation that an FFR can safely experience.[12] Given our target dose of 60 mJ cm^{-2} (0.06 Jcm^{-2}) per side (so 120 mJ cm^{-2} total), this allows for 40 decontamination cycles. Due to normal wear and tear, however, masks will likely not survive for that many cycles of donning and doffing. For the purposes of this calculation, we will make the very conservative assumption that masks can survive three decontamination cycles on the grounds that other studies have proposed using three cycles.[12] Given the importance of FFR in combating COVID-19, we assume that decontamination procedures will be implemented effectively nonstop. If each decontamination procedure takes 40 minutes (our most conservative time estimate), and 28 FFRs can be processed in each procedure, then the number of

FFRs that can be recycled in one day by a single institution is calculated by equation 4:

$$\frac{24\text{ hours}}{\text{day}} \times \frac{1.5\text{ procedures}}{\text{hour}} \times \frac{28\text{ masks}}{\text{procedure}} \times \frac{M\text{ BSC}}{\text{institution}} = \frac{1008\text{ masks}}{\text{day}} \times M, \tag{4}$$

where each of the M BSCs available per institution is running a simultaneous sanitization procedure – more than 1,000 N95 masks per day for every BSC if run at capacity.

The WHO estimated that roughly 89 million FFRs are needed in the response to COVID-19 per month.[22] In order to meet these demands, the worldwide production would need to increase by 40%. However, we estimate that nearly 121 million masks per month ($1008 \times 4000 \times 30$) can be decontaminated for re-use under ideal conditions. Finally, because FFR masks can be UVGI decontaminated at least three times without loss of function,[11] our calculations suggest we can lower FFR requirements by 75%, from roughly 89 million FFRs per month to about 22 million FFRs per month.

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 then bleach, microwave irradiation, and vaporized hydrogen peroxide.[5] Additionally, this and other investigations of UVGI for the purpose of N95 respirator decontamination was motivated by the ubiquity of UV lamp equipped biosafety cabinets, especially at large biomedical research institutions. Various groups have therefore begun sterilizing 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.[15]

From our measurements, normalized to the technical specifications of the manufacturer using a typical BSC, we conservatively estimate the time to sterilize N95 respirators using similar models is 20 min per side. This recommendation represents the time required to deliver a UV dose that is ≈30 times higher than the previously reported dose to inactivate 90% of single-stranded RNA viruses.[2] To scale this protocol to any BSC, we propose that a conservative scaling factor of 1.98 for spatial heterogeneity is likely conserved across BSCs, but the amount of power delivered to the BSC surface likely varies significantly between manufacturers. Note that given the variance between the two BSCs we measured, the true worst-case scaling factor is likely slightly worse than what

we measured, as there almost certainly exist BSCs with greater variation in UV radiation intensity. 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 of the specific BSCs to ensure adequate UV-C dose for decontamination. As we described, these measurements could be taken using photodiodes or UV fluence sensors. In addition, UV test strips could provide an affordable way to ensure an appropriate UV dose is achieved in a given BSC. Therefore, to calculate a time for an arbitrary BSC model, we recommend using Equation 2 if you have an absolute measurement of UV fluence or Equation 3 if you have voltage-based measurements. Note that Equation 3 assumes that the UV radiation output of the BSC matches the manufacturer's specification. Ideally, BSCs should be calibrated before being used for the purposes of sterilizing PPE.

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:[15]

1. Prior to use, respirators 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 masks 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 sterilized.
5. After transfer, adequately sterilize any external surface that came in contact with the used masks or packaging and destroy the packaging via biological waste.
6. Close the hood and power on the UV light for 20 minutes.
7. 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.
8. Close the hood and power on the UV light for 20 minutes.
9. Again, adequately sterilize or dispose of any external surface that comes in contact with the masks.

10. Once the full duration has elapsed, power off the UV light and open the hood.

11. 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.

12. Remove packages from cabinet and redistribute to original owner.

Limitations

Despite the measures taken here to err on the side of overestimating the recommended time for irradiation of N95 respirators, following this protocol by no means guarantees complete sterilization or decontamination. This method should be implemented *only if* respirators *must be reused*. For example, 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 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.

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 PPE such as the N95 mask[2,3]. 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 J/cm^2[23]. Comparably, for a variety of mask models, Mills et al. found that a 1 J/cm^2 UVGI dose conferred a range of 1.42 to 4.84 log reduction of H1N1 viral load [3]. While more *in vitro* studies are likely needed to identify the dose required for safe decontamination, literature suggests that a much higher dose is needed to sterilize porous materials, such as N95 and surgical masks, than to sterilize non-porous surfaces. In addition, the uncertain extent to which UV penetrates the layers of the fibrous mesh that comprise an N95 is a complicating factor. As of yet, there is not compelling evidence that our protocol achieves more than surface decontamination. Virologic testing to determine the degree of decontamination of the inner mask layers is ongoing.

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 lamps can produce visible light without a significant loss of intensity while UV intensity has fallen below the germicidal threshold Ideally, UV fluence in each BSC should be measured and verified as above the germicidal before using this protocol. Given the scarcity of UV fluence meters, however, this will likely not be possible in all cases. The next best solution is to use the newest UV bulbs available. Bulbs should be inspected and cleaned regularly to ensure that debris is not blocking UV radiation[24,25].

As discussed in the background section, UV-mediated degradation of polymers within the respirator is another possible concern. 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.[15], and ensuring this number does not exceed 40, and 3) regularly fit-testing respirators.

It should be noted that our recommendation is based on a radiation dose target that is 30 times higher than the dose needed to inactivate 90% of respiratory viruses.[2] If even more dramatic conservation of PPE was required and the upper bound of 40 decontamination cycles proves to be a limiting factor, it would likely be possible to modify this protocol to utilize a lower UV dose. Such a modification may increase the lifespan of each unit of PPE at the cost of potentially incomplete decontamination. Though the situation that necessitates the reuse of PPE is far from ideal, using presently-unused BSCs to decontaminate N95 respirators has the potential to reduce the current PPE burden by 75%.

Code and Data Availability

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

Acknowledgements

Thanks to Tyler Cassidy, Jessica Cunningham and Lydia Kisley for their help. We would also like to thank everyone who supported this work with their encouraging tweets. In particular, we thank Mohamed Abazeed for his helpful comments on Twitter. While this specific project was not directly funded by any body, we would like to thank our funders in the form of the National Institutes of Health and the American Cancer Society and the Taussig Cancer and Lerner Research Institute.

Author contributions statement

This was a massive team effort with everyone contributing their specific expertise (Fig 5):

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

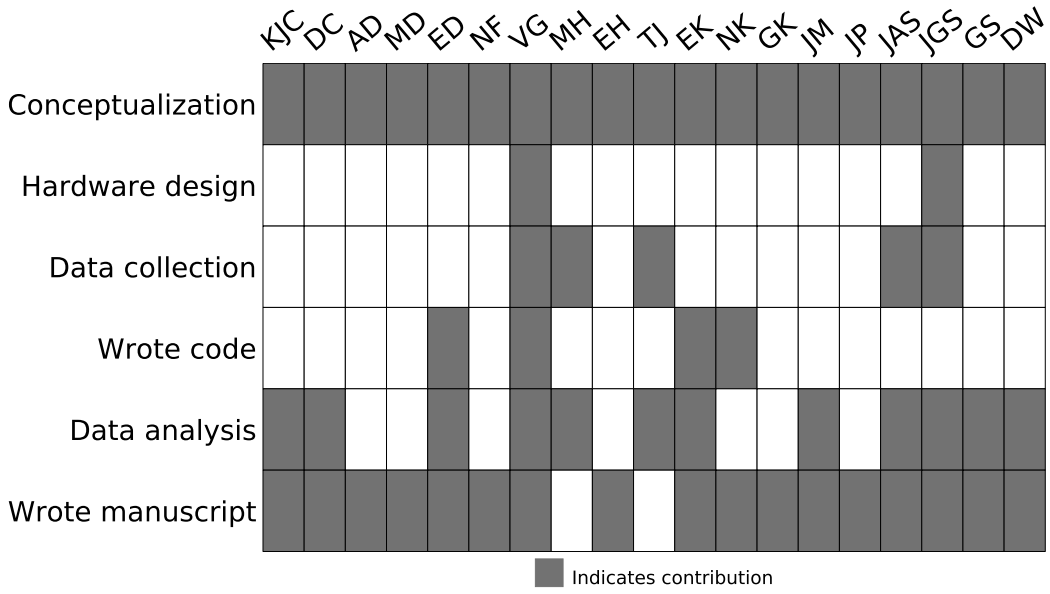

Figure 5. Author contributions

conservation of PPE during this dire global situation. We welcome feedback from the community.

References

1. for Occupational Safety, N. I. & Health. Niosh guide to the selection and use of particulate respirators certified under 42 cfr 84 (1996).

2. Tseng, C.-C. & Li, C.-S. Inactivation of viruses on surfaces by ultraviolet germicidal irradiation. *Journal of Occupational and Environmental Hygiene* **4**, 400–405 (2007).

3. Mills, D., Harnish, D. A., Lawrence, C., Sandoval-Powers, M. & Heimbuch, B. K. Ultraviolet germicidal irradiation of influenza-contaminated n95 filtering facepiece respirators. *American journal of infection control* **46**, e49–e55 (2018).

4. Lindsley, W. G. *et al.* Effects of ultraviolet germicidal irradiation (uvgi) on n95 respirator filtration performance and structural integrity. *Journal of Occupational and Environmental Hygiene* **12**, 509–517, DOI: 10.1080/15459624.2015.1018518 (2015). PMID: 25806411, https://doi.org/10.1080/15459624.2015.1018518.

5. Viscusi, D. J. e. a. Evaluation of five decontamination methods for filtering facepiece respirators. *The Annals of Occupational Hygiene* (2009).

6. Fisher, E. M. & Shaffer, R. E. A method to determine the available uv-c dose for the decontamination of filtering facepiece respirators. *Journal of applied microbiology* **110**, 287–295 (2011).

7. Meulemans, C. The basic principles of uv–disinfection of water. (1987).

8. Kowalski, W. *Ultraviolet germicidal irradiation handbook: UVGI for air and surface disinfection* (Springer science & business media, 2010).

9. Dunn, C. G., Campbell, W. L., Fram, H. & Hutchins, A. Biological and photo-chemical effects of high energy, electrostatically produced roentgen rays and cathode rays. *Journal of Applied Physics* **19**, 605–616 (1948).

10. Sureka, C. & Armpilia, C. *Radiation biology for medical physicists* (CRC Press, 2017).

11. Lore, M. B., Heimbuch, B. K., Brown, T. L., Wander, J. D. & Hinrichs, S. H. Effectiveness of three decontamination treatments against influenza virus applied to filtering facepiece respirators. *Annals of occupational hygiene* **56**, 92–101 (2012).

12. Bergman, M. S. *et al.* Evaluation of multiple (3-cycle) decontamination processing for filtering facepiece respirators. *Journal of Engineered Fibers and Fabrics* **5**, 155892501000500405 (2010).

13. Heimbuch, B. Research to Mitigate a Shortage of Respiratory Protection Devices During Public Health Emergencies. Tech. Rep. HHSF223201400158C, Applied research associates (2019).

14. Darnell, M. E., Subbarao, K., Feinstone, S. M. & Taylor, D. R. Inactivation of the coronavirus that induces severe acute respiratory syndrome, sars-cov. *Journal of virological methods* **121**, 85–91 (2004).

15. Lowe, J. J. *et al.* N95 filtering facemask respirator ultraviolet germicidal irridation (uvgi) process for decontamination and reuse. Tech. Rep., Nebraska Medicine (2020).

16. Team, R. C. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria (2019).

17. Wickham, H. *ggplot2: Elegant Graphics for Data Analysis* (Springer-Verlag New York, 2016).

18. Wickham, H., François, R., Henry, L. & Müller, K. *dplyr: A Grammar of Data Manipulation* (2020). R package version 0.8.4.

19. Dolson, E. & Krishnan, N. Data and analysis for use of uv-c radiation in idle biosafety cabinets to sterilize personal protective equipment, DOI: 10.5281/zenodo.3724005 (2020). URL: https://doi.org/10.5281/zenodo.3724005.

20. NuAire. Labgard es nu-540 series 1 class ii, type a2 biosafety cabinet, operation and maintance manual. (2014).

21. The University of British Columbia. *Use of UV Germicidal Lamps Inside Biosafety Cabinets* (2014).

22. WorldHealthOrganization. Shortage of personal protective equipment endangering health workers worldwide (March 02, 2020).

23. Vo, E., Rengasamy, S. & Shaffer, R. Development of a test system to evaluate procedures for decontamination of respirators containing viral droplets. *Appl. Environ. Microbiol.* **75**, 7303–7309 (2009).

24. Jones, D. Timely uv-c lamp replacement critical but neglected.

25. Mamahlodi, M. T. Potential benefits and harms of the use of uv radiation in transmission of tuberculosis in south african health facilities. *Journal of public health in Africa* **10** (2019).