Scientific Article

Evaluating an Ultraviolet C System for Use During SARS-CoV2 Pandemic and Personal Protective Equipment Shortage

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Abstract

Purpose: The supply of N95 masks and filtering facepiece respirators (FFRs) has been limited nationally owing to the coronavirus disease 2019 pandemic. Ultraviolet C (UVC) light has been suggested as a potential option for decontamination of FFRs by the Centers for Disease Control. There has been a lack of publications characterizing UVC dose distribution across FFRs.

Methods and Materials: A UVC light box and FFR rack system was assembled using low-pressure mercury lamps peaked at 254 nm and aluminum flashing to reduce shadowing effect. Dose was characterized with the use of ultraviolet (UV) intensity labels and an ultraviolet germicidal irradiation (UVGI) National Institute of Standards and Technology traceable meter. Ozone production was evaluated after extended bulb run time.

Results: Calibration of UV intensity labels was noted to have color-change saturation at 100 mJ/cm². Dose measurements with the UV intensity labels on the FFR demonstrated symmetrical dose to all surfaces, but symmetry was not supported by measurements with the UVGI meter. There was substantial dose fall off on the lateral aspects of the FFR. No ozone production was noted in the UVC system.

Conclusions: UV intensity labels for characterization of dose provided a false suggestion of symmetry compared with the UVGI meter. Estimates of appropriate exposure times to reach 1000 mJ/cm² should be significantly increased to account for geometry of FFR and lateral dose fall off.

Introduction

The severe acute respiratory syndrome 2 (SARS-CoV2) pandemic has caused a patient surge in many hospitals and clinics, resulting in a nationwide shortage of personal protective equipment (PPE). One of the valuable pieces of PPE for health care personnel is the N95 mask or filtering face piece respirator (FFR).
Control and Prevention (CDC) has recommended several strategies to avoid crisis capacity of FFRs. If decontamination is deemed necessary, ultraviolet germicidal irradiation (UVGI), vaporous hydrogen peroxide (VHP), and moist heat are suggested when new respirators are not available. Of these methods, VHP has been granted emergency use authorization by the Food and Drug Administration for N95 respirator decontamination. This provides a great reprieve for institutions that can use these services but does not yet reach the critical need in many clinics and small communities nationwide.

The University of Nebraska Medical Center has been using ultraviolet C (UVC) light for decontamination of FFRs for several months, and their protocol has been widely shared. Unless identical equipment and room geometry can be used, it is challenging to replicate this system for use in other clinics. UVC has great potential use during the coronavirus disease 2019 pandemic, but there remains a need to describe the implementation of any device.

UVC light has a wavelength between 100 to 280 nm and is found in artificial sources, such as low pressure mercury lamps, which have a spectral peak at 254 nm. UVC radiation causes DNA/RNA damage by producing cyclobutane pyrimidine dimers that alter DNA/RNA structure, thus interfering with replication. Some low pressure mercury lamps can generate a weak spectral line at 185 nm, which produces ozone in combination with oxygen from ambient air. SARS-CoV2 has been demonstrated to be an enveloped, positive-stranded RNA virus with nucleocapsid from the family of coronaviruses. The family of coronaviruses has been demonstrated to have sensitivity to UVC light at 254-nm wavelength. The D37 is defined as the dose required to inactivate 63% of targets. The D37 of the coronavirus family to UVC light is 2.5-3.9 J/m². With linear survival calculation, the dose required to provide a 6-log kill with the use of the highest estimated D37 (0.39 mL/cm²) is 5.39 mL/cm². This assumes perfect laboratory conditions and does not emulate the porous material of an FFR, though it demonstrates a high sensitivity of the coronavirus family to UVC light. Recent literature has established sensitivity of SARS-CoV2 to UVC light when evaluated on stainless steel surfaces and FFRs, but this research used a light range of 260 to 285 nm. Decontamination was effective, but notably slower on FFR, particularly compared with vaporized hydrogen peroxide.

Multiple prior studies have evaluated the durability of FFRs with UVC exposure. UVC decontamination has been compared with microwave-generated steam, moist heat, bleach solution, ethylene oxide, and VHP decontamination on FFRs. Microwave generated heat and steam have not had agreement on their safety as some studies have noted degradation of the respirator after use, though others contradict this finding. Ethylene oxide has not been recommended, as long drying times are necessary to ensure complete removal of the harmful gas. VHP requires gas chambers and ventilation hoods for use, though it has been shown to have acceptable fit and filtration of the FFR following decontamination cycles. Alcohol can alter the electrostatic charge or degrade the filtration of an FFR. Lastly, any chemical process has the potential to cause sensitivity issues on the skin of health care providers when reused.

The integrity of the FFR when considering aerosol penetration, airflow resistance, or physical appearance of several models of FFRs has been minimal after UVC exposure. Material degradation has been demonstrated after extremely high doses of UVC (710 and 950 J/cm²) to FFRs. The breaking strength of the respirator straps also demonstrated a dose-dependent decline, with a 14% to 28% decrease in strength at 1180 J/cm² and 20% to 51% decrease at 2360 J/cm². A 2018 study examined UVC deactivation of H1N1 influenza on 15 National Institute for Occupational Safety and Health-approved N95 FFRs of varying shapes and materials. Statistically significant reduction in influenza viability was demonstrated for all FFRs exposed to UVC. Specific design characteristics, such as geometry that increases shadowing (folds) and hydrophilic material, were found to make sterilization less amenable to UVC. Even FFRs with these characteristics demonstrated statistically significant reductions in influenza viability following UVC exposure.

Additional research from 2019 supports FFR integrity and fit after several UVC decontamination cycles. This study specifically evaluated the reaction of 15 types of FFRs to UVC exposure. Data presented in the aforementioned study also provided dose and virus susceptibility specific to the family of coronaviruses and UVC on FFR material. Middle Eastern respiratory syndrome coronavirus and SARS-CoV1 were placed on numerous FFRs and exposed to 1000 mL/cm². After exposure to UVC at this dose, no detectable virus was recovered. Notably, this evaluation was completed on flat coupons and did not take into account using UVC for clinical need, which requires evaluation of geometry and shadowing of FFRs. A dose of 1000 mL/cm² should serve as optimal minimum dose to the FFR based upon these data. Total exposure times should be determined by the time required for the lowest dose-receiving location on the FFR to receive at least 1000 mL/cm².

The following sections outline how a UVC system was constructed and evaluated for symmetry of exposure across FFRs. These measurements were used to establish exposure times ensuring the surfaces of the FFR received at least 1000 mL/cm².

Methods and Materials

Materials used in the production of the UVC system were 12 Ushio G30T8 germicidal low pressure mercury
arc lamps, an ILT2400 Meter (calibrated on March 26, 2020), an XSD140T254 detector (silicon sensor), N010-004 UVC intensity labels, 3 garment stands, 6 Lithonia 36" light fixtures, 2 extension cords, a pack of 10 conduit connectors, 16-gauge wire for securing fixtures and hanging FFRs, 1 roll of electrical tape, aluminum reflective insulation, an Aeroqual series 200 Monitor, an ozone sensor head 0 to 0.5 ppm (calibrated January, 2020), and tools for assembly (drill, screw driver, hammer, pliers, wire cutters).

The complete structure consisted of 3 racks: 1 FFR mask rack sandwiched between 2 source racks (Fig 1). The source racks each contained 6 lamps in pairs, fastened to the structure at heights of 75, 112.5, and 153.5 cm, respectively. The mask rack was manufactured to suspend approximately 12 FFRs. There were 4 rows, each able to suspend 3 FFRs at heights of 68.5, 99.5, 131.5, and 162 cm from the base, respectively. The unit was encased in aluminum flashing box to enhance UVC reflectivity and decrease shadowing (Fig 2).

Irradiance (mW/cm²) was measured with an ILT2400 meter and XSD140T254 silicon sensor detector, comprised as a single unit. The meter and sensor were both National Institute of Standards and Technology (NIST) traceable. The spectral sensitivity of this meter is peaked at 254 nm wavelength. The irradiance was measured at 12 locations corresponding to the center of FFR placement and en face to each source rack. The 12 locations are denoted in Figure 1. Horizontal strings were placed at heights of 68.5, 99.5, 131.5, and 162 cm, respectively. The strings provided accurate location of the detector and minimization of detector rotation with respect to the source.

To ensure a constant irradiance, the lamps were initially turned on for 20 minutes before measurements. Before each measurement, the lamps were turned off to reposition the detector. At initiation and 2 minutes of exposure, the output irradiance was found to be on average 85% and 95%, respectively, of the maximum output at 5 minutes. Thus, all individual measurements were made at approximately 5 minutes from the turning on of the lamp.

A calibration curve of UVC intensity labels was created by exposing labels to a known dose. The label was affixed to the UVGI sensor, just inferior to the detector to avoid shadowing, as demonstrated in Figure E1. The dose was determined by using the ILT2400 and XSD140T254 meter and detector system in integration mode while simultaneously exposing the label (Fig E1). The detector system was placed midline 50 cm from the central point of a single lamp. A UVC label calibration was determined by measuring 8 labels in 25 mJ/cm² increments to a maximum of 200 mJ/cm². UVC intensity labels change color from yellow to a dark bluish green based on the increasing irradiance of UVC light. Color change was evaluated by multiple observers in differing lighting scenarios. Photographs of the labels were obtained as soon as the final exposure was completed.

An FFR was placed in the upper corner of the mask rack for UVC exposure evaluation (location 3, 131.5 cm from base as noted in Fig 1). Nine UVC intensity labels were adhered on the convex and concave aspects with clear plastic tape, as noted in Figure E2. The symmetry of UVC dose was tested by exposing the FFR to 20 mJ/cm², which was confirmed by the silicon sensor that was placed next to the FFR.

For further evaluation of symmetry of dose across the respirator, the UVGI meter was adhered to the FFR at 5 different locations on the convex and concave surfaces (Fig 3) and exposed to UVC to evaluate the irradiance. This was repeated at the 4 corner locations (rack height 68.5 cm and 162 cm in both columns 1 and 3), which were felt to be the most divergent from the light sources. Ozone generation was evaluated with an NIST traceable meter. Both light sources were run for 40 minutes at room temperature to assess if any residual ozone was created during the run cycle.

### Results

Table 1 demonstrates the irradiance and output at the 12 different locations along the rack to each light source when placed en face to the bulb rack. A goal dose of 1000 mJ/cm² was reached by running the light sources for 1320 seconds in the absence of aluminum flashing.

The UVC label calibration curve showed discernable color change up to 100 mJ/cm², with the darkest color recorded at 125 mJ/cm². Color darkening was difficult to discern beyond 100 mJ/cm². The most contrasting color change to the labels occurred between 0 and 25 mJ/cm² (Fig E1). Therefore, the symmetry of FFR exposure was evaluated with labels and a dose of 20 mJ/cm².

Based upon findings noted in Figure E2, the FFR appeared to have symmetrical exposure to both the convex and concave surfaces when exposed to 20 mJ/cm² by UV intensity labels. The color change of the labels was noted to be within 20 to 25 mJ/cm² as per comparison to the previous calibration curve.

Additional quantitative evaluation of dose via UVGI meter at 5 different locations on the FFR is demonstrated in Table 2. This confirmed a dose gradient across the FFR, noting substantial dose fall off at the lateral aspect of the respirator. Of the 4 locations measured for mask contouring effect, rack height 68.5 cm, column 3 showed the largest exposure dose gradient, with a minimum of 34% and a maximum of 126% compared with the central convex position 3A. The inner mask exposure range was between 66% and 107% compared with the central convex position 3A. The least-exposed location on the rack was 68.5 cm from the base, column 3, mask position
4A. There was a large gradient in the measured dose compared with the perceived dose based on UV intensity labels. To reach a minimum of 1000 mJ/cm² to the lateral aspects of the respirator, the exposure times required an increase to 1950 seconds. Ozone was measured at baseline to be 0.000 parts per million and 0.000 parts per million when read immediately after bulb sources were run for 40 minutes.

Figure 1  Physical dimensions of ultraviolet C light sources and mask rack. Completed structure includes 2 identical source racks, which contain 6 lamps in pairs, fastened to the structure at heights of 75, 112.5, and 153.5 cm, respectively. The mask rack is sandwiched between the 2 light sources and was manufactured to suspend approximately 12 FFRs. There are 4 rows, each able to suspend 3 FFRs at heights of 68.5, 99.5, 131.5, and 162 cm from the base, respectively. When bases of the garment racks are abutted, the distance from light sources to the rack is 54 cm. **Abbreviation:** FFR = filtering facepiece respirators.
Discussion

The SARS-CoV2 pandemic has placed a significant strain on the medical community with regard to PPE. UVC has been suggested as a potential decontamination method for N95 respirators by the CDC. Filtration and function are retained after UVC exposure until very high doses are reached, as demonstrated in prior studies. Minimum dose exposure to the FFR was evaluated by both UVC labels and a UVGI meter. The meter is likely to underrepresent the total dose that is received by the FFR, as angular response of the meter was not determined. The UVC labels may provide a general guideline for light exposure and to avoid shadowing. UVC labels used here are useful for UVC exposure, but are also reactive to UVA and UVB spectrums of light. Caution should be used as these can potentially overestimate UVC exposure. Furthermore, overexposure has few downsides in comparison to underexposure when considering FFR decontamination. Thus, the UVGI meter is favored for determining minimum exposure times in any given UVC decontamination system.

FFRs with exhalation valves, folds, or coating in hydrophilic material should not be considered for UVC decontamination. Folds and expiratory valves create unavoidable shadowing. FFRs made of hydrophilic material are also felt to be incompatible due to viral particle migration away from the surface of the respirator. Hard-bodied FFRs without these features are considered most optimal for UVC decontamination.

It is important to note that maximum doses should also be evaluated when using any UVC system. We have recommended using a conservative maximum dose of 120 J/cm² based on prior studies. This should include the summation of the maximum dose to the anterior and posterior surfaces of the FFR. Handheld devices or those that cannot have identical geometry for each cycle should not be used in an attempt to decontaminate FFRs. Although a maximum number of decontamination cycles could theoretically be calculated, the user fit will be altered after several wears. User self-seal-check is required to confirm the respirator remains effective for reuse. Any alteration in the seal renders the FFR highly ineffective, and it should be discarded. It is necessary that the FFR is reused only by the original wearer after UVC exposure and should be labeled for this purpose due to the molding of the FFR to the face. The chain of

Figure 2  Light sources with 6 paired bulbs laterally and mask rack centrally within aluminum flashing box that is fully enclosed to increase ultraviolet C reflection and reduce shadowing. Abutment of bases inferiorly ensures identical geometry for each use.

Figure 3  Locations of UVGI meter adherence to 5 positions on the convex (A) and concave (B) locations of the FFR to evaluate exposure dose. Dose output is demonstrated in Table 2. Abbreviations: FFR = filtering facepiece respirators; UVGI = ultraviolet germicidal irradiation.
command within any clinic or hospital setting is highly important to avoid any potential cross contamination between FFRs or to the staff processing the respirators. The wearer of the FFR should avoid any cosmetics, sunblock, or other materials that could transfer to the mask because this will impede the ability of UVC to reach the surface of the respirator. Any FFR straps or masks with defects in integrity should not be sent for decontamination. The respirator should be thoroughly examined before donning to ensure appropriate structure remains intact.

The FFR should not be considered sterile after UVC decontamination because 1000 mJ/cm² has not been evaluated for all potential pathogens. A processed FFR with UVC should be donned with the use of gloves and followed by hand hygiene. The use of UVC for FFR decontamination should only be considered in dire situations in which new FFRs are not available.

Low pressure mercury lamps used in our process were ozone free and peaked at 254 nm. It is necessary to evaluate ozone production within each potential setup of UVC lights as exposure is carcinogenic. UVC lights should be used in a well-ventilated space for extra caution. As low as reasonably achievable should be employed when using UVC, as with any other radiation source. The lights can be carcinogenic and cataractogenic when exposed to bare skin and eyes.

Those that are looking to use UVC light should be aware that we were unable to independently assess the decontamination of any pathogens. Our research used

| Table 1 | Exposure dose en face of each bulb source to 12 different locations along the respirator rack, as denoted in Figure 1 |
|--------------------------------------|--------------------------------------|
| Height (cm) | Irradiance (mW/cm²) | Exposure dose (mJ/cm²) |
|--------------------------------------|--------------------------------------|
| Light source 1 | 1 | 2 | 3 | 1 | 2 | 3 |
| 162.0 | 0.955 | 1.068 | 0.979 | 1261 | 1410 | 1292 |
| 131.5 | 1.236 | 1.406 | 1.292 | 1632 | 1856 | 1705 |
| 99.5 | 1.349 | 1.526 | 1.380 | 1781 | 2014 | 1822 |
| 68.5 | 1.120 | 1.182 | 1.046 | 1478 | 1560 | 1381 |
| Light source 2 | 1 | 2 | 3 | 1 | 2 | 3 |
| 162.0 | 1.012 | 1.085 | 0.941 | 1336 | 1432 | 1242 |
| 131.5 | 1.284 | 1.393 | 1.216 | 1695 | 1839 | 1605 |
| 99.5 | 1.208 | 1.311 | 1.128 | 1595 | 1731 | 1489 |
| 68.5 | 0.873 | 0.908 | 0.784 | 1153 | 1198 | 1035 |
| Goal exposure dose (mJ/cm²) = 1000 |
| Time (seconds) = 1320 |

Measurements obtained via ultraviolet germicidal irradiation meter. The most divergent locations were selected as examples of dose distribution across the FFR. Substantial variation in dose is demonstrated and dependent on distance from bulb, proximity to aluminum flashing, and arced surface of FFR. The irradiance at each position is normalized to position 3A (bold). Additional measurements from other rack locations are demonstrated in Table E1.
physical dose and knowledge of the efficacy of UVC from other studies on coronavirus strains (SARS-CoV1 and Middle Eastern respiratory syndrome coronavirus). Exposure dose should be verified independently to deliver at least 1000 mJ/cm² to all surfaces of the FFR and minimize shadowing. If UVC labels are used, determination of the exposure dose range is recommended through a calibration curve. UVC labels are considered less accurate because the evaluation is based on visual acuity and labels can change in color when exposed to UVA or UVB light. NIST traceable radiometry equipment should be used to accurately measure the exposure dose within the desired UVC spectral range. Substantial dose fall off at the lateral aspects of the FFRs was noted within our system. Therefore, minimum exposure to en face measurements of the light source will not provide adequate dose to FFRs.

Exposure fall off from the light source can be approximated by 1/r² if assumed to be a point source, where r is the distance from the source. If the source of light is spread out, as it is with multiple UV lamps, the exposure fall off will be more gradual than 1/r². Given the geometric complexity of real world light sources, it is essential that exposure be calibrated by measurement rather than calculation. We strongly recommend review of The Ultraviolet Germicidal Irradiation Handbook for further resources on mathematical modeling, safety, and the potential use of UVGI in clinical settings.

An example of a system implemented at a second community hospital is shown in Figure E3, where UVC towers were already in use to sterilize rooms for C. difficile. This system used a circular rack with rotational towers centrally. Dose verification was performed to ensure exposure times were at least 1000 mJ/cm² to the respirators. This system required FFRs to be turned 180° after the first exposure to deliver dose to the anterior and posterior surfaces and to ensure that no part of the elastic strap was outside of the divergence of the UVC light field.

The use of UVC during the pandemic has several limitations. Many FFRs are not compatible with UVC due to their construction and potential shadowing. Evaluation of FFRs from multiple manufacturers could not be completed due to shortages. Viral cultures with SARS-CoV2 could not be directly validated after UVC exposure, and the dose used herein was extrapolated from other studies.

It is imperative that any use of UVC light be completed with a team that has knowledge of its capabilities and limitations, and the input of a medical physicist is strongly recommended.

Conclusions

UVC light has been described as a possible tool for FFR decontamination by the CDC. Many institutions may have UVC lights already in place for C. difficile cleansing of rooms, or they may be available at lighting distributors but will require additional engineering for use during the pandemic.

This article describes the creation, geometry, and dose characterization of a UVC system for FFRs. The total time of UVC exposure was substantially longer once dose fall off of the lateral aspect of the mask was taken into account via the UVGI meter. The use of UV intensity labels did not provide accurate analysis of dose distribution and may lead to false conclusions of symmetrical exposure. The minimum dose used herein was extrapolated from other studies and virucidal effect was not validated. UVC has several limitations in its use due to the susceptibility of shadowing, carcinogenic risk, and possible generation of ozone. Accurate characterization of the spectrum of light and geometry of the UVC system is imperative for success.

Supplementary Materials

Supplementary material for this article can be found at https://doi.org/10.1016/j.adro.2020.100636.

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