Construction and validation of UV-C decontamination cabinets for filtering facepiece respirators: supplemental document

1. Horizontal Cabinet

Construction

The horizontal Cabinet is built on a standard hospital utility cart with locking wheels, allowing for increased mobility of the decontamination station. The cabinet itself, which rests on top of the cart, measures 46cm tall by 61cm wide by 91cm deep (H 18in. X W 24in. X D 36in.). The inside of the cabinet is lined with aluminum foil to increase reflectivity. 12 UVGI lamps are mounted on the interior of the cabinet; six on the ceiling and six on the floor.

The cabinet is powered by a standard 120VAC three-pronged grounded outlet. With each fixture consuming approximately 30W, the total power required to energize all of the lamps comes in at just under 400 W. This design integrated a safety interlock and an automatic shutoff timer once each cycle reached the proper level of exposure. This design lends itself to automated mask transport into and out of it for larger throughput.

In the center of the cabinet, 22cm (8.5 in.) from the lamps, is a horizontal wire mesh tray that the N95 FFRs rest on during their decontamination. The wire mesh was chosen to allow a maximum amount of UV-C exposure on both sides while minimizing interference due to shadowing. Detailed pictures of the cabinet can be seen in Fig. 1. (Fig 1 (and all others) refer to the figures in *Construction and validation of UV-C decontamination cabinets for filtering facepiece respirators*.)

Performance Measurements

The UV-C intensity profile measurements were taken with a thermal power sensor head (PM100D console and S425C power sensor head, Thor labs). The intensity profile measurements were normalized to a level at the center of the cabinet determined by a cosine corrected irradiance power meter (OPHIR model PD300RM-UV) to account for the smaller angular acceptance aperture of the thermal power sensor head. At each location, measurements were taken with the detector up-facing. Stable UV-C irradiance was achieved almost immediately upon activation of the unit. The optical model was found to be in reasonable agreement with the measurements. The lowest irradiance measured, 7.2mW/cm^2, was used as the rate-limiting factor for determining the exposure time needed to reach the minimum acceptable dose of 1J/cm^2.

To assess the degree of shadowing in this cabinet, photochromic UV-C labels were placed in different locations along the surfaces (both interior and exterior) of an N95 FFR (3M 1860S). All labels placed on the mask showed no shadowing except for a nominal area immediately adjacent to where the elastic straps attach to the body of the N95 FFR, Fig. S1. Otherwise, no shadowing was apparent which suggests that there is sufficient fluence across the entire surface of each N95 FFR. The effects of shadowing due to the wire mesh was also determined by placing photochromic UV-C labels directly on the wire mesh, facing the mesh. At a very low-dose test cycle of 0.1 J/cm^2, some shadowing was observed at the points of wire contact. However, after a cycle at the target dose of 1 J/cm^2, no shadowing was detectable. This suggests that the UV-C dose at points of contact with the metal grid is only about 10% lower than at points of non-contact. This result is largely due to the use of both the very fine metal wire, which itself is partially UV-C-reflective, and a wide-area diffuse array of UV-C sources, Fig. S1.

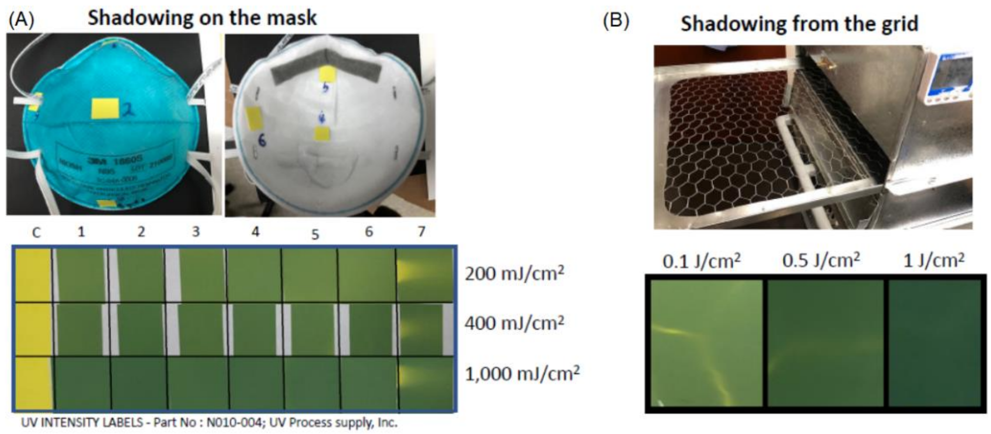

Fig. S1. Photochromic UV-C strips under various levels of exposures that show nominal shadowing (A) directly under the straps and (B) from the wire mesh grid. Notably, the wire mesh shadowing is only detectable at lower exposure levels.

2. Vertical Cabinet

Construction

The Vertical Cabinet uses a standard metal storage cabinet measuring 180cm tall by 90 cm wide by 60 cm deep (H 72 in. X W 36 in. X D 24 in.). The interior of the cabinet is lined with heavy duty household aluminum foil affixed to the cabinet with hot-melt adhesive. 16, 90cm long (35 in.) UVGI lamps (G30T8) are mounted in fixtures (Biolux, 30 W) and arranged in two banks: an upper bank and a lower bank. The spacing between each lamp in the banks is approximately 23 cm. The lamp fixtures position the lamps extended outward approximately 7.5 cm from the front and back surfaces of the metal cabinet. The distance between the lamps and the illumination plane at the center of the metal cabinet is approximately 22.5 cm, roughly equal to the spacing between the lamps.

The upper and lower lamp banks are wired separately and are independently controlled by switches mounted on the outside of the cabinet. The lamps are powered by 120 VAC ballast power supplies. (Biolux fixtures are also available for 220-240 VAC). With each fixture consuming 30W, the total power required to energize all of the lamps is about 500 W. Safety interlocks should be attached to the tops of the doors to de-energize the lamps when the doors are opened, purely for operator safety. A frame was constructed to secureN95 FFRs within the cabinet and ensure that they meet the required levels of exposure on both sides, Fig. 2.

Performance Measurements

The UV-C emission inside the chamber was measured using an irradiance power meter (OPHIR model PD300RM-UV) calibrated at the UV-C emission line of 254 nm. The PD300RM-UV is sensitive to both the UV-C and visible light emitted by the lamps. By filtering out the UV-C light with a standard microscope cover slip (O.D. ~4.0 @ 255 nm) it was determined that 50% of the power measured by the detector is due to UV-C emission. The vertical and horizontal intensity profiles across the chamber are shown in Fig. 6. The intensity is uniform with variation of only ± 10% across the chamber interior when the chamber is empty. The UV-C intensity at the center of the chamber was measured to be approximately 6.0 mW/cm^2. At this fluence level a total exposure of 1 J/cm^2 can be reached in about 180 seconds. The angular dependence of illumination in the empty chamber was also measured and found to be ± 20%. Fig. 6. also contains the results of an optical model of the cabinet design using the ray tracing option in the optical modeling program Zemax OpticStudio® v20.1. The model uses the CAD design file of the cabinet and assumes typical UV-C power outputs of 11.6 W per lamp and aluminum foil total reflectivity of 73%. The optical model is in reasonable agreement with the intensity measurements, replicating the measured vertical and horizontal power intensity variations inside the cabinet. Fig. 6. contains an optical model modified to include 40 N95 FFRs loaded into the chamber. The mask surface is modeled in 3 dimensions and assumes 94% of the incident light is absorbed in the mask, 5% is reflected, and the remaining 1% is diffusely scattered. After factoring in the N95 FFR properties, the ray tracing model predicts that the average intensity in the loaded cabinet reduces from about 7 mW/cm^2 to 6 mW/cm^2, a reduction of 15%.

3. Cylindrical Design

Construction

The cylindrical geometry of this model optimizes normal incidence of light onto the N95 FFR surface, thereby increasing intensity. As the N95 FFRs roughly resemble a section of a spherical surface, the cylindrical geometry tends to match geometrical congruence in a cross-sectional plane while enabling the use of cylindrical light sources. The inherent symmetry of this design enables two-sided exposure by wavefronts reasonably matched to the N95 FFR in a cross-sectional plane. Construction of this chamber is further simplified by the cylindrical geometry with lights placed uniformly around the cylinder perimeter. The inherent cylindrical symmetry also enables simple placement of the N95 FFRs along the cylinder symmetry axis, with irradiance uniformity more or less independent of N95 orientation.

The cylindrical chamber was built out of a simple new cylindrical trash can measuring 51cm in diameter and 69 cm tall (D 20 in. X 27 H in.). The interior of the chamber is lined with heavy duty household aluminum foil affixed to the walls. 8, 25 W lamps are arranged vertically inside the chamber, equally spaced apart along the cylinder wall, and are equidistant from the top and bottom of the container. Being powered by a simple 120V three-prong AC outlet, this device can plug into virtually any wall.

Performance Measurements

The UV-C emission inside the chamber was measured using an irradiance power meter (OPHIR model PD300RM-UV) calibrated at the UV-C emission line of 254 nm. The average irradiance through the chamber is about 10mW/cm^2 with a peak of about 12.5 mW/cm^2 occurring at the center of the chamber. The intensity is lowest at the bottom of the chamber, 6 mW/cm^2. The appropriate decontamination exposure time should be calculated using the lowest measured intensity value. In the cylindrical design the appropriate exposure time would be approximately 3 minutes.

The performance of the cylindrical design was confirmed through detailed Zemax modeling and experimentation. The Zemax modeling uses the same source and detector parameters are used for the other simulations with no additional adjustable parameters to assure comparison of the results. The results of the Zemax simulation are shown in Fig. 7. As can be seen the uniformity of the irradiance in the center of the can is excellent, consistent with the geometry of the experimental setup. All lights radiate towards the center and both sides of the N95 masks receive close to the same irradiance, assuring uniform decontamination of the masks.

4. N95 FFR Properties

Fit Testing

Eight N95 (3M 1860S) respirators were exposed to one, two and five UV-C cycles of 1 J/cm^2 before qualitative fit testing was performed. Fit testing was performed independently per hospital protocol and in accordance with OSHA guidelines. Briefly, a bitter (Bitrex) and a sweet (Saccharin) odor was vaporized into a chamber while the user was using the N95 FFR. The fit test passed when the user could not detect the odor. Three respirators were treated with 1 cycle of 1 J/cm^2, three respirators were treated with 2 cycles of 1 J/cm^2, and two respirators were treated with 5 cycles of 1 J/cm^2. All tested respirators passed the fit test. The sample size of this test was limited due to the current shortage of N95 FFRs. Future investigations should use quantitative fit testing to better measure fit as well as use a significantly larger sample size.

Filtration Testing

Nine N95 FFRs (3M 1860S) were sent out for performance testing to ICS Laboratories, Brunswick, OH. Three N95 FFRs were treated with a single UV-C cycle of 1 J/cm^2, three FFRs were treated with 2 cycles of 1 J/cm^2, and three were treated with 5 cycles of 1 J/cm^2. The N95 FFRs were tested for air flow resistance and penetration of NaCl nanoparticles through the filter material. All nine treated respirators passed these tests with no significant difference to the control FFRs (untreated). The penetration ranged from 0.19 to 1.23 % after 5 treatment cycles, which is comparable to the 0.8 ± 0.2% of the control masks and are within the NIOSH acceptance values of <5% for penetration.

The results for the resistance test for the treated masks were in the range of 9.1-11.3 and well below NIOH acceptance value of <25 mm H_2O for breathing resistance (NIOSH 42 CFR Part 84), Table 2. The sample size of this test was limited by the current shortage of N95 FFRs. Future investigations should use a greater sample size and explore a wider range of dosages to assess possible damage and filter inefficiencies for N95 FFRs exposed to higher dosages.

Strap Elasticity

The elastic straps of N95 FFRs tested for fit and filtration after UV-C exposures as described above were also examined for maintenance of strap elasticity. On gross examination, there was no apparent change in strap elasticity. N95 FFRs were further exposed to 5 and 10 UV-C cycles for a total exposure of 10 J/cm^2 and no apparent change in strap elasticity was noted. Further tests may be needed to quantitatively assess any subtle changes to tensile strength that may not be apparent on gross exam.

Temperature and Humidity Measurements

The temperature over time was monitored inside the horizontal cabinet for the duration of a complete cycle. This was done to ensure that the cabinet does not get too hot as to deform and compromise the N95 FFRs. The external temperature was not found to exceed 34 °C (93.2 °F) and the temperature inside the cabinet hit a plateau at around 47 °C (116.6 °F). Both of these fall well below the documented thresholds where N95 FFRs are found to be structurally compromised from excess heat and humidity [1,2].

Similarly, the temperature and humidity were monitored over time inside the Vertical Cabinet for several on/off cycles of about 5 minutes each. This was done to simulate constant use of the cabinet and ensure that the cabinet does not get too hot as to deform and compromise the N95 FFRs. The temperature was not found to exceed 42 °C (107.6 °F) and the humidity did not exceed 18% rh, Fig 11. Both fall well below the documented thresholds where N95 FFRs are found to be structurally compromised from excess heat and humidity [1,2].

5. Fluence Measurement Techniques

Digital Sensors

Ideally, any power meter being used to determine the total intensity should be NIST-traceable and calibrated to UV-C specifically (~254nm), and be cosine corrected for illumination to account for the large angles incident upon the detector surface. These sensors can be used to both confirm the validity of the optical model as well as ensure that all the N95 masks will receive the required illumination for decontamination.

Photochromic Sensors

Disposable photochromic UV-C dosimeters are commercially available and indicate an UV-C exposure with a visible color change. A few strips available on the market will saturate at around the required dose of 1 J/cm^2. However, these strips require first time verification with a digital sensor. Once a "standard curve" has been created, the strips can be used to verify the fluence along the surface of a few select test masks. Fig S1 shows the color response of a few photochromic sensors after their exposure across varying locations of an N95 FFR.

Unfortunately, the photochromic sensors that saturate at 1J/cm^2 are not widely available. Instead, the strips that are more widely found, especially in healthcare settings, are used to sterilize hard surfaces and saturate at around 0.05mJ/cm^2 to 0.1mJ/cm^2, much lower levels than the required 1J/cm^2 dose. To circumvent this, certain materials can act as an optic filter and be placed on top of the indicator. For cases where the indicator saturates at 0.1 J/cm^2, a filter that reduces transmission by 90%, allowing only 10% of UV-C light to pass through, should be used. This effectively "converts" the 0.1 J/cm^2 indicator to a 1 J/cm^2 indicator. Just as in the case of the 1J/cm^2 sensor, it is best practice to first confirm the exact color that each photochromic sensor saturates at and validate that using an appropriate power meter. It is also important to confirm that the neutral density filter does not change its transmission after repeated exposure due to bleaching, color-center formation, or changes in reflectivity due to the exposure to the high intensity UV-C illumination. Once that is done, the photochromic strips can be used to confirm dosages in the chamber for subsequent cycles, ideally in addition to the digital sensor.

One such filter approach that can be used to attenuate the UV signal is using neutral density mesh filters. In one experiment, photochromic UV-C sensitive strips which normally saturate between 0.5-1 J/cm^2 (Con-Trol-Cure strips #N010-004, UV Process Supply, Chicago IL) were exposed to UV light under different neutral density mesh filters. The results showed that the filters can be used to effectively increase the limit of detection for the photochromic strips to ensure that the unit delivered 1 J/cm^2 to the surface of each N95 FFR, Fig. S2. This simple modification provides an inexpensive method for in situ dosimetry which can be incorporated in each decontamination cycle.

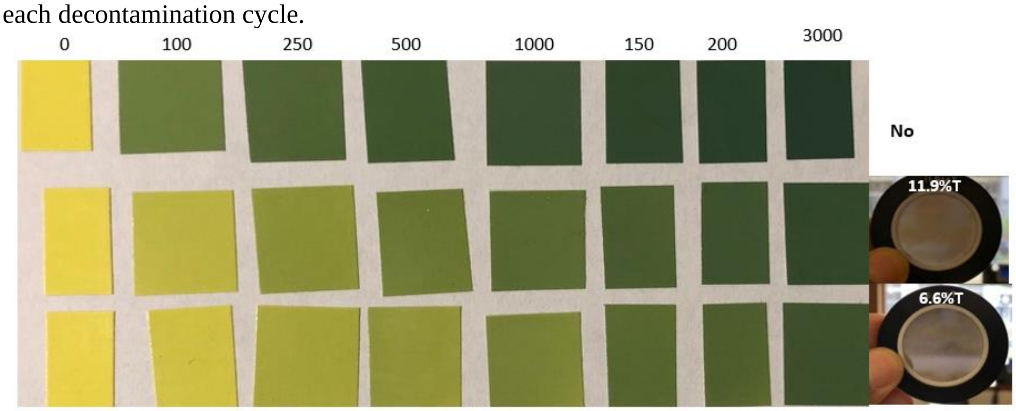

Fig. S2. The results of laying neutral density mesh filters of various transmissions over a few photochromic UV-C strips. This approach effectively increases the detection limit of these test strips from 0.4 to 3 J/cm2.This simple modification allows a cheap in situ dosimetry for the decontamination cycles.

Another approach is the use of simple lens tubes. Figure S3 shows a standard curve of several UV photochromic strips (UV-C Intensity Labels UV104-UV-C, UV Process Supply, Inc., Chicago, IL.) and their color change over time when placed under lens tubes of various heights (Thorlabs SM1L05, SM1L10, SM1L20, and SM1L30). To create this standard curve, a lens tube was placed on top of each strip to attenuate the UV signal. Then, an irradiance power meter (OPHIR model PD300RM-UV) was placed adjacent to the strips to measure the true UV irradiance being emitted. Measurements were taken periodically to show how increasing lens tube height can effectively attenuate the UV light reaching each photochromic strip.

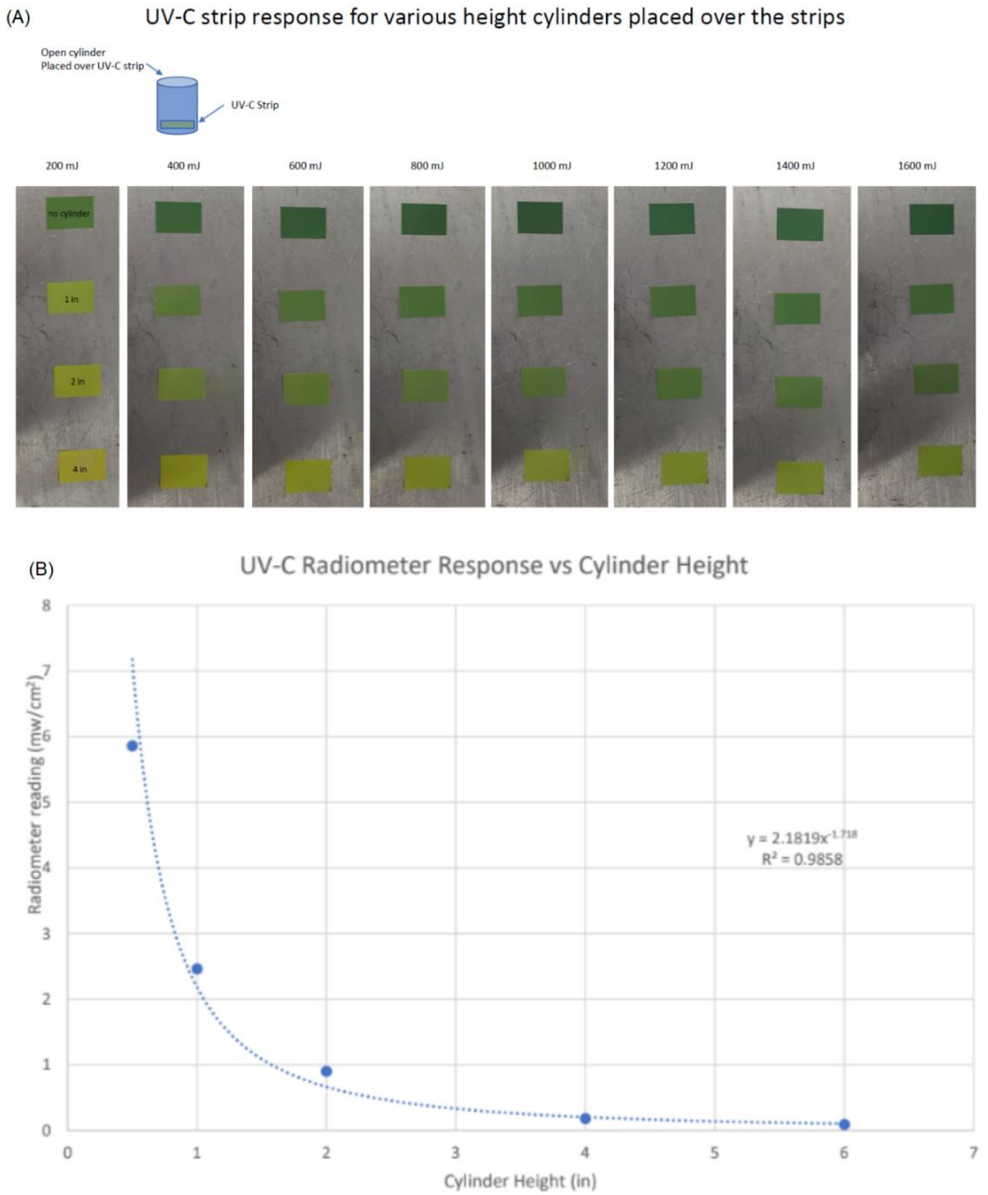

Fig. S3. (A) Photochromic UV-C strips being exposed under lens tubes of various heights. (B) This approach attenuates the UV-C light and creates a standard curve of sort

6. The view factor equation and the derivation of the simplified formula

Step 1: Define the following variables according to **Figure 4**:
L = length of UV source (cm)
D = distance from lamp to point of interest (cm)
R = radius of UV source (cm)

Step 2: Evaluate the following secondary variables according to the primary variables given above:

$$A = \frac{D}{R} \tag{S1}$$

$$B = \frac{L}{R} \tag{S2}$$

$$C = (1 + A)^2 + B^2 \tag{S3}$$

$$D' = (1 - A)^2 + B^2 \tag{S4}$$

$$E = \sqrt{\frac{(A-1)}{(A+1)}} \tag{S5}$$

Step 3: Calculate the fractional radiative irradiance (FRI):

$$FRI = \frac{B}{\pi A}[\frac{1}{B} Atan(\frac{B}{\sqrt{A^2-1}}) - Atan(E) + \frac{C-2A}{\sqrt{CD\prime}} Atan(E\sqrt{\frac{C}{D\prime}})] \tag{S6}$$

Step 4: Calculate the irradiance in units of W/cm^2

$$Irradiance = \frac{UV\ Output * FRI}{2\pi * \mathrm{R} * L} \tag{S7}$$

Step 5: Calculate the exposure time needed to achieve the minimal dose.

$$Exposure\ Time\ Needed = Target\ Dose/Irradiance \tag{S8}$$

In the limits where the cylinder length is much greater than the distance to the illumination point and the diameter of the lamps, the second and third terms in equation S6 cancel out and the first term reduces to the emission expected from an infinitely long cylindrical source. In other words, for all instances where B>20 and A<15, equation S6 can be simplified down to the following within 5% accuracy:

$$FRI = \frac{R}{2 * D} \tag{S9}$$

Equation S9 can then be further combined with equation 7 to yield the following:

$$Irradiance = \frac{UV\ Output}{4\pi * L * D} \tag{S10}$$

References

1. A. Kumar, S. Kasloff, A. Leung, T. Cutts, J. Strong, K. Hills, G. Vazquez-Grande, B. Rush, S. Lother, R. Zarychanski, J. Krishnan, "N95 Mask Decontamination using Standard Hospital Sterilization Technologies," medrXiv: 10.1101/2020.04.05.20049346 (2020).
2. D. Viscusi, W. King, R. Shaffer, "Effect of Decontamination on the Filtration Efficiency of Two Filtering Facepiece Respirator Models," Journal of the Internationl Society for Respiratory Protection., 2007, Vol. 24, pp.93-107.