Determining Exposure Times for UV-C Irradiation of PPE Filtration Facemasks for Sterilization and Potential Reuse in Times of Shortages

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Throughout the country, and around the world, we are facing a pandemic from SARS-COV-2 infections. At the same time, many health professionals, and others who are involved in public safety, are facing a drastic shortage in available Personal Protective Equipment (PPE) such as N95 face masks and surgical masks. In this moment of difficulty, many groups around the country and throughout the world are attempting to find emergency backup measures to extend the life of their PPE. We are involved in one such regional effort. One option being used is irradiating filtration masks with UV-C (254 nm) light for deactivating viral loads for potential reuse (subject to fit and form following irradiation), such as that outlined in a procedure used Nebraska Med [1]. The Nebraska Med procedure looked at two doses at the mask sites: a) total exposure doses of 180 to 240 mJ/cm^2 and b) total exposure doses of 900 to 1200 mJ/cm^2, both (a) and (b) a sum of intensities in each direction. In both cases, the total exposure is the sum of the exposure at the surface of a mask as determined by use of a detector that has a different response to UV light that comes in from varying directions. This response peaks when the light comes in perpendicular to the surface of the detector, and follows a response curve which decreases with increasing angle, not far from a cosine curve. Another group, a consortium of scientists (N95DECON.org) has recently come out with guidelines for mask irradiation by analyzing many sources and recommending a surface exposure of ≥ 1 J/cm^2 [2]. A very detailed study on issues associated with processing masks for reuse was performed in 2019 by Applied Research Associates, with a final report in 2020 [3]. While detailed, all of these are plagued by the question of what a "cumulative exposure dose" is, as the UV detection is not specific to direction or detailed at specific mask locations. Some studies look at light from one direction, and some look at light coming in to the mask surface at a variety of directions, without a breakdown by direction of light. Studies that have light incident on masks from both sides assume the sum of the dose on the front side and the dose on the back side, as measured by a detector that includes light from all angles with different weighting functions, is the "dose" the mask experiences.

The situation is complicated by three competing factors:
a) the light intensity at the surface of the mask can be higher than the detector indicates, but is determined by the angles at which the light actually comes in to the detector,
b) the fact that light coming in at an angle to a mask surface that is transmitted has a longer path length through the mask, and
c) the light coming in at an angle to a mask surface may reflect off a mask layer may vary as a function of that angle.
On the second point we have determined approximate transmission coefficients through a filter layer as a function of angle, but do not have enough information, with appropriate precision on reflection coefficients. So, for example, light coming in at 30 degrees away from the perpendicular to the mask surface would be

measured by the detector as about cos(30º) = 0.866 of the actual intensity, but the path length through the material is longer by a factor of (1/cos(30º)) = 1.155. Our experiments indicate that the transmission for light incident at an angle through the primary filter layers varies by a factor between a $\cos(\theta)$ response and a more minor reduction. The studies in the literature about whole mask exposure to UV-C for reuse do not account for the case where light comes in at an angle, and the general response is to increase exposure times, and therefore exposure doses, in an attempt to blast enough light through to take care of all such problems. This has several effects, one of which is that it becomes difficult to compare studies done on required exposure for any given mask, and another is that it leads to decreases in throughput as well as decreases in useable lifetime, from form and fit perspectives, due to unnecessary overexposure of the mask.

The important piece of information to know is what the UV-C intensity is *inside* the mask at the filter layers where the viral load would accumulate. To determine this, we also need to look at the way light responds to any mask layer. Light comes in at some incident angle to a mask layer and the light beam is subject to the following effects:
a) Some light is reflected backward into an outward hemisphere away from the surface of the layer the incident beam hits,
b) Some light is transmitted through the layer, but exits the layer in a broader cone due to scattering of light (including multiple internal reflections) in the layer, and
c) Some light is absorbed in the layers themselves.
In looking at these effects, the scattering of light into a broader cone is the least important when considering masks bathed in broad beams of light that are incident on all surfaces. We used a broad uniform beam of UV-C light to determine the transmission through any mask or mask layer so that any scattering from a pencil of light, causing some of the light to be directed away from the detector, would be compensated by scattered light from the pencil next to the original one scattering light into the detector. We determined the nature of the reflected light from any layer, which was found to generally be characterized as a diffuse reflection that is peaked in the specular reflection direction, and quantified the amount of light reflected by any layer. Our experiments first looked at the overall transmission through layers as a first step in determining minimum UV-C intensity levels inside a mask, then added in the reflections from the different mask layers in sequence to get a final understanding of the minimum internal intensity levels for a given external intensity.

There are anywhere from 3 to 6 layers in most N95 masks, with some having the filtration parts in the center, and some more toward the exterior. To understand the effect of UV-C light on a mask, we need to understand what is happening inside the mask, and how to determine the UV-C intensity, and cumulative exposure, inside the mask, not just at the surface. Most detailed research on the effect of UV-C on N95 masks uses light that almost exclusively comes in to the mask sections perpendicular to the mask surface. A look at the effect of cumulative exposure dose, as measured by detectors at the surface of masks that have a weighting function with respect to incident angle, but are not tested by controlling the angular part, is shown in Figure 4 of the 2019 Applied Research Associates paper [3], and shows that there is a large variation in log reduction by different masks. As most studies on whole masks use a detector that also does not give information about the direction of the light intensity, issues such as shadowing and mask contour are handled by using reflective walls, ceilings, and sometimes floors, to get light coming in to the masks from a variety of directions, but without much knowledge of how this affects the UV intensity inside the mask. It also makes it difficult to compare studies done on actual masks with the bulk of the research done on mask sections.   It is clear that a better understanding of the response of individual masks needs to look at the construction of the layers, and how a surface dose, controlled for angular incidence of light corresponds to a dose inside the mask, including both the transmission and reflection at the various layers.

When considering any variation on procedures to deactivate viruses in masks using UV-C light, it is necessary to know how long to expose any mask to a given intensity of UV-C light to achieve that result. If the dose is too small, the virus will not be deactivated. If the dose is too large it both slows down the process of getting the masks prepared for reuse and risks making some mask elements too brittle to be reused. While there are almost no published results on what level of UV-C exposure renders SARS-COV-2 inactive at the time of this writing, some in this emergency are seeking any reasonable guide from the levels that work on other viruses, and building in a safety factor. Experience with this method of UV-C sterilization is being tested rapidly around the country and it is likely that information about the intensity of UV-C radiation required to render SARS-COV-2 inactive will soon be available.

This paper describes research at Bowdoin College to determine the transmission through, and reflection off, the various layers in some common N95 masks, updating the research done in 2010 by Fisher and Shaffer [4] where the dose on individual layers was explored. This paper also reports preliminary work on the UV transmission for light that is incident on the mask at angles other than perpendicular.   As a result, combining this information, we determine comparative UV-C doses inside the various masks, correlated with surface intensity measurements, for comparison of various log reductions in viral load.   In addition, the research validates an extremely simple and quick method for determining a safe dose for any mask being considered for a UV-C process to deactivate the virus. Another modification was to use a smaller size detector (0.10 cm^2 compared with 1.5 to 5 cm^2 in previous studies) to assess whether there were any small-scale spatial differences that their approach might have missed by using a large detector. It turns out there were small-scale spatial variations, and some of them vary by up to a factor of at least 5 in some layers. Since these layers combine with other layers with their own small-scale spatial variation in UV transmission, randomly being aligned or not, we used an uncertainty analysis to arrive at the average intensity at any point in the mask with an associated uncertainty. The minimum value of intensity at any point in the mask therefore is the average minus the combined uncertainties in intensity at that point. For application with bidirectional sources (UV sources on either side of the mask) the values of intensity with associated uncertainty for their respective directions is added in the usual way for propagation of uncertainty (See addendum). For this paper, this was only done for light incident on the mask which is perpendicular to the surface of the mask layers. For analyzing the intensity level in any enclosed area, the intensity as a function of angle relative to the local mask surface is used.

Measurement

To measure the UV-C intensity I used Tocon-ABC6 and Tocon-ABC5 UV-C detector and amplifier combinations, as well as an SXL-55 UV radiometer, all from Sglux through Boston Electronics. Due to the position of the detector relative to the surface of the radiometer, I used the SXL-55 to cross-calibrate, as well as to determine the effect of scattering in the primary filtration layers of masks, but most measurements were done with the Tocon devices. While the Tocon-ABC series covers UV-A through UV-C, measurements were checked with both 254 nm filters and the SXL-55 UV-C radiometer. Measurements of the reflection were done by locating the small Tocon-ABC5 detector at various positions in the backward hemisphere. Doing this latter set of measurements in a precise way is extremely time-consuming, and for the purposes of this initial paper we get estimates that have an uncertainty of about 15%, but this uncertainty is often smaller than the spatial variations. Precise measurements will be published in a later paper, but this level of uncertainty pales in comparison to the small-scale (3.6 mm diameter spot size) variations in the response of the mask fabrics themselves. The Tocon-ABC6 is capable of measuring a factor of 10,000 in intensity, from 1.8 mW/cm^2 down to 180 nW/cm^2 and the Tocon-ABC5 measures intensities from 0.18 mW/cm^2 down to 18 nW/cm^2. The voltage output is directly proportional to the light intensity measured. The detectors have an integral thin piece of Teflon (PTFE) to diffuse the UV light that comes through the detector's aperture. The detector's aperture is 0.10 cm^2. The UV-C source used was a low pressure mercury lamp. The SXL-55 radiometer has a PTFE diffuser as well, a larger detector size, and a minimum measurable intensity level of about 2 μW/cm^2, with the surface of the PTFE diffuser 2mm below the overall surface of the detector, which was used to compare results with the Tocon detectors.

The measurement setup for measuring transmission values had a 2.5 mm slit place in front of the low pressure Hg source, with the detector place at 50 to 55 mm from the slit. The mask sections were placed between the source and the detector, directly over the detector. In addition, the entire undisturbed mask was placed between the source and the detector to measure the total transmission of the mask as a whole. The output of the Tocon detectors was measured on a 6-digit precision multimeter for 2 conditions without a mask present and one condition with the mask in place: a) The dark output voltage, V_{out}^{dark}, from the detector in the absence of any UV light, b) the output voltage from the detector with the UV light on and no mask present, $V_{o,surface}$, for the layer in question, and c) the output voltage from the detector with the mask layers, or entire mask, moved around between the source and detector to find the "average" transmission value, $V_{out,ave}$, and the spatial variation giving the range δV_{out} for the element being measured. This range is not strictly speaking an uncertainty. Many layers had occasional outliers at specific points in that layer's material, but since we are not interested in the average statistical properties of a layer, but rather the absolute minimum transmission, we defined the "average" as halfway between the minimum value measured and the maximum value measured, even if it was not representative of most of the mask layer. The range δV_{out} is therefore defined relative to the "average" so that it accurately portrays the minimum value when subtracted from the average. The output voltages are then used to find the transmitted fraction of UV light intensity using the following equation:

$$F_{Tn} = F_{\substack{ave,fraction \\ transmitted}} = \frac{V_{out,ave} - V_{out}^{dark}}{V_{o,surface}} . \qquad \text{Eqn. 1}$$

The Tocon detectors can be replaced by any calibrated detector, and the 6 digit multimeter can be replaced by any multimeter that measures up to 5 volts and can measure as small as 0.1 millivolts, but the size of the detector matters if spatial variation is of interest. The SXL-55 radiometer gives direct readings of intensity levels, and has a calibrated response. Layer 1 is the outside layer, with subsequent layers proceding toward the inside layer next to the wearer's face. The fraction of transmitted intensity across the nth layer is just F_{Tn}, which is the same in either direction at the spot checked. When calculating UV-C intensity at any point for a situation with bi-directional sources, the intensity at any point, such as "c" (I_C), after passing through the 3rd layer (using the convention established by Fisher and Shaffer [3]) is then labelled with either an L or an R for light coming from a specific direction, and proceeding in one direction. The total intensity inside the mask at point c is higher than the sum of I_{CL} and I_{CR} due to the internal reflections. The uncertainties for the two directions, due to spatial variations, are combined in the usual way (see addendum). Thus the total intensity for equal bidirectional sources, in the absence of reflections from the various layers, for a mask with 5 layers is

$$I_{C,Total} = I_{CL} + I_{CR} = I_{o,surface}\{(F_{T1} \cdot F_{T2} \cdot F_{T3}) + (F_{T5} \cdot F_{T4})\}. \qquad \text{Eqn. 2}$$

When internal reflections are included, where R_i is the reflected fraction off of the i^{th} layer, the light intensity progressing in one direction from the L side at point C is

$$I_{CL} = I_{o,surface}\{F_{T1}(1 + R_2R_1 + R_2^2R_1^2 + \cdots)F_{T2}(1 + R_3R_2 + \cdots)F_{T3}(1 + R_4R_3 + \cdots)\}. \qquad \text{Eqn. 3}$$

If reflection values and transmission values are high enough, the calculation may have to be iterated to include reflections going in the other direction, and transmit through to the prior layer before reflecting back. When finding the absolute total level of intensity in between layers, the intensity in both directions is included, so the total intensity level at point B for light that was incident on the L side is

$$I_{BL,tot} = I_{o,surface}\{F_{T1}(1 + R_2R_1 + R_2^2R_1^2 + \cdots)F_{T2}(1 + R_2 + R_2R_1 + R_2^2R_1 + R_2^2R_1^2 + \cdots)\}. \qquad \text{Eqn. 4}$$

The total intensity from bidirectional sources at point C is just $I_{C,tot} = I_{CL,tot} + I_{CR,tot}$.

Below are tables for four masks, the 3M 1860, 3M 1870, 3M 1870+, and the O&M Halyard Fluidshield 46727 (level 3), showing transmitted fractions for each layer as an average value and spatial variation range, as well as transmission for the entire undisturbed mask from one direction and calculated values from the above equations for the various quantities. The 3M 1870+ facemask has a different construction on the different parts of the mask (top, center, bottom) and is shown for the two least transmissible sections. (Note well: the "uncertainties" are not an uncertainty in measured values, but an uncertainty in the value due to spatial variations. Some masks have parts with large spatial variations.)

Table 1.
Raw transmitted fractions for each layer, and whole mask transmitted fraction. The experimental setup for this did not have to correct for scattering, as any light scattered out away from the detector was compensated for by an equal amount of light scattering into the detector, using a wider homogeneous beam of UV light. The range in values for each entry is a spatial difference, not a measurement uncertainty. Some of the fabric layers have wide ranges in transmission.

Mask	F_{T1}	F_{T2}	F_{T3}	F_{T4}	F_{T5}	$F_{whole\ mask}$ Measured
3M 1860 (4 layers)	.12 ± 0.02	.27 ± .04	.28 ± .04	.0062 ± .0043	NA	4.3 E-5 ± 2.6 E-5
3M 1870	.24 ± .07	.61 ± .11	.31 ± .10	.31 ± .08	.65 ± .07	.014 ± .007
3M 1870+ center section	.39 ± .06	.52 ± .08	.025 ± .011	.61 ± .06	NA	.0023 ± .0010
3M 1870+ bottom section	.33 ± .10	.11[(a)] ± .06	.081[(a)] ± .038	.60 ± .07	NA	.0021 ± .0013
O&M Halyard Fluidshield[(b)] 46727 (level 3)	.58 ± .16	.18[(c)] ± .03	.88 ± .03	.35 ± .21	NA	.027 ± .013

(a) These are two tightly compressed layers, pulling these layers apart gives a better sense of the minimum possible intensity inside the mask, and when combined with reflection coefficients yield the same combined effect of having them together.
(b) there is a “white side” and a “pink side” to the outer layer, and while they have slightly different transmitted fractions the layer is dominated by the spatial variations, and here an average of the two is used, resulting in slightly larger spatial variation, but for purposes of this paper it is not that important as this mask has such a short exposure time (see below) it is easy to expose it a bit longer to handle any differences between the two parts.
(c) this “layer” is actually 3 tightly compressed layers, but the transmitted fraction was not particularly low, so this collective value for the 3 layers was used.

To measure the reflection coefficients, a 1.0 mm diameter hole was placed at a distance of 30 mm from the 2.5 mm slit over the Hg source. The Tocon-ABC5 detector was placed to the side of the 1 mm hole, centers separated by 7.2 mm, but further forward by 3 mm. The Tocon-ABC5 was in one of two orientations, either oriented parallel to the light beam emanating from the 1mm hole, or at 10 degrees toward the beam. The mask layer being investigated was placed at 10mm from the 1mm hole, at various orientations relative to the incoming beam, with a spot size at the layer of about 2 mm in diameter. The distance from the spot on the layer to the detector was about 10 mm, and readings were corrected for the angular response of the detector. The spatial area being sampled by the incoming beam incident on the layer was about 0.03 cm^2. The reflection was diffuse, but peaked in the specular direction. The readings at various angles allowed us to determine the approximate total amount of light reflected in the backward hemisphere. The coefficients for the total amount of reflected light are shown in Table 2 below.

Table 2. The total reflected fraction of the incoming light incident on a mask layer. The uncertainties are a combination of the spatial variations and uncertainties in the measurements, but in most cases are dominated by the spatial variations.

Mask	Reflected fraction, Layer 1	Reflected fraction, Layer 2	Reflected fraction, Layer 3	Reflected fraction, Layer 4	Reflected fraction, Layer 5
3M 1860 (4 layers)	.02 ± .01	.45 ± .15	.45 ± .15	< .01	NA
3M 1870	.01 ± .01	.1 ± .03	.45 ± .15	.45 ± .15	.1 ± .03
3M 1870+ middle section	.03 ± .01	.02 ± .01	.15 ± .05	.15 ± .04	NA
3M 1870+ bottom section	.02 ± .01	.35 ± .1	.35 ± .1	.15 ± .05	NA
O&M Halyard Fluidshield 46727 (level 3)	.02± .01	.55 ± .18	< .01	< .01	NA

The above reflection coefficients were combined with the transmission coefficients from Table 1, and substituted into Equation 3 to determine the unidirectional transmitted fraction after each layer, for a beam going from the outside of the mask toward the face inside. These transmitted fractions are summarized below in Table 3.

Table 3.

Calculated transmitted fractions for each layer, with light heading from the outermost layer to the innermost layer (from the L side), including multiple reflections from primary filter layers, showing cumulative fraction heading in the transmitted direction. All notes in Table 1 apply here.

Mask	Transmitted F after layer 1	Transmitted F after layer 2	Transmitted F after layer 3	Transmitted F after layer 4	Transmitted F after layer 5	$F_{\text{whole mask}}$ Measured
3M 1860 (4 layers)	.12 ± .02	.041 ± .009	.0114 ± .003	7.0 E-5 ± 5.2 E-5	NA	4.3 E-5 ± 2.6 E-5
3M 1870	.24 ± .07	.15 ± .05	.075 ± .034	.025 ± .013	.012 ± .006	.014 ± .007
3M 1870+ middle section	.39 ± .06	.21 ± .05	.0054 ± .0027	.0033 ± .0017	NA	.0036 ± .0006
3M 1870+ bottom section	.33 ± .10	.040 ± .025	.0035 ± .0027	.0021 ± .016	NA	.0021 ± .0013
O&M Halyard Fluidshield	.59 ± .16	.105 ± .033	.093 ± .029	.032 ± .021	NA	.027 ± .013

The first thing to note is that the transmitted fraction after the last layer correlates well with that measured through the whole mask, which is excellent support that we have calculated and measured things correctly. It should be expected that we would not get exact agreement between the calculations and the actual measurements as there is a random alignment of regions of high or low transmission or reflection in the actual mask and the calculated values tell us what range we can normally expect. All the values and associated spatial "uncertainties" have significant overlap, validating the procedures. Next it is worth noting the very wide range in the overall transmitted fraction between masks. The minimum fraction transmitted varies by about a factor of 1000. It is clear that the internal intensities at the filter layers are exposed to very different levels of UV-C intensity, and we should expect a very different value of exposure times to deactivate a viral load between the different masks.

Determination of Exposure Times for Deactivation of Virus

The calculation of the minimum UV light intensity inside the mask from the transmitted light intensity through the various layers, from bidirectional sources, is what is needed to determine exposure times for any particular incident light intensity from the two UV sources. This minimum intensity will occur at the filtration layers, as in the 2010 paper [4]. It is clear from our measurements that the exposure times for the 3M 1870+ mask are going to be dominated by the middle and bottom sections, so only those parts are shown below. The longest exposure for either of those parts should determine the exposure for the entire 1870+ mask. The cumulative dose for the exposure times necessary to reach 7 mJ/cm^2 are shown in Table 4 along with the minimum internal exposure dose when subjected to a surface dose of 500 mJ/cm^2 on both sides of the mask. These results do not include any geometrical corrections for the shapes of the masks, which are discussed in the next section. As I show in the final section, there is a simple and quick way to determine this minimum intensity inside the mask, and it is validated as an absolute minimum by the calculations of Equation (2) using the data from Table 1, and it is very close for some masks. As Table 4 shows there are variations of almost a factor of 30 in the minimum internal intensity for bidirectional sources of the same intensity. While detailed measurements have not been performed on other masks, it is clear that the minimum internal intensity roughly correlates with the total transmission through the entire mask. We have found that he North 7130 is similar to the 3M 1860 in the overall low transmission, whereas the Moldex 2212G, the Kimberley Clark 46767, and the 3M 9210 are similar to the other higher transmission models measured above. Note that because an uncertainty analysis is used to propagate the effects of the spatial variations, the values quoted as "uncertainties" in Table 4 (the " +/- " values) have a meaning closer to the usual meaning of uncertainties, with the Table 4 values representing what we might get for 68% of the comparisons between different regions of the mask in question.

Table 4
Exposure times and internal intensity with light intensity that is incident perpendicular to the surface of the mask, including all internal reflections, for bidirectional sources. The cumulative dose (the product of intensity and elapsed time = cumulative dose) can be adjusted based on future known values of the known cumulative dose necessary to deactivate SARS-COV-2, when properly accounting for the transmission through the mask. The value of 7 mJ/cm^2 minimum internal dose chosen is near an inflection point in the dose-reduction curve, and is near a 2.3 log reduction (99.5%), and represents a level 40% above what is required on a flat surface to deactivate a viral load.

Mask: Maker, Model #	Minimum value of $\Sigma F_{\substack{fraction \\ transmitted}}$ (Minimum sum between layers of both directions, max value = 2)	Min. Intensity Inside mask per 100µW/cm^2 at each exterior surface for light perpendicular to mask surface	Exposure time to reach 7 mJ/cm^2 min internal intensity with 500µW/cm^2 at each mask surface for light perpendicular to surface (a)	Minimum internal dose when exposed to 500 mJ/cm^2 at each mask surface for light perpendicular to the mask surface, i.e. "total dose" of 1J/cm^2
3M, 1860	0.021 ± .007	2.1 µW/cm^2 ± 0.7 µW/cm^2	Average: 11 minutes, 7 sec. (334 mJ/cm^2 ea. surf.) Minimum: 16 minutes, 40 sec (500 mJ/cm^2 ea. surf.)	10.5 mJ/cm^2 ± 3.5 mJ/cm^2 minimum internal dose
3M, 1870	0.32 ± .06	32 µW/cm^2 ± 6 µW/cm^2	Average: 44 seconds (22 mJ/cm^2 ea. surf.) Minimum: 54 seconds (27 mJ/cm^2 ea. surf.)	160 mJ/cm^2 ± 30 mJ/cm^2 minimum internal dose
3M, 1870+ middle section	0.26 ± .05	26 µW/cm^2 ± 5 µW/cm^2	Average: 54 seconds (27 mJ/cm^2 ea. surf.) Minimum: 1 min 7 sec (33.3 mJ/cm^2 ea. surf.)	130 mJ/cm^2 ± 25 mJ/cm^2 minimum internal dose
3M, 1870+ bottom section	0.13 ± .04	13 µW/cm^2 ave. ± 4 µW/cm^2	Average: 1 min. 48 sec. (54 mJ/cm^2 ea. surf.) Minimum: 2 min 36 sec 78 mJ/cm^2 dose)	65 mJ/cm^2 ± 20 mJ/cm^2 minimum internal dose
O&M Halyard Fluidshield 46727 (level 3)	0.58 ± .19	58 µW/cm^2 ± 19 µW/cm^2	Average: 24 seconds (12.0 mJ/cm^2 ea. surf.) Minimum: 36 seconds (18.0 mJ/cm^2 ea. surf.)	290 mJ/cm^2 ± 95 mJ/cm^2 minimum internal dose

(a) For practical application for a real process, the effect of the mask shape must be taken into account, as well as the variation with light intensity as a function of direction in any region where masks are exposed to UV light.

One of the most interesting things to note in Table 4 is the large variation in minimum internal UV-C exposure when exposed to a cumulative external surface "dose" of 1 J/cm^2. This is the most likely reason for the nearly full factor of 10 variation in reduction of viral load measured for a the variety of masks measured for Figure 4 of the Applied Research Associates paper [3] for a total dose of 0.5 J/cm^2 (half the dose of column 5 in our Table 4). To get a sense of how important bidirectional sources are, we looked at a comparison of the 3M 1870 in reference [3] with our results. Using the results in Table 1 above for transmission through the mask in one direction (exterior to interior) gives a minimum internal dose in the filter layers, layers 3 and 4, of about 7.6 mJ/cm^2 when subjected to a "dose" of 1 J/cm^2 at the surface from one direction. This is very similar to what is found inside the 3M 1860 mask for the same "dose". However, for bidirectional sources the minimum internal dose is very different, over 20 times higher. These results indicate it is highly likely that correctly quantifying the minimum internal dose will lead to very different necessary times for deactivation of viruses when exposed to some bidirectional sources of UV-C. The 1 J/cm^2 "dose" is likely overkill for many PPE masks, slowing throughput and decreasing reuse lifetime, depending on the setup used to deactivate viral loads in these masks.

UV-C exposure of masks in enclosed spaces designed for deactivation of viruses

One of the large unknowns in a room designed to subject masks to UV-C light is what the distribution of light intensity is as a function of angle coming in to the masks, and coming in to the detector. The Nebraska Med setup [1] has highly UV-reflective paint, and light coming in at a variety of angles to the masks, in an attempt to minimize effects due to shadowing, mask construction, etc. Our local group has constructed a room that has reflections from the metal walls, ceilings and floor. PPE masks with molded construction like the 3M 1860 have the sides typically at an angle of 50º to 60º relative to the front center of the mask. PPE masks with one or two folds, such as the Halyard Fluidshield or the 3M 1870, typically have sides that are at angles between 60 and 75 degrees relative to the front center of the mask, depending on use patterns and the way they are hung for UV irradiation. In our irradiation room, we have measured the intensity coming in at a variety of angles. This is not simply a result of orienting the detector at different angles. We outfitted our detector with a cone that restricts light within a cone of 15º with respect to the direction the detector is pointed. For simplicity, we will separate the incident light into the following approximate components: a) perpendicular to the surface of the mask (usually toward the center of the mask), distributed over ± 15º to the left and right, having intensity I_{perp}, b) light between 15º and 50º that is 30% of the perpendicular light intensity, distributed over that angular range, on either left or right side, and c) 15% of the perpendicular light intensity between angles of 50º and 75º distributed over that angular range. In our room, masks were hung in areas that matched these approximations. For a reasonable estimate, and simple model, we will use a response as a function of angle relative to the mask surface that is proportional to the cosine of the angle. Light with perpendicular intensity I_{perp} hitting the mask center has an effective intensity of approximately $I_{perp}[1 + (0.3)\cos(\theta_{ave} \approx 30^o) + (0.15)\cos(\theta_{ave} \approx 60^o)] = 1.33(I_{perp})$. Light hitting the sidewall of a 3M 1860 has an effective intensity of approximately $I_{perp}[\cos(\theta_{ave} \approx 55^o) + (0.3)\cos(\theta_{ave} \approx 20^o) + (0.15)\cos(\theta_{ave} \approx 22^o)] = 1.00(I_{perp})$. Light hitting the sidewall of a 3M 1870 or Halyard Fluidshield has an effective intensity of approximately $I_{perp}[\cos(\theta_{ave} \approx 67^o) + (0.3)\cos(\theta_{ave} \approx 37^o) + (0.15)\cos(\theta_{ave} \approx 5^o)] = I_{perp}(1.34)$. A detector also gives a measurement of $1.36(I_{perp}) = I_{meas}$. Thus putting this in terms of I_{meas}, we have for the intensity straight ahead, $I_{0deg} = I_{meas}$, the intensity hitting a sidewall of a 3M 1860 would be $I_{1860side} = .75\ I_{meas}$, and the intensity hitting the sidewall of a 3M 1870 or Halyard Fluidshield would be $1.01\ I_{meas}$. As you can see, depending on the distribution of light from multiple reflections of the source, the results can be counterintuitive, and requiring measurement to determine. This was a simple model, and the reality can be more complex, but dividing the hemisphere of light coming in to a mask location into 15 to 20 degree cones can make it easy to determine the minimum intensity hitting a mask relative to what is measured at the detector.

Without multiple reflections off the walls, ceiling, and for some rooms the floor as well, and with bidirectional UV-C light only coming straight ahead toward the center of the mask, the transmission of the light through the sidewalls of a Halyard Fluidshield or 3M 1870 would result in a dose at those locations that is ½ of what it is at the center. This would require slightly more than doubling the dose over what is measured by detectors at the center position of those masks, and listed in Table 2, whereas the 3M 1860 would require slightly less than double the dose. A room with high reflectivity from all surfaces could end up needing no more of a dose than what is measured by the detector, depending on the angular distribution of light intensity.

In the previous studies of appropriate doses to render viruses inactive, the effect of transmission through individual mask types, and the effect of the angular distribution of light at the mask is not monitored, giving an unnecessarily high value of cumulative UV-C dose for virus eradication, as it often comes down to a worst-mask scenario. For the masks listed in Table 1 (except the 3M 1860) and any mask with a whole mask transmitted fraction greater than .003, all are likely to have at least a 4 log reduction in virus load with bidirectional sources of UV-C intensity in a room with reflective surfaces where the cumulative dose as measured by a detector at the mask locations is a total of 500 mJ/cm^2 or less (250 mJ/cm^2 for each direction at the surface of the mask). As this is an estimate, it has at least a factor of two safety margin over the expected total dose necessary. A mask like the 3M 1860 would need a cumulative dose as measured by a detector estimated around 1.3 J/cm^2. Masks irradiated with light that is only coming directly from the two sources, with no reflective walls, ceiling, or floor would require twice that amount, except for the 3M 1860 as the minimum intensity inside that mask is dominated by light from one direction. For this latter case that would be a total dose of 1.0 J/cm^2 for most masks, and 1.3 J/cm^2 for the 3M 1860. As one of the main problems for reuse after deactivation is the effect of large doses on form and fit, these guidelines coupled with a well-designed reflective room should extend the reuse life of most masks by a factor between 2 and 15. Future research keeping track of the light intensity at different angular ranges will be able to much more precisely track the necessary exposure for each type of mask. We have embarked on studies with different masks and known viral loads from other viruses, and will report results in a future paper.

<u>A quick method for determining absolute minimum times for a deactivation process with mask</u>

Any point between the outer surface of the mask and the inner surface of the mask (along a line following the incident light path for light perpendicular to a mask surface) divides the mask section into two parts, one on the inner side and one on the outer side. This point doesn't have to be between layers. For two equal intensity light beams from either direction (bidirectional light), and no internal reflections (just transmission and absorption), the total intensity at this point is just the 2-layer version of Eqn. 2, namely

$$I_{\substack{total\\between\\2\,parts}} = I_{\substack{transmitted\\through\\outer\,part,\\left\,source}} + I_{\substack{transmitted\\through\\inner\,part,\\right\,source}} , \qquad \text{Eqn. 5}$$

and this is just the same as

$$I_{\substack{total\\between\\2\,parts}} = I_{o,source}\left[F_{\substack{T,Left\\part}} + F_{\substack{T,Right\\part}}\right]. \qquad \text{Eqn. 6}$$

But we also have $T_{\text{Left part}} \cdot T_{\text{Right part}} = T_{\text{whole mask}}$, so we can rewrite Eqn. 6 as

$$I_{\substack{total\\between\\2\,parts}} = I_{o,source}\left[F_{\substack{T,Left\\part}} + \frac{F_{T,whole\,mask}}{F_{T,Left\,part}}\right] \qquad \text{Eqn. 7}$$

This simple equation (Eqn. 7) has an absolute minimum, and taking the derivative with respect to $F_{\substack{T,Left\\part}}$ and setting it to zero, we find that the absolute minimum value of $F_{\substack{T,Left\\part}}$, F_{Tmin} , is just $\sqrt{F_{T,whole\,mask}}$.

Thus, we have

$$I_{min,internal} = \left(I_{o,surface}\right)\sqrt{F_{min}} \ . \qquad \text{Eqn. 8}$$

This can be used to find the absolute minimum value for any mask with just one measurement of the UV-C transmission through the entire mask. It is quick and gives an absolute guide to irradiating the mask so that the resulting minimum value of intensity, and minimum internal dose has to be enough to deactivate the virus, given a benchmark value for that dose.

Since the 2010 study, there has been a proliferation of facemasks by a variety of makers, and no simple *and quick* way to determine the minimum transmitted intensities inside a mask. This measurement of transmitted fraction through the entire mask is done from either side, and as the detector size is small, many different parts of the mask can be sampled to get the smallest percentage of transmitted light throughout the mask in one direction. This single number for any mask is all that is needed to be able to calculate the minimum possible UV-C intensity, and therefore dose, at any point inside any mask. Table 5 below lists the minimum internal transmitted fraction for bidirectional intensities of light for each mask, with associated uncertainty, and compares with the values from the quick method outlined above.

Table 5.
Comparison between minimum fraction of transmitted UV-C light and the quick method for determining the minimum value inside the mask at any point.

Mask: Maker, Model #	Minimum value of $\Sigma F_{\substack{fraction \\ transmitted}}$ (Minimum sum between layers bidirectional sources, including reflections, max value = 2)	Value of the minimum transmitted fraction for equal intensity bidirectional sources at any point in the mask, using $\sqrt{F_{T,whole\ mask}}$
3M, 1860	0.021 ± .007	0.0065 ± .0020
3M, 1870	0.32 ± .06	0.118 ± .030
3M, 1870+ middle	0.26 ± .05	0.060 ±.005
3M, 1870+ bottom	0.13 ± .04	0.046 ± .014
O&M Halyard Fluidshield .46727 (level 3)	0.45 ± .21	0.16 ± .04

As shown in Table 5, the absolute minimum transmitted fraction inside a mask (or mask section) compared to that calculated by the quick method is generally between 2.5 and 4.5 times larger than the quick method. Most of that excess ratio is due to the multiple internal reflections. Using the quick method would guarantee that any mask is exposed to sufficient UV-C to deactivate the viral load, as it is an absolute minimum.

In conclusion, the transmission of UV-C through the various layers, combined with the reflections off those layers, determines the internal intensities inside the mask and predicts the overall transmission through a mask. The mask layers are found to have large spatial variations on the scale of 0.1 cm^2. The minimum internal intensities serve as a guide to how much exposure to UV-C light is needed to deactivate a viral load. Understanding how this will be realized in any specific enclosed space used to deactivate a potential viral load in complete masks requires an understanding of the directional nature of the UV-C light in that enclosed space. Determining the directional nature is not as simple as reorienting the detector. And finally, there is a quick method to determine the absolute minimum intensity inside the mask from a single non-destructive measurement of transmission through a complete mask, giving safe guidelines for exposure to any mask where detailed measurements are not available.

Addendum

Uncertainty analysis and comparison of the quick method for determining times for exposure to UV-C light on any N95 mask, or surgical mask.

Uncertainty Analysis for those unfamiliar with it

Consider quantities x, y, … w which are measured quantities, each with uncertainties δx, δy, … δw. For our purposes these might be the UV transmission values of a particular layer and the associated spatial variation. We may use these measured quantities to calculate any quantity q, which is a function of x, y, …w, i.e. q = f(x, y, … w). If the uncertainties in x, y, …w are known to be independent and random (as they are in the layers of material in a mask), then the uncertainty in q is given by:

$$\delta q = \left[\left(\frac{\partial q}{\partial x}\,\delta x\right)^2 + \ldots + \left(\frac{\partial q}{\partial w}\,\delta w\right)^2\right]^{1/2} \qquad \text{Eqn. A1}$$

References:

[1] **N95 Filtering Facepiece Respirator Ultraviolet Germicidal Irradiation (UVGI) Process for Decontam ination and Reuse**, John J Lowe et al., Nebraska Med 2020, https://www.nebraskamed.com/sites/default/files/documents/covid-19/n-95-decon-process.pdf

[2] Visit N95DECON.org, see April 1, 2020 and April 5, 2020 publications

[3] https://www.ara.com/sites/default/files/MitigateShortageofRespiratoryProtectionDevices_3.pdf

[4] **A method to determine the available UV-C dose for the decontamination of filtering facepiece respirators,** E. M. Fisher and R. E. Shaffer, Journal of Applied Microbiology, Volume 110, Issue 1, January 2011, Pages 287-295. (available at https://sfamjournals.onlinelibrary.wiley.com/doi/full/10.1111/j.1365-2672.2010.04881.x)