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. I am involved in one such regional effort. One option being considered is irradiating filtration masks with UV-C (254 nm) light for sterilization and potential reuse (subject to fit and form following irradiation), such as that outlined in a procedure used Nebraska Med [1], where they looked at two doses at the mask sites: a) total exposure doses of 180 to 240 mJ/cm² and b) total exposure doses of 900 to 1200 mJ/cm², 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, peaking when the light comes in perpendicular to the surface of the detector, and following 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 $\geq 1$ J/cm² [2]. A very detailed study on issues associated with processing masks for reuse was performed in 2019 by Applied Research Associates [3]. While detailed, this latter study is also 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 two 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, and b) the fact that light coming in at an angle to a mask surface has a longer path length through the mask. On this latter point there has not been enough time to indicate whether the transmission through a filter layer follows any particular functional form. So, for example, light coming in at 30 degrees to the mask surface would be measured by the detector as about $\cos(30^\circ) = 0.866$ of the actual intensity, which is 1.155 greater than measured by the detector, but the path length through the material is longer by a factor of $(1/\cos(30^\circ)) = 1.155$. Whether this cancels out in the case of a linear response, is dominated by an exponential decay with distance, or has some
other functional form is not known at present. 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 usable lifetime, from form and fit perspectives, due to unnecessary overexposure of the mask.

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. 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. 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.

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. 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 transmission through the mask as the “total exposure dose” is determined by a detector that does not give that information. It also makes it difficult to compare studies done on actual masks with the bulk of the research done on mask sections. One of the most important pieces of information for those considering any variation on UV-C procedures to deactivate viruses in masks is how long to expose any mask to a given intensity of UV-C light. 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 large 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 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. In addition this paper reports preliminary work on the UV transmission for light that is incident on the mask at angles other than perpendicular. As a result, we determine approximate UV-C doses for the various masks, for various log reductions in viral load. While a 4 log reduction (99.99% deactivated) is an important threshold, in emergency situations there may be times when a need to match a throughput in deactivation, given a particular UV setup, with available supply and may force those using this to consider trade-offs not normally tolerable, as the alternative can be just not having any N95 mask available at all. 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.
The process used by Fisher and Shaffer [4] was modified in this research to measure the UV-C transmission through the various layers of any specific mask. In that previous work the authors looked at the “cumulative dose” absorbed by a layer which included the UV light absorbed by the layer itself. In this study we look only at the transmitted light intensity which gives a better sense of what surface intensity is necessary to deactivate a virus load. Another modification was to use a smaller size detector (0.32 cm$^2$ compared with 5 cm$^2$ in their study) 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.

**Measurement**

To measure the UV-C intensity I used Tocon-ABC6 and Tocon-ABC5 UV-C detector and amplifier combinations from Sglux through Boston Electronics. 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 0.32 cm$^2$. The UV-C source used was a low pressure mercury lamp. 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. Other measurements indicated there is some scattering of UV light by the facemasks, so to minimize this the surface of the mask being measured is right on top of the detector. The output 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 uncertainty $\delta V_{out}$ for the element being measured. The output voltages are then used to find the transmitted fraction of UV light intensity using the following equation:

$$F_{Tn} = F_{ave,fraction \ transmitted} = \frac{V_{out,ave} - V_{out}^{dark}}{V_{o,surface}}.$$  \hspace{1cm} 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. Layer 1 is the outside layer, with subsequent layers proceeding 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” (IC), 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. The intensity inside the mask at point c is the sum of ICL and ICR. The uncertainties for the two directions are combined in the usual way (see addendum). Thus the total intensity for equal bidirectional sources for a mask with 5 layers is

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

Below are tables for four masks the 3M 1860, 3M 1870, 3M 1870+, and the O&M Halyard Fluidshield (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 and calculated values from the product of all layer F values. The 3M 1870+ facemask has a different construction on the different parts of the mask and is broken apart to note the data for each section. (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.
Transmitted fractions for each layer, and cumulative transmitted fraction.

<table>
<thead>
<tr>
<th>Mask</th>
<th>( F_{T1} )</th>
<th>( F_{T2} )</th>
<th>( F_{T3} )</th>
<th>( F_{T4} )</th>
<th>( F_{T5} )</th>
<th>( \prod_{i=1}^{n} F_{Ti} )</th>
<th>( F_{\text{whole mask}} ) Measured (^{(a)} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M 1860 (4 layers)</td>
<td>.120 ± .02</td>
<td>.268 ± .04</td>
<td>.275 ± .035</td>
<td>.0062 ± .0043</td>
<td>NA</td>
<td>5.5 E-5 ± 4.0 E-5</td>
<td>1.0 E-4 ± .3 E-4</td>
</tr>
<tr>
<td>3M 1870</td>
<td>.240 ± .06</td>
<td>.521 ± .048</td>
<td>.219 ± .019</td>
<td>.276 ± .044</td>
<td>.654 ± .030</td>
<td>.0049 ± .0015</td>
<td>.010 ± .004</td>
</tr>
<tr>
<td>3M 1870+ top section</td>
<td>.491 ± .023</td>
<td>.0434 ± .0137</td>
<td>.602 ± .036</td>
<td>NA</td>
<td>NA</td>
<td>.0128 ± .004</td>
<td>.013 ± .002</td>
</tr>
<tr>
<td>3M 1870+ middle section</td>
<td>.401 ± .031</td>
<td>.490 ± .035</td>
<td>--</td>
<td>.0131 (^{(b)} ) ± .0049</td>
<td>NA</td>
<td>.0026 ± .0010</td>
<td>.00355 ± .00057</td>
</tr>
<tr>
<td>3M 1870+ bottom section, all separated</td>
<td>.404 ± .042</td>
<td>.148 (^{(c)} ) ± .039</td>
<td>.090 (^{(c)} ) ± .027</td>
<td>.571 ± .091</td>
<td>NA</td>
<td>.0031 ± .0014</td>
<td>.00631 ± .00074</td>
</tr>
<tr>
<td>3M 1870+ bottom section, two layers combined</td>
<td>.404 ± .042</td>
<td>--</td>
<td>.0214 (^{(b)} ) ± .0041</td>
<td>.571 ± .091</td>
<td>NA</td>
<td>.0049 ± .0013</td>
<td>.0063 ± .0007</td>
</tr>
<tr>
<td>O&amp;M Halyard (d) Fluidshield</td>
<td>.531 ± .127</td>
<td>.206 (^{(c)} ) ± .019</td>
<td>.848 ± .0004</td>
<td>.359 ± .009</td>
<td>NA</td>
<td>.033 ± .0085</td>
<td>.027 ± .009</td>
</tr>
</tbody>
</table>

(a) this range in values is a spatial difference, not a measurement uncertainty.
(b) pulling these layers apart tended to give large variations in their spatial transmissions, so this combined measurement for the layers was felt to be more accurate (c & d for middle section, b &c for bottom section) for calculating overall transmission.
(c) pulling these layers apart gives a better sense of the minimum possible intensity inside the mask.
(d) there is a “white side” and a “pink side” to the outer layer, and they have somewhat different transmitted fractions, and here an average of the two is used, resulting in a larger spatial variation, but for purposes of the initial draft this 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.
(e) 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.

From the observation of the decrease in the detected light from a layer, as that layer is moved away from the surface of the detector, it is clear that a number of the layers tested scatter some of the transmitted UV light at large angles. In a single thin layer this can direct some of the UV light just beyond the aperture of the detector. But in a multilayer material like these masks, some of the light that scatters outward from a layer can hit another nearby layer that also scatters light and bring some fraction of that scattered light back into the aperture of the detector. Thus, we should expect the transmission of UV light through the mask as a whole to be slightly larger than the product of the individual layer transmission coefficients, but large spatial
variations in a mask can overrule that general principle. We have started to do experiments on this, and model it as well, and will present this in subsequent papers. However, some preliminary experiments indicate the scattering of light through the mask causes no less than 20% of the light scattered by the filter layers of the mask scatter back into the detector when the layers are together, using our 0.32 cm$^2$ detector. This large effect is due to the small size of the detector, with an optical diameter of 6.35 mm, and the scattering through the entire mask sends some scattered light out for another 1.0 to 1.4 mm in diameter. This effect would result in only a 5% effect on a 5 cm$^2$ detector and would only be noticeable in precision measurements. This does mean that the measured values for the transmission through any filter layer, and through the mask as a whole are at least 20% lower than the value the entire mask experiences, as measured with our small detector, because distances of 1.0 to 1.4 mm are negligible over the surface of the mask (i.e whatever is scattered outside our detector hits another part of the mask). However this scattering effect does not affect the relative measurements of transmission comparing a mask model to any other mask model.

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]. From Table 1 it is clear 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 2, on the next page, 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.
Table 2
Exposure times and internal intensity with light intensity that is incident perpendicular to the surface of the mask. 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/cm² 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.

<table>
<thead>
<tr>
<th>Mask: Maker, Model #</th>
<th>Minimum value of $\Sigma F_{\text{fraction transmitted}}$ (Minimum sum between layers of both directions, max value = 2)</th>
<th>Min. Intensity Inside mask per 100(\mu)W/cm² at each exterior surface for light perpendicular to mask surface</th>
<th>Exposure time to reach 7 mJ/cm² min internal intensity with 500(\mu)W/cm² at each mask surface for light perpendicular to surface (^{(a)})</th>
<th>Minimum internal dose when exposed to 500 mJ/cm² at each mask surface for light perpendicular to the mask surface, i.e. “total dose” of 1 J/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M, 1860</td>
<td>0.015 ± .005</td>
<td>1.5 (\mu)W/cm² ± 0.5 (\mu)W/cm²</td>
<td>15 minutes, 33 sec. (surface dose: 467 mJ/cm²) (23 min, 20 sec if using ave minus uncertainty for dose of 700 mJ/cm²)</td>
<td>7.5 mJ/cm² ± 2.5 mJ/cm² minimum internal dose</td>
</tr>
<tr>
<td>3M, 1870</td>
<td>0.165 ± .034</td>
<td>16.5 (\mu)W/cm² ± 3.4 (\mu)W/cm²</td>
<td>1 min, 25 sec. (surface dose: 42.4 mJ/cm²) (1 min 47 sec if using ave minus uncertainty for 53.4 mJ/cm² dose)</td>
<td>82.5 mJ/cm² ± 17 mJ/cm² minimum internal dose</td>
</tr>
<tr>
<td>3M, 1870+ middle section</td>
<td>0.21 ± .021</td>
<td>21 (\mu)W/cm² ± 2.1 (\mu)W/cm²</td>
<td>1 min, 7 sec. (surface dose: 33.3 mJ/cm²) (1 min 14 sec if using ave minus uncertainty for 37.0 mJ/cm² dose)</td>
<td>105 mJ/cm² ± 10.5 mJ/cm² minimum internal dose</td>
</tr>
<tr>
<td>3M, 1870+ bottom section</td>
<td>.111 ave.(^{(b)}) .079 absolute min. (^{(b)})</td>
<td>11.1 (\mu)W/cm² ave. 7.9 (\mu)W/cm² absolute min.</td>
<td>2 min, 6 sec. (surface dose: 63.1 mJ/cm²) (2 min 57 sec using absolute min for 88.6 mJ/cm² dose)</td>
<td>55.5 mJ/cm² ave. 39.5 mJ/cm² min. (^{(b)}) internal dose</td>
</tr>
<tr>
<td>O&amp;M Halyard Fluidshield (level 3)</td>
<td>0.413 ± .029</td>
<td>41.3 (\mu)W/cm² ± 2.9 (\mu)W/cm²</td>
<td>34 seconds (surface dose: 17.6 mJ/cm²) (37 sec if using ave minus uncertainty for 18.2 mJ/cm² dose)</td>
<td>206 mJ/cm² ± 14.5 mJ/cm² minimum internal dose</td>
</tr>
</tbody>
</table>

\(^{(a)}\) For practical application for a real process, the effect of the mask shape must be taken into account.

\(^{(b)}\) The transmitted fraction minimum value is the one described in the quick method below. Without that the minimum internal intensity would calculate as 0.111 ± .093, which has an impossible lower value.
One of the most interesting things to note in Table 2 is the large variation in minimum internal UV-C exposure when exposed to a cumulative external surface “dose” of 1 J/cm². 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/cm² (half the dose of column 5 in Table 2). The most surprising result, though, is the low level of internal dose for the 3M 1860 mask (model D in reference [3]). However, it is most likely that the 4th layer from the exterior of the mask has a high reflectivity, not just a low transmission. UV-light coming in only from the exterior of the mask (using the single source test from reference [3]), would result in no less than 8 mJ/cm² in the filter layers without reflection, and may be in the range of 10-15 mJ/cm² due to the reflection from the 4th layer.

Comparison with the 3M 1870 in the same paper, 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/cm² when subjected to a “dose” of 1 J/cm² 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. 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/cm² “dose” is likely overkill for many PPE masks, slowing throughput and decreasing reuse lifetime.

UV-C exposure of masks in room 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 also 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 50° to 60° 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. For simplicity, we will assume light that is a) perpendicular to the surface of the mask (usually toward the center of the mask), distributed over ±15° to the left and right, having intensity $I_{\text{perp}}$, b) light between 15° and 50° 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 50° and 75° distributed over that angular range. 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 $I_{\text{perp}}$ hitting the mask has an effective intensity of approximately $I_{\text{eff}}[1 + (0.3)\cos(\theta_{\text{ave}} \approx 30°) + (0.15)\cos(\theta_{\text{ave}} \approx 60°)] = 1.33(I_{\text{perp}})$. Light hitting the sidewall of a 3M 1860 has an effective intensity of approximately $I_{\text{eff}}[\cos(\theta_{\text{ave}} \approx 55°) + (0.3)\cos(\theta_{\text{ave}} \approx 20°) + (0.15)\cos(\theta_{\text{ave}} \approx 22°)] = 1.00(I_{\text{perp}})$. Light hitting the sidewall of a 3M 1870 or Halyard Fluidshield has an effective intensity of approximately $I_{\text{eff}}[\cos(\theta_{\text{ave}} \approx 67°) + (0.3)\cos(\theta_{\text{ave}} \approx 37°) + (0.15)\cos(\theta_{\text{ave}} \approx 5°)] = I_{\text{perp}}(1.34)$. A detector also gives an measurement of 1.36$I_{\text{perp}} = I_{\text{meas}}$. Thus putting this in terms of $I_{\text{meas}}$, we have for the intensity straight ahead, $I_{\text{0deg}} = I_{\text{meas}}$, the intensity hitting a sidewall of a 3M 1860 would be $I_{\text{1860side}} = .75 I_{\text{meas}}$, and the intensity hitting the sidewall of a 3M 1870 or Halyard Fluidshield would be 1.01$I_{\text{meas}}$. 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 \( \frac{1}{2} \) of what it is at the center. This would requires 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\(^2\) (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 of around 1.3 J/cm\(^2\). Masks irradiated with only light that is 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 of 2. 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.

A quick method for determining absolute minimum times for a deactivation process with mask

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), the total intensity at this point is just the 2-layer version of Eqn. 2, namely

\[
I_{\text{total between 2 parts}} = I_{\text{transmitted through outer part, left source}} + I_{\text{transmitted through inner part, right source}}, \quad \text{Eqn. 3}
\]

and this is just the same as
\[ I_{\text{total \ between \ 2 \ parts}} = I_{o,\text{source}} \left( F_{T,\text{Left \ part}} + F_{T,\text{Right \ part}} \right). \quad \text{Eqn. 4} \]

But we also have \( T_{\text{Left \ part}} \cdot T_{\text{Right \ part}} = T_{\text{whole \ mask}} \), so we can rewrite Eqn. 4 as

\[ I_{\text{total \ between \ 2 \ parts}} = I_{o,\text{source}} \left( F_{T,\text{Left \ part}} + \frac{F_{T,\text{whole \ mask}}}{F_{T,\text{Left \ part}}} \right) \quad \text{Eqn. 5} \]

This simple equation (Eqn. 5) has an absolute minimum, and taking the derivative with respect to \( F_{T,\text{Left \ part}} \) and setting it to zero, we find that the absolute minimum value of \( F_{T,\text{Left \ part}}, F_{T,\text{min}} \), is just \( \sqrt{F_{T,\text{whole \ mask}}} \).

Thus, we have

\[ I_{\text{min,\text{internal}}} = (I_{o,\text{surface}})\sqrt{F_{\text{min}}}. \]

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.

The table 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 3.
Comparison between minimum fraction of transmitted UV-C light and the quick method for determining the minimum value inside the mask at any point.

<table>
<thead>
<tr>
<th>Mask: Maker, Model #</th>
<th>Minimum value of $\Sigma F_{\text{fraction transmitted}}$ (Minimum sum between layers bidirectional sources, max value = 2)</th>
<th>Value of the minimum transmitted fraction for equal intensity bidirectional sources at any point in the mask, using $\sqrt{F_{T,\text{whole mask}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M, 1860</td>
<td>0.015 $\pm$ .005</td>
<td>0.0116 $\pm$ .0018</td>
</tr>
<tr>
<td>3M, 1870</td>
<td>0.165 $\pm$ .034</td>
<td>0.0689 $\pm$ .0018</td>
</tr>
<tr>
<td>3M, 1870+ middle</td>
<td>0.210 $\pm$ .021</td>
<td>.188 $\pm$ .012</td>
</tr>
<tr>
<td>3M, 1870+ bottom</td>
<td>0.111 ave.</td>
<td>.079 $\pm$ .004</td>
</tr>
<tr>
<td>O&amp;M Halyard Fluidshield (level 3)</td>
<td>0.413 $\pm$ .029</td>
<td>.164 $\pm$ .027</td>
</tr>
</tbody>
</table>

As shown in Table 3, the absolute minimum transmitted fraction inside a mask (or mask section), as calculated by the quick method is close to the minimum measured value between layers for 3 of the masks and a clear lower bound for the other two. The values in the middle column are likely somewhat larger than the actual values inside a mask as scattering from multiple layers likely leads to slightly larger values, as discussed in the article text. This will be explored more fully in subsequent research.
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:

\[ \delta q = \left[ \left( \frac{\partial q}{\partial x} \delta x \right)^2 + \ldots + \left( \frac{\partial q}{\partial w} \delta w \right)^2 \right]^{1/2} \]

Eqn. A1

References:

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