Optical Attenuators Extend Dynamic Range but Alter Angular Response of Planar Ultraviolet-C Dosimeters
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ABSTRACT
Effective ultraviolet-C (UV-C) decontamination protocols of N95 respirators require validation that the entire N95 surface receives sufficient dose. Photochromic indicators (PCIs) can accurately measure UV-C dose on nonplanar surfaces, but often saturate below doses required to decontaminate porous, multilayered textiles like N95s. Here, we investigate the use of optical attenuators to extend PCI dynamic range while maintaining a near-ideal angular response—critical for accurate measurements of uncollimated UV-C. We show analytically that tuning attenuator refractive index, attenuation coefficient, and thickness can extend dynamic range, but compromises angular response unless the attenuator is an ideal diffuser. To investigate this tradeoff empirically, we stack PCIs behind model specular (floated borosilicate) and diffuse (polytetrafluoroethylene) attenuators, characterize the angular response, and evaluate on-N95 UV-C measurement accuracy within a decontamination system. Both attenuators increase PCI dynamic range >4x, but simultaneously introduce angle-dependent transmittance, which causes location-dependent underestimation of UV-C dose. PCI-borosilicate and PCI-polytetrafluoroethylene stacks underreport true on-N95 dose by (1) 14.7% and 3.6%, respectively, when near-normal to the source lamp array, and (2) 40.8% and 19.8%, respectively, in a steeply sloped location. Overall, we demonstrate that while planar attenuators can increase PCI dynamic range, verifying near-ideal angular response is critical for accurate UV-C measurements.

INTRODUCTION
Ultraviolet-C (UV-C) radiation is a key germicidal technique regularly applied in healthcare settings to decontaminate air (1), surfaces (2), and recently, N95 respirators to address the COVID-19 pandemic-induced shortages (3–5). UV-C photons catalyze protein and nucleic acid photodegradation; after sufficient cumulative photon absorption (UV-C dose), compromised pathogens are inactivated. The UV-C dose needed for decontamination depends on the pathogen, substrate, and other factors (6). In particular, porous and multilayered textiles such as N95 respirators and surgical masks and gowns require higher applied outer surface doses as compared to nonporous materials, to offset attenuation of UV-C reaching pathogens embedded in the inner material layers (7,8). Decontamination efficacy is directly related to UV-C dose, and UV-C dose measurements are frequently the only metric bridging laboratory viral inactivation studies and clinical implementation; thus, accurate UV-C dose measurements are critical for protocol validation.

Validation of decontamination of N95s and other porous and/or nonplanar substrates poses unique UV-C measurement challenges. The ~100x higher UV-C dose required to decontaminate porous materials as compared to nonporous surfaces (2,7,9) requires UV-C sensors with sufficiently high dynamic range. UV-C systems often deliver nonlinear doses over time (10,11), precluding extrapolation from short exposures. Additionally, the complex N95 surface geometry complicates measurement accuracy, as the UV-C dose received by a surface at a given angle of incidence $\theta$ is reduced by a factor of $\cos(\theta)$ from the dose received at normal incidence (Lambert’s cosine law (12)). Thus, UV-C dose measurement accuracy depends on how proportional the sensor readout over angles of incidence $0^\circ \leq \theta \leq 90^\circ$ (termed “angular response”) is to $\cos(\theta)$ (termed “ideal response”). A sensor with an ideal response is critical for applications such as N95 decontamination, which involves both nonplanar targets and uncollimated UV-C. However, sensor housing, spectral filters, and other elements in the optical path often alter angular response (13) and sensor angular response is often nonideal (14,15), uncharacterized, or unreported.

UV-C photochromic indicators (PCIs), which change color in response to UV-C dose, overcome many challenges associated with on-N95 measurements. PCIs can have an ideal angular response (16) because PCI dose response and specificity are governed by chemistry (17) rather than additional physical elements within the optical path. Although PCI readout is traditionally qualitative or at best semi-quantitative (if a color swatch to dose reference is provided), a recent study developed a robust workflow to quantify UV-C dose from PCI color change to map UV-C dose across N95 facepieces (10). However, because PCIs were originally designed to validate nonporous surface decontamination, UV-C doses required for porous material decontamination typically exceed the PCI dynamic range. Thus, an extended PCI
dynamic range spanning higher UV-C doses is urgently needed to validate decontamination of porous materials like N95s. There are two approaches to extend the PCI dynamic range: (1) altering the chemistry governing the PCI color change (e.g., adding reagents to modify the reaction kinetics or equilibrium (17,18)) or (2) attenuating UV-C incident on the PCI (19,20). As a PCI-agnostic approach, attenuation lends itself to widespread adoption across diverse settings. However, objects within the optical path may alter the PCI angular response due to angle-dependent refraction, reflection, scattering, and absorption (13,21). A nonideal angular response will cause angle-dependent dose measurement errors. If the angle of incidence is known or constant, an angle-dependent correction factor can be determined (10,22,23). However, the deformable N95 facepiece shape combined with significant UV-C scattering and reflection renders this correction-factor approach infeasible for N95 UV-C decontamination systems.

Here, we employ theoretical and empirical approaches to investigate whether readily available materials can serve as optical attenuators to extend PCI dynamic range while maintaining measurement accuracy for N95 decontamination protocol validation. We develop an analytical model based on fundamental optics principles and attenuator properties to predict attenuator transmittance as a function of angle of incidence. Analytically and empirically with a point-like UV-C source, we characterize the angular response of PCIs stacked directly behind (with respect to the optical axis) each of two model attenuator materials: one nondiffuse and one diffuse. Finally, to mimic implementation in an N95 decontamination protocol, we evaluate the measurement accuracy of each PCI-attenuator stack on two differently sloped N95 facepiece locations in a decontamination chamber, where UV-C angles of incidence are unknown. We demonstrate that although attenuators with diffuse properties improve angular response as compared to nondiffuse attenuators, a model planar diffuse attenuator still alters angular response, which compromises measurement accuracy. In total, we develop frameworks to relate key material properties of optical attenuators to the dynamic range and angular response of the PCI-attenuator stack and assess model PCI-attenuator stacks in an example end-use case to highlight critical considerations when modifying planar dosimeters for measurements on nonplanar surfaces.

MATERIALS AND METHODS

Materials. The attenuators used were floated borosilicate (Borofloat®), 25.4 mm width × 25.4 mm length × 1.1 mm ± 0.1 mm thickness, 80/50 scratch/dig quality, Precision Glass & Optics 0025-0025-0011-GE-CA), referred to as “borosilicate,” and polytetrafluoroethylene film (Teflon®), 0.51 mm thickness, cut into 25.4 mm squares, McMaster-Carr 8569K23), referred to as “PTFE.” All radiometer measurements were collected using a calibrated ILT1254 UV-C radiometer with a Teflon dome diffuser (International Light Technologies). PCIs were UVC 100 Dosimeter dots (American Ultraviolet). For transmittance and angular response measurements, a modified handheld UV-C lamp (EF-140) with one B10-25375 amalgam bulb (254 nm emission) and a UV-C-blocking plate with a 25.4 mm-diameter aperture installed were used as a point-like UV-C source (Spectronics). PCI and PCI-attenuator stack calibration curves and on-N95 measurements were made in a commercial UV-C decontamination chamber (Spectronics XL-1000 with an array of 5 BLE-8T254 254 nm low-pressure amalgam bulbs along the top) with a small custom notch in the door for the reference radiometer cord to pass through. All on-N95 measurements were made on one 3M 1860 N95 respirator.

All analytical modeling and analyses were performed in MATLAB® R2012b.

Analytical model. The direct transmittance (TDirect) of 254-nm radiation through 1.1 mm-thick borosilicate was estimated at 8.7% from transmission curves reported by the manufacturer (24), quantified using a plot-digitalization tool (25). The manufacturer reports direct transmittance, which does not account for UV-C that scatters away from the detector. However, because borosilicate is a nondiffuse material (26,27) with minimal scattering, we assume that direct and total transmittance of borosilicate are approximately the same (i.e., TDirect ≈ TTotal). The attenuation coefficient (µ) of borosilicate was calculated from the borosilicate transmittance Ttotal (assuming manufacturer-specified TDirect ≈ TTotal), modeled interface transmittance Tint at 0°, and the attenuator thickness d, according to Eq. 1:

\[ \alpha = -\ln \left( \frac{T_{\text{int}}(0°)}{T_{\text{int}}(d°)} \right) \]

We estimated the refractive index n = 1.50 at 254 nm for borosilicate based on linear extrapolation of n for the two shortest wavelengths reported (~365 nm and 405 nm) (24). We estimated nInt ≈ 1.38 for PTFE, as reported by the manufacturer (28). Integrated cosine error was calculated in MATLAB® using the “cumtrapz” function.

PCI quantification. PCIs were quantified as described previously (10). Briefly, D65/10° L*a*b* values of PCIs were measured using an RM2000QC spectrocolorimeter (X-rite®). Color change with respect to an unexposed PCI was quantified using the CIEDE2000 ΔE formula (10,29). To generate calibration curves, a radiometer and a PCI were positioned within the UV-C chamber at planar locations of equivalent irradiance (Figure S1) to measure UV-C dose and CIEDE2000 ΔE, respectively. The PCI and the Teflon dome base of the radiometer were coplanar at ~3.5 mm above the manufacturer-specified reference plane. The radiometer reported that the 3.5-mm height difference yielded a 3.01% ± 0.25% difference in irradiance from that at the reference plane, which is less than the total radiometer uncertainty (±6.9%, as specified by the manufacturer). Thus, the height difference between the PCI and manufacturer-specified radiometer reference plane appears to negligibly affect the calibration curves and dynamic range measurements. CIEDE2000 ΔE values and corresponding UV-C doses were fit to a function based on first-order reaction kinetics (10). Unless otherwise noted, reported errors are the root-sum-square of standard deviations corresponding to both replicate variation and PCI quantification uncertainty.

Angular response measurements with aperture UV-C source. The angular responses of PCI-attenuator stacks were determined from the dose measured by PCIs mounted on a rotating optical post to expose the PCIs to quasi-parallel UV-C rays at different angles of incidence (0° in 15° increments) (30) from a point-like source (Figure S2). To approximate a point-like UV-C source, we determined the minimum distance between the optical post and apertured UV-C source at which UV-C output power was independent of distance (<5% change between measurements) using the Keitz formula (31). This distance was determined to be ~102 mm, which meets the suggested separation criterion of >2x the aperture diameter of 25.4 mm (31). Note that to represent a true far-field response, the angular response measurements should be collected at a distance ≥5x the aperture diameter (25.4 mm) (32). In a practical consideration, the low UV-C source irradiance—compounded by the presence of an attenuator and high angles of incidence—made angular response measurements infeasible at a separation distance of ≥5x the aperture diameter. Measurement at the 102-mm separation distance is estimated to introduce a theoretical relative error of 1.53% compared to a true far-field measurement (32).

To monitor UV-C source stability and ensure that all PCIs within an angular response set were exposed to the same nominal dose along the optical axis (i.e., all PCIs would receive the same dose if perpendicular to the optical axis), dose was monitored using a radiometer fixed at an offset, nonshadowed location. For all PCI exposures within an angular response set, the dose measured by the radiometer was the same. After UV-C exposure, the PCI-attenuator stack was disassembled and dose received by the PCI was immediately determined (“PCI quantification”). To monitor PCIs with PCI-attenuator pairs, dose measurements were made at two N95 facepiece locations: near the apex where the N95 surface is nearly normal to the UV-C bulb array (“low-
angle”), and near the base where the N95 surface is steeply sloped with respect to the UV-C bulb array (“high-angle”). To measure on-N95 dose with PCI-attenuator stacks, PClIs were taped to the attenuator with the UV-C-sensitive side flush against the attenuator. The PCI-attenuator stack was then attached to the N95 facepiece using double-sided tape. Measured on-N95 dose was determined from PCI-attenuator calibration curves generated within the UV-C chamber. To compare to the bare-PCI results, PCI-attenuator stack calibration curves were generated from the same locations in-chamber.

We evaluated the accuracy of on-N95 PCI-attenuator stack measurements by comparison to true on-N95 dose. To calculate the true UV-C dose applied at the N95 surface when either the dose exceeded the PCI upper limit of quantification or an attenuator was used, we first quantified the ratio of true dose at each N95 surface location to the dose at a radiometer positioned at a fixed location in the chamber (N = 3 replicates). On-N95 dose was measured using bare PClIs exposed to lower doses within the bare-PCI dynamic range, whereas the dose at the radiometer was calculated by integrating recorded irradiance over exposure time. All exposure times used for on-N95 measurements were substantially shorter (≤ 6 min) than the timescales over which spatial variation in bulb output has been observed (33). Thus, we assume that the ratio of doses is equivalent to the ratio of irradiances between the on-N95 and radiometer locations for the exposure times used here (i.e., dose ratio = Irradiance Ratio = \( \frac{I_{\text{on-N95}}}{I_{\text{radiometer}}} \)). Then, in subsequent experiments, the in-situ dose measured by the radiometer in the fixed location was multiplied by the predetermined Irradiance Ratio at each on-N95 location to estimate the true dose applied at each respective N95 location: true dose = dose_{\text{radiometer}} \times \text{Irradiance Ratio}.

For consistent placement, high- and low-angle locations were marked on the N95 facepiece, and facepiece deformation was minimized. During each exposure, the N95 was centered in the UV-C chamber, and a radiometer at a fixed location in the chamber recorded irradiance. A chamber floor map reduced positioning error (Figure S3).

RESULTS AND DISCUSSION

Design specifications relevant to pathogen inactivation

In this study, we sought to characterize the performance of PClIs stacked behind optical attenuators in measuring UV-C surface doses required for viral inactivation throughout porous materials on nonplanar N95 facepieces. Because planar materials are accessible and scalable (can be cut to size from bulk material), we chose to study planar attenuators. We identified key performance specifications relevant to measurement accuracy: dynamic range and angular response (Fig. 1a). We define the PCI dynamic range (10) as the UV-C doses between a lower and upper limit of quantification (LLOQ and ULOQ, respectively) where the relative PCI quantification uncertainty is < 10% (Figure S4). As studies support ≥ 1.0 J cm\(^{-2}\) for ≥ 99.9% inactivation of enveloped viruses on most N95 models (34–36), the PCI-attenuator stack ULOQ must exceed 1.0 J cm\(^{-2}\) for N95 decontamination protocol validation. However, pathogen- and model-specific UV-C efficacy may require higher ULOQ and should be determined on a case-by-case basis. Additionally, on-N95 dose has been found to vary by ~20× within a decontamination system (10). To maximize the continuous measurement range in order to characterize the full range of nonuniform doses within a system, the PCI-attenuator stack LLOQ must remain below the bare-PCI ULOQ (0.261 J cm\(^{-2}\) for the PCI model and color-readout method used here (10); Figure S4).

UV-C dose measurement accuracy on nonplanar surfaces depends on the angular response of the detector. Depending on attenuator material properties, transmittance may change with angle of incidence due to angle-dependent refraction, reflection, absorption, and degree of scattering (e.g., specular or diffuse reflectance and transmittance), leading to a nonideal angular response. Because nonideal angular response is infeasible to correct for without prior knowledge of the angle(s) of incidence, we sought to identify a PCI-attenuator stack with near-ideal angular response. At a given angle of incidence \( \theta \) where \( 0^\circ \leq \theta < 90^\circ \), deviation from the ideal angular response is defined as the cosine error (37) (Eq. 2):

\[
\text{Cosine error} = f_2(\theta) = \left( \frac{\text{response}(\theta)}{\text{response}(0^\circ) \cdot \cos(\theta)} - 1 \right) \times 100\%.
\]

(2)

To match the order of magnitude of bare-PCI measurement error (10) (average error of 7%), PCI-attenuator stack cosine error magnitude must remain ≤ 10% over all angles of incidence \( 0^\circ \leq \theta < 90^\circ \). Integration of the cosine error between 0° and 80° (integrated cosine error, Eq. 3, defined (37) in ISO/CIE 19476:2014(E)) quantifies the overall deviation from the ideal angular response (38):

\[
\text{Integrated cosine error} = \int_0^{80^\circ} \left| f_2(\theta) \right| \cdot \sin(2\theta) d\theta.
\]

(3)

Optical properties governing attenuator design for measurements on nonplanar surfaces

To inform design of an attenuator that meets the required specifications, we first sought to identify and relate optical properties that affect attenuator transmittance through a planar material. Transmittance will affect both the dynamic range and angular response of a PCI-attenuator stack. Attenuators may exhibit entirely specular reflection and transmission (i.e., no scattering effects, “nondiffuse”), or diffuse scattering at the interface (“surface diffusers”), within the material (“volume diffusers”), or at both the interface and throughout the material. We developed an analytical model for total transmittance \( T_{\text{total}} \) through materials based on two main interactions (Eq. 4): (1) reflection and refraction at air-attenuator interfaces, which govern the transmittance across the interfaces \( T_{\text{int1}} \) and \( T_{\text{int2}} \) and (2) attenuation throughout the attenuator thickness, which governs the transmittance through the attenuator volume \( T_{\text{mat}} \).

\[
T_{\text{total}} = T_{\text{int1}} \cdot T_{\text{mat}} \cdot T_{\text{int2}}
\]

(4)

At each air-attenuator interface, the Fresnel equations (13) (Eq. 5) for randomly polarized radiation describe \( T_{\text{int}} \) based on the air and attenuator refractive indices \( n_{\text{air}} \) and \( n_{\text{att}} \) respectively and angle of incidence with respect to the surface normal \( \theta_{\text{air}} \). Snell’s law (39) (Eq. 6) governs the angle of refraction within the attenuator \( \theta_{\text{mat}} \) (Fig. 1b),

\[
T_{\text{int}} = 1 - \left| \frac{1}{2} \left( \frac{n_{\text{air}} \cos(\theta_{\text{air}}) - n_{\text{att}} \cos(\theta_{\text{att}})}{n_{\text{air}} \cos(\theta_{\text{air}}) + n_{\text{att}} \cos(\theta_{\text{att}})} \right)^2 \frac{n_{\text{att}} \cos(\theta_{\text{att}}) - n_{\text{att}} \cos(\theta_{\text{att}})}{n_{\text{att}} \cos(\theta_{\text{att}}) + n_{\text{att}} \cos(\theta_{\text{att}})} \right|^2 \right)^2
\]

(5)

\[
n_{\text{att}} \sin(\theta_{\text{air}}) = n_{\text{att}} \sin(\theta_{\text{att}}).
\]

(6)

Note that the attenuator-to-air interface transmittance \( T_{\text{int1}} \) calculation requires interchanging \( n_{\text{att}} \) and \( n_{\text{air}} \) as well as \( \theta_{\text{air}} \) and \( \theta_{\text{att}} \) in Eq. 5. Specular reflectors have a microscopically flat interface, such that a collimated UV-C beam will strike the material at a single \( \theta_{\text{att}} \) that governs \( T_{\text{int1}} \). In contrast, due to interface roughness on surface diffusers, the surface normal varies randomly over distances much smaller than the length scale of...
interest (e.g., dimensions of the PCI) (13). Thus, the textured interface causes collimated UV-C at any angle to actually strike the microscopically textured interface over a range of \( \theta \) values. As a result, the proportion of UV-C transmitted across a surface diffuser interface does not depend on the angle of incidence (Fig. 1b).

Using this analytical framework, we modeled specular and diffuse interface transmittance as a function of both refractive index difference \( \Delta n \) (Fig. 1c) and the angle of incidence \( \theta_{\text{air}} \) (Fig. 1d). Increasing \( \Delta n \) decreases \( T_{\text{int}} \), thus extending the dynamic range of the PCI-attenuator stack (Eq. 5; Fig. 1c). To characterize the effect of \( \Delta n \) on angular response, we evaluated \( T_{\text{int}} \) normalized to \( T_{\text{int}}(0^\circ) \) as a function of \( \theta_{\text{air}} \). Because \( n \) of most materials (40) is \( \leq 2 \) and \( n_{\text{air}} \approx 1 \), we evaluated \( \Delta n \leq 1 \). Surface diffusers exhibit angle-independent transmittance at the interface regardless of \( \Delta n \). However, interfaces with specular reflection and transmission have increasingly angle-dependent transmittance as both \( \theta_{\text{air}} \) and \( \Delta n \) increase within the range of values modeled.

Internal transmittance through the attenuator thickness \( d \) depends on two parameters: the material attenuation coefficient \( \alpha \) and the optical path length through the material \( L \). Bouguer’s law (39) relates \( T_{\text{mat}} \) to \( \alpha \) and \( L \) (Eq. 7):

\[
T_{\text{mat}} = e^{-\alpha d}.
\]  

In nondiffuse materials and surface diffusers with no internal scattering, \( L \) is dependent on \( d \) and \( \theta_{\text{att}} \) (Eq. 8):

\[
L = \frac{d}{\cos(\theta_{\text{att}})}.
\]

In volume diffusers, microstructures within the material scatter rays in random directions (41), decoupling \( L \) from \( \theta_{\text{att}} \). Thus, in volume diffusers, \( T_{\text{mat}} \) is independent of angle of incidence (Fig. 1b).

To elucidate contributions of attenuator properties \( (\alpha \text{ and } d) \) to the magnitude and angle-dependence of \( T_{\text{mat}} \), we modeled \( T_{\text{mat}} \) as a function of a nondimensional parameter \( \alpha d \) (Fig. 1e) and \( \theta_{\text{att}} \) (Fig. 1f). Increasing \( \alpha d \) decreases transmittance via increased

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**Figure 1.** Attenuator material properties govern dynamic range and angular response of PCI-attenuator stacks. (a) 3D rendering of N95 UV-C decontamination system with 2D top-down view of N95 in chamber (right). Attenuators stacked in front of PCIs can extend the PCI dynamic range to measure on-N95 dose variation (simulated UV-C doses shown as on-N95 heatmap), but measurement accuracy on nonplanar surfaces like N95s requires an ideal PCI-attenuator angular response. (b) Schematic representation of UV-C transmittance through ideal specular and diffuse attenuators at varying angles of incidence: UV-C enters through the air-attenuator interface \( (T_{\text{int}}) \), traverses the attenuator material \( (T_{\text{mat}}) \), and exits via the attenuator-air interface \( (T_{\text{int}2}) \). Grayscale arrow shade represents irradiance magnitude. In nondiffuse materials, reflection and attenuation increase with angle of incidence. In ideal diffusely transmitting materials, transmittance is independent of angle of incidence due to surface and volume diffuser behavior. (c, d) Non-zero \( \Delta n \) yields both decreased (c) and angle-dependent (d) transmittance at a specular interface. (e, f) Material thickness \( d \) and attenuation coefficient \( \alpha \) yield both decreased (e) and angle-dependent (f) transmittance in a nondiffuse material. (g) Two attenuator materials, borosilicate (specular) and PTFE (diffuse) extend the PCI upper limit of quantification (dashed vertical lines) beyond 1.0 J cm\(^{-2}\). Shaded regions around dose–response curves indicate the 95% prediction interval for PCI color change from measured UV-C dose.
material attenuation, thereby extending the PCI dynamic range (Fig. 1e). For UV-C transmittance through volume diffusers at any angle, $T_{\text{total}}/T_{\text{max}} (0^\circ)$ is independent of angle of incidence regardless of $\alpha d$. However, increasing $\alpha d$ for nondiffuse materials increases angular dependence of transmittance because (1) increasing $d$ expands the range of optical path lengths over which attenuation occurs, and (2) increasing $\alpha$ increases the sensitivity of $T_{\text{total}}$ on varying path lengths (Fig. 1f).

Since the irradiance incident on the PCI-attenuator stack follows Lambert’s cosine law (12), the irradiance ultimately incident on the PCI is proportional to $T_{\text{total}} \cos(\theta_{\text{air}})$. Thus, PCIs stacked directly behind planar attenuators (relative to the optical path) will maintain an ideal response only if $T_{\text{total}}$ remains constant over $0^\circ \leq \theta_{\text{air}} < 90^\circ$. However, the parameters ($\Delta n$, $d$, and $\alpha$) required to reduce attenuator transmittance and thus increase the dynamic range of the PCI-attenuator stack concomitantly introduce angle-dependent transmittance. Thus, unless the attenuator diffuses UV-C sufficiently to transmit UV-C independent of angle (“ideally diffuse”), there is a fundamental tradeoff between reducing transmittance to extend PCI dynamic range and maintaining an ideal cosine angular response.

**Model diffuse and nondiffuse materials extend the PCI dynamic range beyond 1.0 J cm$^{-2}$**

To investigate how attenuator material properties affect UV-C dose quantification accuracy, we chose to characterize the performance of PCIs stacked behind each of two widely accessible materials with different degrees of diffuse scattering. Floated borosilicate (“borosilicate”) has been demonstrated (10) to extend PCI dynamic range on planar surfaces by 5×, and thus was chosen as a model nondiffuse attenuator (i.e., exhibits specular reflection and transmission). A variety of ultraviolet diffusers, including fused silica diffusers containing internal air bubbles, have been found to improve angular response (42,43). Here, we chose to study polytetrafluoroethylene (“PTFE”) as a model volume diffuser (44), as PTFE is commonly used to improve angular response of radiometers within the ultraviolet range (45,46). Additionally, PTFE is available as relatively affordable flexible sheets which may better conform to the nonplanar N95 surface. Based on three primary observations, we employ a working assumption that any fluorescence exhibited by the attenuator materials would negligibly impact PCI readouts used in angular response and on-N95 dose measurements. The three observations supporting this working assumption are as follows:

1. Floated borosilicate is reported to emit minimal fluorescence between ~380 and 800 nm when excited at 280 nm (47), although fluorescence emitted when excited at 254 nm remains an open area of investigation.
2. Others (48) have observed no measurable fluorescence emitted between 200 and 1000 nm for PTFE when excited between 220 and 600 nm. Additionally, commercial UV-C sensors use PTFE as a diffuser, which further suggests that PTFE should not fluoresce significantly within the PCI spectral region of sensitivity upon exposure to UV-C wavelengths (46).
3. The PCIs used for all PCI-attenuator measurements are known to have a negligible response over a 5-min exposure to sunlight (10), which contains most wavelengths between ~300 and 1300 nm (49). Consequently, we would anticipate that any fluorescence that could be emitted by the attenuator materials would minimally alter the PCI readout.

We generated calibration curves for PCIs and PCI-attenuator stacks to verify that chosen attenuator thicknesses extend the PCI dynamic range beyond 1.0 J cm$^{-2}$ (Fig. 1g, Figure S4). The bare-PCI ULOQ was 0.261 J cm$^{-2}$, below the 1.0 J cm$^{-2}$ design specification for on-N95 dose validation and in line with previous studies (10). We found that 0.51 mm-thick PTFE and 1.1 mm-thick borosilicate increased the ULOQ to 1.259 and 1.853 J cm$^{-2}$, respectively, thus meeting the dynamic range specification. Although we only studied one batch of each attenuator material, transmittance may vary by batch and should be characterized prior to implementation.

**Analytical and empirical characterization demonstrate nonideal angular response of a model nondiffuse attenuator**

To assess quantification accuracy of the PCI-borosilicate stack at different angles of incidence, we compared both the analytical and empirical angular responses of a PCI stacked behind 1.1 mm-thick borosilicate to an ideal response. We used the manufacturer-specified borosilicate thickness and direct transmittance (24) (1.1 mm and 8.7%, respectively), as well as the assumption that $T_{\text{direct}} \approx T_{\text{total}}$, to analytically predict the PCI-borosilicate stack angular response. We compared these predictions to the angular response measured with the point-like UV-C source.

As a nondiffuse material, we hypothesized that the PCI-borosilicate stack would read out lower UV-C doses at nonzero angles of incidence than expected from Lambert’s cosine law, with deviations from ideal increasing with angle of incidence due to angle-dependent reflection and absorption (21) (Fig. 2a).

We calculated the integrated cosine error (Eq. 3) using an upper limit of integration of 75°, the last angle measured that is less than 80° (the standard upper limit for integration for integrated cosine error (37)). For the PCI-borosilicate stack, we predicted analytically and measured an integrated cosine error of 15.3% and 14.5%, respectively. Both analytically and empirically, we observed that the UV-C dose transmitted through borosilicate to the PCI underestimated an ideal angular response (Fig. 2b). To quantify the deviation from the ideal response as a function of angle of incidence, we calculated the cosine error (Eq. 2, Fig. 2e). At angles of incidence of 15° and 75°, our model predicted cosine errors of ~3.5% and ~70.5%, respectively, and we measured cosine errors of ~8.2% ± 3.0% and ~82.9% ± 5.7%, respectively. Thus, the PCI-borosilicate stack deviated more from an ideal response at higher angles of incidence (Fig. 2c), as hypothesized. Importantly, the PCI-borosilicate stack only meets the angular response design specification (i.e., magnitude of cosine error $\leq 10\%$) at near-normal nonzero angles of incidence: 15° empirically, and up to ~26° analytically. Although angle-specific correction factors have been determined and applied in tightly controlled systems (23), this approach is not feasible when the distribution of angles of incidence is not precisely known. For N95s in a UV-C chamber, both the 3D N95 facepiece morphology and collimated radiation confound application of an angle-specific correction factor to adjust inaccurate on-N95 UV-C dose measurements.

To evaluate the agreement between the analytical model and experiment, we compared the empirical angular response to
Analytical and empirical angular responses and cosine error are compared for PCIs stacked behind (a–c) borosilicate, a model nondiffuse material, and (d–f) PTFE, a model volume diffuser. (a) Analytically, both reflections at the attenuator interfaces and path-length-dependent absorption through the material thickness contribute to the modeled angular response of nondiffuse materials. The (b) angular response and (c) cosine error of PCI-borosilicate stacks shows a nonideal angular response at all non-normal angles of incidence. (d) The analytical model for PTFE as a volume diffuser includes specular reflection at interfaces, but assumes constant path length (and thus, absorption) through the material for all angles of incidence. The (e) angular response and (f) cosine error of PCI-PTFE stacks illustrate near-ideal response at low angles of incidence and nonideal angular response at high angles of incidence. Error bars indicate total error, comprising both the standard deviation of N = 3 replicates and the quantification uncertainty of PCI measurements.

Model predictions. At 2 out of the 6 assessed non-normal angles, empirical angular response was within error (total propagated error of PCI quantification uncertainty and replicate variation) of model predictions (Figure S5a,b). The difference between empirical and analytical angular responses was most substantial at 15° and 75° (Figure S5b), where the normalized empirical angular response was 0.0448 ± 0.0291 and 0.0320 ± 0.0147 below the model predictions, respectively. We hypothesize that the discrepancy between the empirical and analytical angular responses arises from error in estimated model parameters (e.g., refractive index, , total at 0°), which will alter the predicted angular response (Fig. 1d,f). Overall, however, analytical and empirical angular response measurements for the PCI-borosilicate stack correspond well. Both show a nonideal angular response with cosine error magnitude >10% for the majority of angles 0° ≤ θ < 90° and thus do not meet the angular response design specification. Negative cosine error at all non-normal angles of incidence means that the PCI-borosilicate stack underestimates UV-C dose, though to different amounts depending on angle.

Diffuse attenuators cause less deviation from ideal angular response

Materials like borosilicate that exhibit specular reflection and transmittance highlight a fundamental tradeoff between extending the PCI dynamic range and minimizing cosine error. In contrast, diffuse materials are predicted to overcome this tradeoff by reducing angle-dependent reflectance (surface diffusers) and/or by reducing angle-dependent optical path length (volume diffusers). Available in numerous thicknesses and sizes at relatively low cost as compared to glass diffusers, PTFE is a readily available attenuator material appropriate for a wide range of environments. As a volume diffuser (44), we hypothesized that bulk scattering within PTFE would reduce path length dependence on angle of incidence. Due to unspecified surface roughness, we could not assume ideal surface diffuser behavior; thus, we modeled PTFE analytically as a volume diffuser with specular reflection and transmission at the interfaces (Fig. 2d).

To assess the accuracy of the volume diffuser analytical model and characterize the extent to which PTFE alters PCI angular response, we compared both the analytical and empirical angular responses of a PCI-PTFE stack to an ideal response (Fig. 2e–f). For UV-C angles of incidence ≤ 75°, we predicted analytically and measured an integrated cosine error of 2.7% and 0.97%, respectively. Both the analytical and empirical integrated cosine errors of the PCI-PTFE stack are smaller in magnitude than those observed for the PCI-borosilicate stack, as anticipated, and are lower than others that have been measured for 0.5 mm-thick PTFE (38,50). We hypothesize that the lower integrated cosine error observed here could arise from differing limits of integration. Due to the limited number of angles of incidence characterized empirically, we integrate through 75°, whereas others (38,50) integrate through 85° (past the ISO/CIE 19476:2014(E) definition (37)), incorporating contributions from an additional 10° over which cosine error is typically large. At each rotation angle measured except 90°, PCI-PTFE angular response was within error of the ideal response (Fig. 2f), suggesting a near-ideal angular response. Empirical angular response was within error of model predictions at < 60°; at ≥ 60°, the empirical PCI-PTFE stack angular response was closer to an ideal response than model predictions (Figure S5c,d). We hypothesize that the empirical angular response of the PCI-PTFE stack was closer to ideal due to some surface diffuser behavior at the interface (not incorporated in the model), and/or slight curvature or non-negligible spacing between the deformable PTFE and PCI. Diffuser-sensor spacing and diffuser curvature have been shown to substantially alter the angular response of radiometers (50–52).
Quantifying error in on-N95 UV-C dose measurements by PCI-attenuator stacks

Based on the modeled and measured angular response measurements from the point-like UV-C source, we hypothesized that a PCI-PTFE stack would measure on-N95 dose more accurately than a PCI-borosilicate stack, particularly at on-N95 locations subject to high angles of incidence. To test this hypothesis, we compared UV-C dose measured with PCIs and PCI-attenuator stacks to true applied dose at two locations on an N95 centered in a chamber with 5 UV-C bulbs arrayed across the top. The presence of multiple UV-C bulbs, as well as scattering and reflection (53) in this and other commercial decontamination systems, stymie determination of angle of incidence distribution at any given location. We chose two on-N95 measurement locations which we hypothesized receive substantially different angles of incidence: (1) near the apex (“low-angle”: near-normal), and (2) near the base (“high-angle”: non-normal) (Fig. 3a). Based on the analytical model and the point-like UV-C source measurements (Fig. 2), we hypothesized that the PCI-borosilicate stack would underestimate UV-C dose at both N95 locations, with greater underestimation at the high-angle location. In contrast, PCI-PTFE angular response had cosine error magnitudes < 10% at all angles of incidence measured empirically and at angles ≤ 61° analytically, so we hypothesized that the PCI-PTFE stack would measure on-N95 UV-C dose accurately at the low-angle location, with some error introduced at the high-angle N95 location.

At both on-N95 locations, UV-C dose was measured from PCI color change using PCI-attenuator-specific calibration curves (Fig. 1g). To evaluate the measurement accuracy, the true dose applied at each on-N95 location was determined by multiplying a radiometer measurement obtained in each exposure by the respective predetermined Irradiance Ratio at each on-N95 location and at the radiometer (\( \frac{I_{\text{Irr,lowangle}}}{I_{\text{Irr}}}; \frac{I_{\text{Irr,highangle}}}{I_{\text{Irr}}}; \frac{I_{\text{Irr,attenuator}}}{I_{\text{Irr}}}; \)). Based on the ULOQ of the two PCI-attenuator stacks, on-N95 UV-C dose measurements up to ~1.200 J cm\(^{-2}\) were characterized and compared to the true dose to evaluate the on-N95 dynamic range and angular response of PCI, PCI-borosilicate, and PCI-PTFE (Fig. 3b–d). In agreement with the dynamic ranges measured on a planar surface (Fig. 1g), the measured UV-C dose of the PCI-attenuator stacks is linearly proportional to true dose throughout the entire dose range tested at each on-N95 location (~0.050 to ~1.200 J cm\(^{-2}\), Fig. 3c,d, top; Table S1). Thus, both borosilicate and PTFE meet the design specification of extending on-N95 PCI dynamic range to ≥ 1.0 J cm\(^{-2}\). In contrast, UV-C dose measured by the bare PCI plateaus at true doses above ~0.250 J cm\(^{-2}\) (Fig. 3b), yielding poor correlation between true and measured dose (Table S1) and in agreement with the PCI ULOQ (Fig. 1g).

To evaluate overall measurement accuracy, we calculated the percent error of on-N95 UV-C dose measurements (Fig. 3b–d, bottom). Doses measured with the PCI-borosilicate stack underestimated the true dose by 14.7% ± 4.0% and 40.8% ± 3.0% at the low-angle and high-angle on-N95 locations, respectively (errors are the standard deviation of the percent differences between true and measured dose over 18 measurements at a given location). Thus, in agreement with our hypothesis, we found that dose measured with the PCI-borosilicate stack underestimated true UV-C dose to a greater extent at the more steeply sloped, high-angle on-N95 location. Inaccuracy in the measured dose also arises due to differences in the distribution of angles of incidence between the calibration curve and on-N95 measurements. As discussed, it is infeasible to generate calibration curves or

Figure 3. On-N95 UV-C dose measurement error depends on attenuator and on-N95 location. (a) UV-C dose was measured at two different on-N95 positions (top image): near the apex (“low-angle”), and on the steeply sloped side (“high-angle”). For PCI-attenuator stacks (PTFE or borosilicate), a PCI was placed directly underneath an attenuator (bottom image). On-N95 UV-C dose measurement accuracy of a (b) bare PCI, (c) PCI-borosilicate stack, or (d) PCI-PTFE stack was determined by comparing measured to true applied dose calculated from radiometer measurements and the predetermined ratio between the irradiance at the radiometer and at each on-N95 location. Measured dose (top) and percent error in measured dose (bottom) were plotted against true applied dose. UV-C dose measurements made using an attenuator tend to underestimate true applied dose, particularly at the high-angle location.
correction factors specific to each on-N95 location in the chamber. In contrast, doses measured with the PCI-PTFE stack only underestimated the true dose by 3.6% ± 6.7% and 19.8% ± 5.8% at the low-angle and high-angle on-N95 locations, respectively. Thus, UV-C dose measurements by the PCI-PTFE stack were more accurate than those by the PCI-borosilicate stack, supporting our hypothesis and model predictions that PCs stacked behind diffuse materials have an angular response nearer to an ideal response than when stacked behind a nondiffuse material. Overall, PCI-PTFE dose measurements were within error of the true dose at the low-angle on-N95 location (measured dose underestimated true dose by 3.6% ± 6.7% over 18 measurements), in agreement with our hypothesis that PCI-PTFE has near-ideal angular response at low angles of incidence.

We observed greater error in PCI-PTFE-measured dose at the high-angle on-N95 location than observed at all angles measured with the point-like UV-C source (Fig. 2). The larger error at the high-angle location on-N95 may indicate an average angle of incidence > 75° at that location, yielding a greater cosine error than that measured with the point-like UV-C source at angles ≤ 75°. As discussed previously, geometrical factors such as slight variations in PTFE curvature, as well as the use of calibration curves not specific to each experimental measurement location, may have also contributed to angular response differences measured in the two systems. Additionally, while guidance on the acceptable source-to-detector distance for accurate angular response measurements varies (11,54), insufficient distance can yield artificially high angular response (54). This artifact may contribute to the near-ideal angular response measured with the point-like source, where the maximum source-to-detector distance was limited due to low source irradiance (described in “Materials & Methods”). On-N95, the PCI-PTFE attenuator stack underestimated dose to a greater extent with increasing dose, a phenomenon not observed with the PCI-borosilicate stack (Fig. 3 c,d). We hypothesize that the dose-dependent error may arise from an increasing difference between the true and applied calibration curves at higher doses (Figure S6), and/or temperature-induced changes in PTFE transmittance (55) not captured in the PCI-PTFE calibration curve (generated off-N95) due to differences in heat dissipation on-N95.

Overall, both modeling and measurements in two different UV-C systems demonstrate that diffuse attenuators such as PTFE alter the ideal angular response of PCs less than nondiffuse materials such as borosilicate, but that both planar attenuator materials cause deviation from ideal at high angles of incidence. Unless the material is ideally diffuse, the factors which decrease attenuator transmittance (thus increasing PCI-attenuator ULOQ) also increase the angular dependence of transmittance, yielding a fundamental tradeoff between the two design requirements of increased dynamic range and minimal cosine error. Both attenuators increased the PCI ULOQ by > 4x, but the nonideal angular response of PCI-attenuator stacks led to underestimation of measured on-N95 dose at one or both locations. The on-N95 results highlight a critical consideration for designing optical attenuators: materials that lead to measurements within error of the ideal angular response in a controlled setting may not accurately translate to user environments. Additionally, cumulative UV-C exposure also affects the transmission properties of some attenuators (e.g., solarization of glass (56)), which limits reuse. Although relatively low-cost materials such as PTFE may be feasible for single-use applications, the stability of attenuator transmittance with increasing cumulative UV-C dose must be robustly characterized prior to implementation of any attenuator material. Future study could consider introducing surface roughness and/or curvature to volume diffusers, or investigating alternative UV-C diffuser materials that exhibit near-ideal angular response, to create PCI-attenuator stacks with smaller cosine error at higher angles of incidence. Development of diffusers with near-ideal angular response is an open area of interest (57). Alternative strategies to extend PCI dynamic range, such as the development of new PCI formulations, are also a promising approach that may be more robust than physically attenuating UV-C incident on the PCI.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article:

- **Figure S1.** UV-C chamber floor map for calibration curve measurements.
- **Figure S2.** Measurement setup to characterize PCI-attenuator stack angular response.
- **Figure S3.** UV-C chamber floor map for on-N95 measurements.
- **Figure S4.** Attenuators extend PCI dynamic range.
- **Figure S5.** Analytical and empirical angular responses of PCI-attenuator pairs are concordant.
- **Figure S6.** Use of incorrect calibration curve can yield dose-dependent measurement error.

**Table S1.** Significance of linear correlation between true and measured doses for each attenuator and on-N95 location tested.

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