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Short Communication



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# Surface Dosimetry of Ultraviolet Germicidal Irradiation Using a Colorimetric Technique

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## Abstract

Ultraviolet germicidal irradiation uses ultraviolet C (UV-C) energy to disinfect surfaces in clinical settings. Verifying that the doses of UV-C energy received by surfaces are adequate for proper disinfection levels can be difficult and expensive. Our study aimed to test commercially available colorimetric labels, sensitive to UV-C energy, and compare their precision with an accepted radiometric technique. The color-changing labels were found to predictably change color in a dose-dependent manner that would allow them to act as a qualitative alternative to radiometry when determining the minimum UV-C energy dosage received at surfaces. If deployed using careful protective techniques to avoid unintentional exposure to sunlight or other light sources, the use of colorimetric labels could provide inexpensive, easy, and accurate verification of effective UV-C dosing in clinical spaces.

**Keywords:** color-changing labels; colorimetric; disinfection; dosimetry; germicidal; radiometric; radiometry; ultraviolet; UV-C; UVGI

## Introduction

Ultraviolet germicidal irradiation (UVGI) presents an emerging method for rapid disinfection of a variety of surfaces. Ultraviolet C (UV-C) energy, which is ultraviolet energy in the 100–280 nm wavelength range (IESNA, 2000), has been shown to effectively inactivate microorganisms. The entire UV spectrum is capable of inactivating microorganisms, but UV-C energy provides the most germicidal effect, with 265 nm being the optimum wavelength (DIN, 1979; IESNA, 2000). Most modern UVGI lamps are quartz tubes that create UV-C energy by passing an electrical discharge through a low-pressure gas (including mercury vapor) (Philips, 2006). Roughly, 95% of the energy produced by these lamps is emitted at a near-optimal wavelength of 254 nm (IESNA, 2000). Its use in clinical environments as a method of terminal disinfection has been studied (Weber *et al.*, 2016). LED-based UV-C units of varying frequency and bandwidth outputs have also shown effectiveness but are considered an emerging technology (Beck, 2017). As such, this research focused on the more common low-pressure mercury vapor lamps. Far UV-C

**What's important about this paper?**

Ultraviolet germicidal irradiation (UVGI) is used to decontaminate healthcare environments, but UVGI system performance can decrease over time. This article provides evidence that commercially available colorimetric methods can be used to verify ongoing UVGI system performance. These inexpensive and easy to use methods will allow for continued, effective use of UGVI systems, helping to prevent the transmission of infectious diseases to healthcare workers and patients.

(205–230 nm) has been shown to have germicidal effectiveness in laboratory settings but have limited use in the market (IES, 2020). Given the prevalence of 254 nm wavelength in the clinical environment, we focused on this wavelength in this research.

As systems utilizing UV-C energy for terminal disinfection become more common (Memarzadeh, 2010), it is important that users and care providers ensure these systems function as intended and that the doses of UV-C received by surfaces are effective in providing germicidal outcomes. It is also important to ensure that occupational exposures to UV-C energy be controlled to ensure compliance with the relevant ACGIH TLV and NIOSH REL of 6 mJ/cm$^2$ for an 8-h time period at 254 nm (NIOSH, 1972; ACGIH, 2019).

Different surfaces receive varying amounts of UV-C energy based on distance from the source, occlusion, angle of incidence, surface finish and reflectivity, and other factors. Lindsley *et al.* (2018) showed that different locations in the same environment can have large variations in the amount of UV-C energy received, resulting in the need for longer exposure times to adequately disinfect all surfaces. Furthermore, UVGI lamps deteriorate over their life span, producing less UV-C energy over time than when originally put into service. For example, Philips, the manufacturer of the UV-C lamps used in this research, states that its lamps provide about 80% of their original UV-C output after 9000 h—approximately 1 year of service (Philips, 2006). The cleanliness and upkeep of the fixtures can also negatively affect output.

To ensure proper continued clinical effectiveness, doses of UV-C energy should be verified at different locations in the space being irradiated, especially those locations that receive less UV-C energy. Unfortunately, it is difficult and expensive to accurately verify the amount of UV-C energy delivered to a surface. Radiometers with specialized filters can be used (Ryer, 2009; Kowalski, 2009) but can be cumbersome and complex to set up. Actinometric methods that can measure irradiance omnidirectionally are useful in laboratory settings but are difficult to set up and impractical for field use (Rahn *et al.*, 1999). Testing the efficacy of the disinfecting system with samples of live microorganisms is also possible (Lindsley *et al.*, 2018) but requires time and facilities to prepare, grow, and count bacterial colonies.

Radiachromic labels are widely used to monitor the amount of UV radiation received by surfaces in industrial processes using UV-curing coatings and adhesives (Stowe, 2007). Because of their low cost and ease of use, these labels could provide a simple alternative method for verifying the efficacy of UVGI systems. While microbiological testing may still be required as the gold standard in demonstrating initial effectiveness of a UVGI installation, these labels could provide an effective, ongoing verification of system performance. In this article, a method of quickly validating the received UV-C dose using a color-changing intensity label sensitive to UV-C energy was evaluated and compared to a radiometric technique. These labels are small, self-adhesive stickers that begin yellow and change to green with exposure to UV energy. This color change can be quantified to give a measure of the energy to which the label was exposed.

## Materials and methods

To test different aspects of the UV-C color-changing intensity labels for UVGI system verification, we used three experimental methods: (i) an ambient light exposure test, (ii) an angle-dose equivalence test, and (iii) a dose–response range and correlation test. The ambient light exposure test determines how effective the labels were at keeping a stable color when exposed to ambient lighting conditions likely encountered during their use, like fluorescent lights and sunlight. The angle-dose equivalence test detects whether the same dose delivered to a label at varying angles resulted in the same corresponding change in label color. The dose delivered in each run of this test, 30 mJ/cm$^2$, was chosen so the time required to reach the dose was reasonable for all tested angles, about 2–30 min. The dose–response range and correlation test measures two items: first, the range of UV-C energy exposure over which the color would measurably change and second, the correlation of the measured color change and the energy received as measured by the radiometer.

### Colorimetric stickers

This research was completed using 19 × 13 mm (0.75″ × 0.5″) self-adhesive UV-C Intensity Labels (N010-004, UV Process Supply, Chicago, IL). These labels have a color-changing ink that responds to UV energy exposure. The labels have specific sensitivity in the UV-C range but will also respond to light near this wavelength, such as UVA and UVB energy. To quantitatively measure the change in color after UV exposure, a spectrophotometer was used (i1Pro colorimeter, X-Rite, Incorporated, Grand Rapids, MI) with measurements made in the $L^*a^*b^*$ color space. These measurements are a three-dimensional quantification of color: lightness ($L^*$), red-green ($a^*$), and blue-yellow ($b^*$).

In all experiments, two control labels that remained unexposed to the light/energy source were measured—one before the test group exposures (pre-control) and one after the test group exposures (post-control). To calculate the color change of the test group labels, the post-exposure color values were compared to the average measured color of the two control labels. The change was calculated as the square root of the sum of the relative changes in each color dimension squared. This color change measurement is analogous to the straight-line distance between two points within the 3-dimensional $L^*a^*b^*$ color space.

$$(L_{\text{control}}, a_{\text{control}}, b_{\text{control}}) = \left(\frac{L_{\text{pre}} + L_{\text{post}}}{2}, \frac{a_{\text{pre}} + a_{\text{post}}}{2}, \frac{b_{\text{pre}} + b_{\text{post}}}{2}\right);$$

$$\text{Color change} = \sqrt{(L - L_{\text{control}})^2 + (a - a_{\text{control}})^2 + (b - b_{\text{control}})^2}$$

### UVGI exposure chamber

We constructed a polycarbonate chamber measuring 27.9 × 20.3 × 40.6 cm (11” × 8” × 16”) with three internal collimators to ensure light rays reaching the test surface were parallel (see Fig. 1). All interior surfaces of the box were painted with matte black spray paint to prevent external light sources from passing through the polycarbonate and interfering with the experiments. On one end of the chamber, an 18W UV-C lamp (Philips TUV PL-L 18W/4P, Philips Lighting Holding B.V.) with >100 h of burn-in time was installed. On the other end, we installed a custom 3D-printed base. The base supported a moveable platform for holding a SED033/NS254/TD detector/filter/diffuser combination sensor (International Light Technologies) that was wired to a radiometer (ILT-1700 Research Radiometer, International Light Technologies, Peabody, MA) outside the chamber. The platform also held an insert for placing a UV-C Intensity Label. The moveable platform was adjustable to different angles relative to the UV-C lamp (0°–80° angle of incidence in increments of 10°, with an additional position at 45° angle of incidence). The label insert and platform were built so that the surface of the label was at the same position as the calibration plane of the UV-C sensor.

### Test methods

The procedures for the three experimental test methods—ambient light exposure, angle-dose equivalence, and dose–response range and correlation—follow:

1. Ambient light exposure
   a. A total of eight test group labels were exposed to either fluorescent lamps or sunlight for a set period of time, 15–120 min in increments of 15 min, and their color measured. For trials in sunlight, tests were performed outside in direct sunlight with the weather conditions [cloud cover, temperature, humidity, and UV Index] recorded. For trials under fluorescent lamps, tests were performed in the same location under 20 lamps (GE F32T8/SP35/ECO, General Electric Company, Boston, MA).
   b. The UV-C sensor and radiometer were set to measure the UV-C dose at the same location and the total dose was recorded at each time point.
   c. The procedure was conducted four times in fluorescent lighting and three times in sunlight, each in the same location. For tests in fluorescent light, the fluorescent lamps were turned on at least 1 h prior to testing to allow for stabilization of light output.
2. Angle-dose equivalence
   a. The UV-C lamp in the exposure chamber was activated for one hour prior to testing to reach a stable output.
   b. The UV-C sensor was positioned in the platform at an angle of incidence randomly chosen out of 10 possibilities (0°–80° at 10° intervals with an additional test at 45°) and dose measurement was started. The time required to reach 30 mJ/cm$^2$ was measured.
   c. A pre-control label’s color was measured.
   d. A UV-C intensity label was then placed in the platform at the same angle and exposed for the same amount of time required to reach 30 mJ/cm$^2$. The color of the test label and post-control label were then measured and recorded.
   e. The procedure was conducted three times at each angle condition for a total of 30 labels exposed.

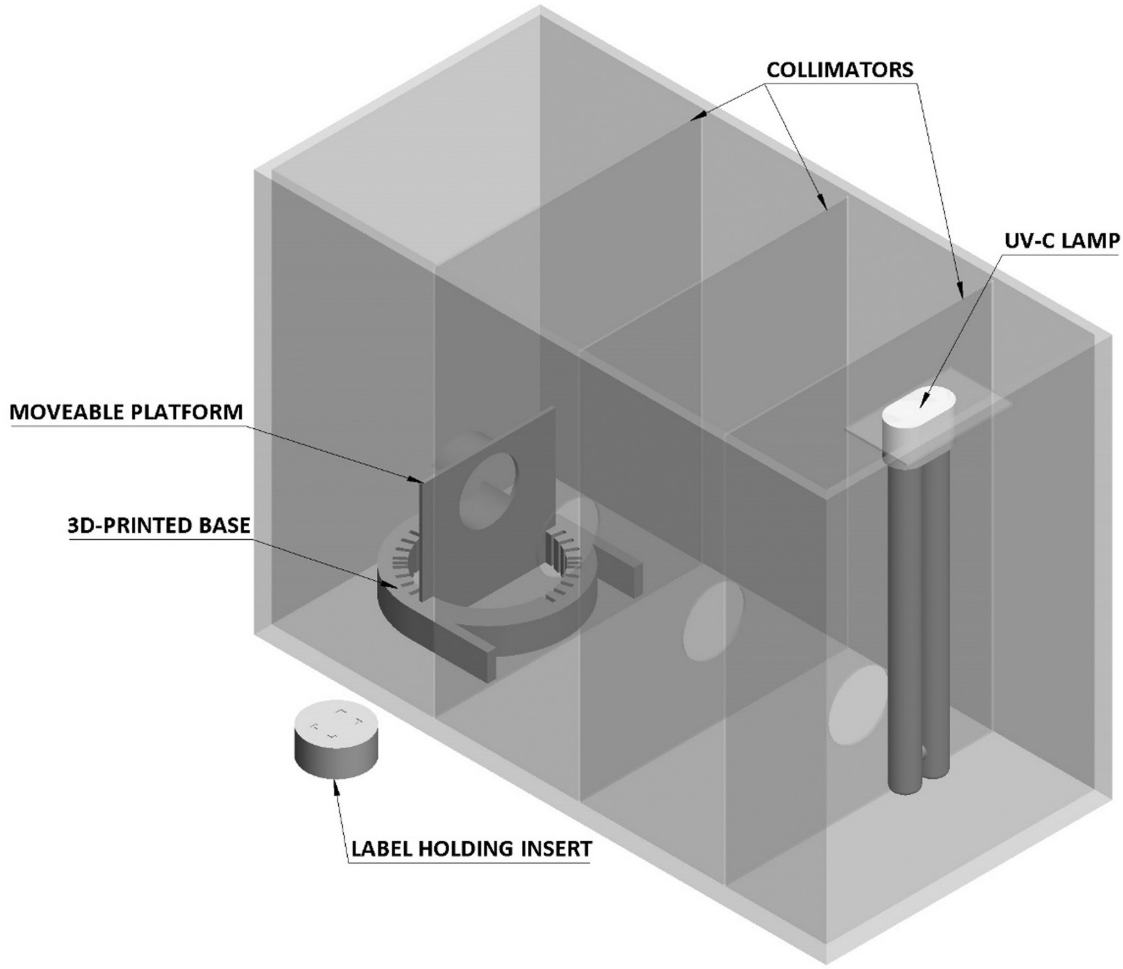


**Figure 1.** Exposure chamber with three internal collimators, test platform, and label holding insert.

3. Dose–response range and correlation
   a. The UV-C lamp in the exposure chamber was activated for one hour prior to testing to reach a stable output.
   b. The UV-C sensor was positioned in the platform at the 45° angle position and the irradiance (radiation energy) was measured.
   c. A pre-control label's color was measured.
   d. A UV-C intensity label was then placed in the platform insert at the same angle and exposed for a set period of time: 1–24 min in 1 min intervals with the time interval being randomly varied.
   e. The color of the test label was measured as well as a post-control label.
   f. The dose was calculated based on the measured irradiance and time interval.
   g. Steps c–e were repeated with the remaining time intervals.
   h. This procedure was conducted four times for a total of 96 test labels.

## Results

### Ambient light exposure

Results observed under fluorescent exposure showed small color changes (mean = 1.375, standard deviation (SD) = 0.907, $n$ = 32) with no difference across the range of time intervals. Results in sunlight showed much larger changes in color (mean = 54.077, SD = 8.148, $n$ = 24), exhibiting the largest color change at time ($t$) = 15 min, with a decrease in color change as exposure length

increased (mean = 64.76, SD = 3.026 at $t$ = 15, $n$ = 3 and mean = 45.258, SD = 5.697 at $t$ = 120, $n$ = 3).

### Angle-dose equivalence

Results showed a color change of mean = 25.471 (SD = 3.926, $n$ = 40) for a dose of 30 mJ/cm$^2$. SAS 9.4 analysis of variance (ANOVA) models with an $F$-test was used to test the differences in color change among the different angles. There was no statistical difference found among the angles ($P$ = 0.52).

### Dose–response and correlation

The SAS/STAT 9.4 Reg procedure was used to model the color change response with a log scale of the dose, and 95% confidence limits and prediction interval were generated, shown in Fig. 2. The analysis shows that the measured color change and the measured dose show dependent behaviors. Therefore, if multiple samples are collected at the same dose, there is a 95% chance that the average color change of those labels would fall within the narrow confidence limit. Any single measurement taken at a given dose would have a 95% chance of being within the wider prediction interval. The color changes logarithmically with an increase in dose with the relationship holding up to the maximum measured dose of 196.7 mJ/cm$^2$.

## Discussion

The ambient light exposure test indicated that the intensity labels showed little to no measured color change when exposed to fluorescent light for short periods of time, specifically, in a range of 15–120 min. These exposure times are greater than would be expected when moving the labels from storage to the locations where they would be used. Thus, incidental exposure to normal fluorescent lighting conditions should not be expected to cause errors in the measurement process. Note, however, that because the labels were only tested under a single type of fluorescent fixture, it is possible that exposure to other fluorescent lamps, incandescent bulbs, or LED light fixtures may cause a greater color change, especially if their emission spectra is higher in the UV range. It is also possible that the visible portion of the spectrum generated by the UV-C lamp used in this research contributed to the color change. Because of the narrow band filter used with the radiometer, we did not measure the intensity of the lamp in this portion of the emission spectrum. Other lamps with similar UV-C output could have a different visible spectrum output. Since fluorescent lamps showed little to no color change and have a wide visible spectrum output, this effect would likely be small but could be investigated further.

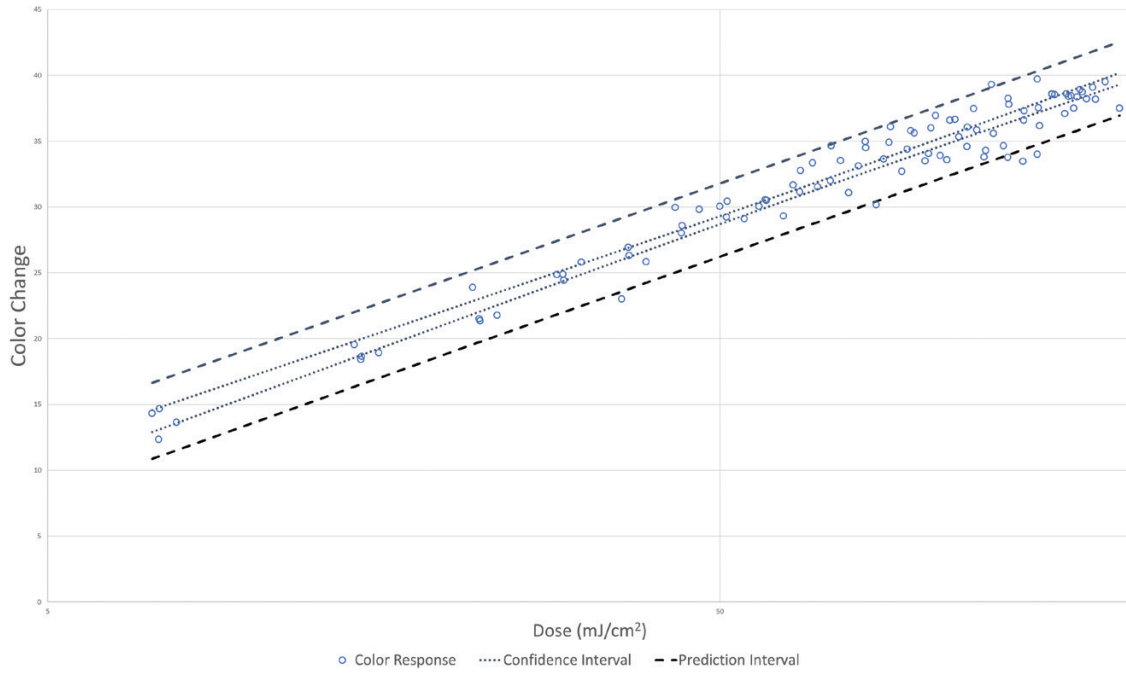


**Figure 2.** Regression Model for Color Change Response—this shows the 95% prediction and confidence limits based on a regression model of the data. Note the *x*-axis *is logarithmic while the y*-axis *is linear*.

In contrast to fluorescent light, sunlight caused visible changes to the labels within seconds of exposure. Tests indicated that over a period up to 2 h, prolonged sunlight exposure first produced a large, measured color change followed by a decrease in a measured color change. This indicates that labels that are accidentally exposed to sunlight should be discarded because the maximum color change appears to be reached very quickly. This is likely due to the labels' sensitivity to a wider range of wavelengths other than UV-C, since sunlight contains very little UV-C energy when it reaches the earth's surface.

The angle-dose equivalence test showed that when a surface received equivalent doses of UV-C at different angles, there was no statistical difference in the measured color changes of the labels. For example, a UV-C dose of 30 mJ/cm$^2$ received at a 10° angle of incidence would induce the same change in color as a 30 mJ/cm$^2$ dose received at an 80° angle of incidence. Therefore, labels used at multiple points in an irradiated space should produce similar estimations of dose regardless of the angle of incidence from the UV light source. Labels can be placed in any desired location within the irradiated space.

The dose–response correlation test showed that the labels were effective at differentiating dose levels to at least as high as the maximum tested dose of 196.70 mJ/cm$^2$. The data collected shows that it is possible to estimate the lower bound of the dose of UV-C energy received with greater than 95% certainty based on the measured color change of the label.

## Conclusions

This research demonstrates that UV-C Intensity Labels can be used to determine a lower bound of the UV-C dose received on a surface if the color can be accurately measured with an easy to use a colorimeter. The technique can also be employed to measure surface dose at multiple locations with the labels exposed simultaneously and their color change measured after the fact. This would be more economical than using multiple photometers and more time-efficient than measuring each location individually with one photometer. Label handling both prior to and after exposure measurement should include protective measures that inhibit accidental light exposure. For a fast and simple qualitative approach, it should be possible to develop a preprinted color chart relating the minimum color change required to ensure delivery of a specific minimum UV-C dose. The UV-C dose received at a location can be verified to be greater than a specified required dose for clinical effectiveness using this technique, regardless of the relative angle of the location surface to the UV-C source. Because the labels are sensitive to UVA and UVB energy, as well as other wavelengths, care should be taken to avoid exposing the labels to sunlight or other UV energy sources prior to use.

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## Conflict of interest

The authors do not have any conflict of interest regarding this research. The findings and conclusions in this article are solely those of the authors.

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