Estimating UV-C Sterilization Dosage for COVID-19 Pandemic Mitigation Efforts

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***Abstract*—The COVID-19 pandemic caused by SARS-CoV-2 has invoked widespread interest in effective and reliable disinfection methods to help combat the virus, including ultraviolet germicidal inactivation (UVGI). Due to the novelty of this coronavirus strain at the time of writing, there are significant gaps in literature on the UV susceptibility of the pathogen. In this paper, estimates of the SARS-CoV-2 UVGI response are derived from studies reporting UV susceptibility of SARS-CoV-1, a close genomic relative. To motivate this comparison, the genome sequences of both coronavirus strains were analyzed and found to have effectively identical theoretical UV-C susceptibility, differing by only 1.48%. Conducting a curve fitting analysis on SARS-CoV-1 survivorship data obtained from existing literature, the approximate UV-C dosage required to inactivate the virus below assay limit of detection was found to be 36144 J/m^2 ($\geq$5-log). Using this dosage as a benchmark for UVGI applications against SARS-CoV-2, a benchmark minimum exposure time can be determined by $\mathrm{t} \approx (1.5 \times 10^6)\pi \cdot (\mathrm{r}^2/\mathrm{P})$, where r is the distance from the UV-C source to the sample surface, P is the wattage of the germicidal bulb, and t is expressed in seconds. This amounts to at least 2 hours for a 15 W UV-C bulb placed 6 inches from a disinfecting surface. The intent of this paper is to provide readers with a tool to evaluate the effectiveness of a simple UVGI system without the need for complex instrumentation in an effort to guide COVID-19 pandemic mitigation efforts and inform operational policy.**

***Index Terms*—COVID-19, SARS-CoV-2, UV-C, dosage, exposure time, UVGI**

I. Introduction and Background

SARS-CoV-2, the highly contagious virus that caused the COVID-19 global pandemic, is believed to be spread primarily through droplet and contact transmission [1]. The former occurs through direct or close contact with an infected individual. The latter occurs when an infected individual leaves viral particles on a surface or fomite. When another person comes into contact with the same surface, remnants of the viable virus may enter their respiratory tract, causing the second person to become infected. As the demand for home delivery spikes due to social distancing measures during the pandemic, the transmission of viable viral loads through cardboard and plastic packaging remains a significant concern. A recent study [2] found that remnants of SARS-CoV-2 were found to live on cardboard for over 24 hours and plastic for 3 days.

The potential for contact transmission has sparked widespread interest in effective and reliable sterilization methods, including ultraviolet germicidal inactivation (UVGI), a disinfection method that uses ultraviolet light in the 280 nm - 100 nm range (UV-C) to inactivate pathogens. Excitations at these wavelengths can be absorbed by genetic material, introducing mutations that can ultimately inactivate the organism [3]. While UVGI has conventionally been used in air purification and water treatment systems [3], the current pandemic has spurred a number of novel applications for this technology such as the mass disinfection of public buses [4] and airplane cabins [5], autonomous robots that enter potentially infected hospital rooms [6], and chambers to sterilize N95 masks for reuse in healthcare settings in order to manage personal protective equipment (PPE) scarcity [7].

Due to the novelty of this coronavirus strain at the time of writing, there have been no studies reporting the inactivation effects of UV-C radiation on SARS-CoV-2. However, there is a body of literature reporting inactivation dosimetry for SARS-CoV-1, the coronavirus strain responsible for the 2002 SARS outbreak. To motivate the arguments and comparisons made in this paper, a genomic analysis is conducted (Section II) to establish that SARS-CoV-1 is a viable proxy for the novel coronavirus in the context of UV-C inactivation. Applying curve fitting techniques to existing literature on SARS-CoV-1, an equation is proposed to determine the amount of exposure time required to effectively inactivate the novel coronavirus given UV-C bulb wattage and distance (Section III). The intent of this paper is to make clear the extent of the effectiveness of UVGI on the novel coronavirus in an effort to guide COVID-19 pandemic mitigation efforts and inform operational policy.

II. Genomic Comparison of SARS-CoV Strains

When absorbed by genetic material, excitation at UV-C wavelengths can cause cross-linking in adjacent pyrimidine bases. This phenomenon, called pyrimidine dimerization, can inhibit successful replication and eventually lead to inactivation [3], [8]. Since these mutations have a higher probability of occurring in regions of the genetic sequence with consecutive pyrimidine bases, a dimerization probability can be derived by counting such instances in the genomic sequence. This metric can then be used to quantify UV-C susceptibility in viruses. Kowalski [3], [8] gives the following equation to predict dimerization probability D_v for single-stranded RNA (ssRNA) viruses such as SARS-CoV-2:

$$D_v = \frac{\sqrt{\sum tt + \alpha \sum \overleftrightarrow{ct} + \beta \sum cc + \gamma \sum \overleftrightarrow{YYU}}}{\sqrt[3]{n_{bp}^2}} \quad (1)$$

where $\sum tt$, $\sum cc$, and $\sum \overleftrightarrow{ct}$ represent all instances of adjacent pyrimidines (i.e., `TT`, `CC`, and `CT/TC`, respectively) in the genomic sequence; $\sum \overleftrightarrow{YYU}$ represents instances where a

pyrimidine doublet is adjacent to an adenine or guanine purine (e.g., ATT and GTC); n_{bp} is the number of base pairs; and α, β, and γ are dimer proportionality constants. Suggested values are $\alpha = 0.1$, $\beta = 6$, and $\gamma = 4$ based on a linear fit analysis of 28 ssRNA viruses [3], [8].

The genome sequences of both viruses were collected from the National Institutes of Health (NIH) genetic sequence database (NC_004718 for SARS-CoV-1, NC_045512 for SARS-CoV-2) [9] and analyzed in a Python script according to (1) using the suggested ssRNA dimer proportionality constants. The results of this analysis are summarized in Table I.

TABLE I
GENOMIC COMPARISON OF SARS-COV STRAINS

	SARS-CoV-1	SARS-CoV-2
$\sum tt$	2207	2454
$\sum cc$	850	784
$\sum \overleftrightarrow{ct}$	3744	3494
$\sum \overleftrightarrow{YYU}$	7732	7736
n_{bp}	29751	29903
D_v	0.2458	0.2422

The two pathogens are close genomic relatives with 79% sequence identity [10], suggesting that the strains have comparable UV-C inactivation responses. The calculated dimerization probabilities of the two coronavirus strains were found to be effectively identical, differing by only 1.48%. These results suggest that SARS-CoV-1 is a sound proxy for SARS-CoV-2 in the context of UV-C inactivation.

III. UV-C INACTIVATION OF SARS-COV-2

For a given UV-C dosage D (expressed in J/m^2) viral concentration decays exponentially as a function of time. Useful parameters such as applied dosage can be numerically extracted from experimental data by fitting the survivorship curve to a decaying exponential with the form:

$$S = e^{-KIt} \tag{2}$$

where S is the surviving fraction of the original virus population after UV-C radiation is applied, K is a factor called UV susceptibility, and I is the intensity at the sample surface [11]. UV-C dosage D is related to susceptibility K by:

$$D = \frac{-\ln S}{K} \tag{3}$$

Combining (2) and (3) yields the simplified relation:

$$D = It \tag{4}$$

This numerical method is applied to multiple studies to extract the approximate dosages for various stages of inactivation. The results are tabulated in Table II. Each study either directly reports a dosage or the measured intensity of the UV-C source at the viral sample, in which case (4) is used to calculate approximate dosage. Values in the first three rows were taken from a literature review by Kowalski [17] which tabulates experimentally derived UV-C dosages across various SARS-CoV-1 papers. The D_{99} column was omitted due to insufficient data across all five studies. The largest reported dosage $D = 36144$ J/m^2 will be used here as the target UV-C inactivation dosage against SARS-CoV-2.

TABLE II
LITERATURE REVIEW OF SARS-COV-1 INACTIVATION DOSAGES

Study	D_{90}	$D_{99.9}$	$D_{99.99}$	$D_{99.999}$
Walker 2007 [12]	7	-	-	-
Duan 2003 [13]	9	-	-	-
Kariwa 2006 [14]	-	134	-	-
Eickmann 2020 [15]	-	5000	10000-15000	-
Darnell 2004 [16]	2410	6020	12050	36144

** values are approximate and expressed in J/m^2*

IV. DETERMINING MINIMUM EXPOSURE TIME

In this section, a simple approximation to determine minimum exposure time is derived and presented. In an effort to help guide operational policy, conservative assumptions are made where necessary in order to express the equation in terms of known parameters such as the wattage of the bulb used and distance to the sample. Minimum exposure time is determined by solving (4) for t, given $D = 36144$ J/m^2. Intensity at the sample surface I is approximated by:

$$I = \frac{P_{\text{UVC}}}{A_{\text{exposed}}} = \frac{\eta P}{4\pi r^2} \tag{5}$$

where P is the power rating of the germicidal bulb (typically either 15 W or 36 W), η is an attenuation factor where $\eta \leq 1$, and r is the distance from the bulb to the sample.

For a conventional 15 W germicidal bulb, only about one-third (5 W) of the original power P is dissipated as UV-C radiation [18]. Additionally, depending on the placement and shape of the bulb, only a fraction of the emitted UV-C radiation will hit the surface. Forgoing further analysis, a conservative and reasonable estimate used here is $\eta \approx 10\%$. The exposed area A_{exposed} is estimated using spherical spreading, where r is the distance from the UV-C source to the irradiated surface.

Combining (4) and (5) yields an equation to determine approximate exposure time t to achieve the target inactivation dosage $D = 36144$ J/m^2 for SARS-CoV-2:

$$t \approx 1.5 \times 10^6 \left(\frac{\pi r^2}{P} \right) \tag{6}$$

where P is the power rating of the germicidal bulb, η is a coefficient representing heat and scattering losses, and t is expressed in seconds. Using (6), a simple UVGI chamber setup consisting of a 15 W UV-C bulb placed 0.15 meters (6 inches) away from the sanitizing surface will require at least 2 hours of exposure to achieve the target inactivation dosage.

V. DISCUSSION

The Centers for Disease Control and Prevention (CDC) recommend a minimum UV-C dosage of 10000 J/m^2 [19] for N95 mask sterilization based on studies that report significant viral inactivation ($\geq$3-log) at this dosage. Several of these studies were omitted from the literature review here because

the sample pathogen was not SARS-CoV-1. Nevertheless, the results of the literature review conducted here are in close agreement with those studies and reinforces the CDC recommendation.

However, the expression of UVGI effectiveness in terms of dosage may be too much of an abstraction for some readers. The approximation in (6) provides readers with a tool to evaluate the effectiveness of a simple UVGI system based on bulb wattage and distance to the sample surface without the need for complex instrumentation. The target dosage $D = 36144$ J/m^2 derived here has been shown to inactivate 99.999% ($\geq$5-log) of SARS-CoV-1 contaminants in a laboratory setting and provides significant margin relative to the minimum CDC recommendation of $D = 10000$ J/m^2.

A. Limitations of UVGI

As a number of studies have noted, there are many factors that can impede UVGI ability in practice [20], [21]. For N95 respirator disinfection applications, there are significant concerns as to whether UVGI systems can deliver the sufficient dosage to inactivate viral particles trapped within the fibers of the mask surface [22]. Shadowing effects must also be taken into consideration when designing UVGI systems [23].

It is important to note that while [16] demonstrated a 5-log reduction in SARS-CoV-1 concentration, this should not be taken to mean that sterilized surfaces no longer pose an infectivity threat. For surfaces containing extremely high viral loads, for instance, 99.999% inactivation does not necessarily translate to complete sterilization. In one recent study, researchers reported SARS-CoV-2 viral loads (expressed in copies/mL) from COVID-19 patient samples ranging from 641 to 1.34×10^{11} with a reported median of 7.52×10^5 [24]. Supposing a surface is infected with the median value, a theoretical 5-log reduction in virus concentration would decrease the viral load to 100 copies/mL. However, taking the upper bound of the dataset would still leave a viable residual viral load of 10^6 copies/mL.

While UVGI has been shown to reduce the risk of contact transmission, more robust disinfection protocols can be designed by implementing a multimodal approach that provides redundancy if environmental factors do not allow for complete UV-C inactivation. The CDC recommends the use of UVGI methods in conjunction with vaporous hydrogen peroxide treatment and moist heat [19]. A well designed protocol that uses UVGI in conjunction with other proven disinfection methods can be a good way to manage and mitigate viral infectivity risk during the COVID-19 pandemic.

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