Germicidal and Antiviral decontamination of air by UV irradiation and UV recirculator method

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Abstract

Ultraviolet irradiation is a well-studied method for air, water and surfaces decontamination that has been successfully used against various pathogens. Ultraviolet radiation has a lethal effect on plant, bacterial viruses (phages) and unicellular organisms (microbes and protozoa). The lethal effect is manifested in the loss of the ability of viruses and phages to reproduce intracellularly, and in microorganisms — in the death of cells before the first division or in the early generations. When radiation is absorbed by nucleic acid molecules in DNA, pyrimidine bases, mainly thymine, dimerize. Inactivation of RNA viruses involves more than just pyrimidine dimers. Hydrates of pyrimidine bases also make a significant contribution to inactivation. The lethal effect spectra have a nucleic acid maximum at 260–265 nm. For individual organisms, both "protein" with a maximum at 280 nm and spectra of lethal effect with maxima at 260 and 280 nm are described, suggesting that proteins and nucleic acids are also involved in the absorption of UV light. Despite the microbial ability to recover from the photodamage by photoreactivation, at high doses, microorganisms can be inactivated down to log 7 (99.99999%) reduction. It have been shown, that the cause of 2020 pandemics, SARS-CoV-2 is susceptible to UV irradiation with significant damage caused at doses below 12 mJ/cm^2. UV radiation, its mechanism of action, evidence of effectiveness against various infectious agents (including the COVID-19 agent) are discussed in the article. Also, we discuss a mathematical efficiency model of Biosan devices that utilizes UV for air disinfection.

Introduction

To the day of this review (13 January 2021), there were above 90 million confirmed cases of COVID-19 and nearly 2 million lethal outcomes (WHO, 2020[a]). It was determined that the disease pathogen, virus SARS-CoV-2, transmitted in multiple ways, but mainly through airborne transmission. Particularly, the virus spread human-to-human within respiratory droplets or aerosols from sneezing and coughing (Vardoulakis et al., 2020; WHO, 2020[b]). Similarly, other infectious diseases, such as flu (Influenza), tuberculosis (Mycobacterium tuberculosis) and tularemia (Francisella tularensis) are believed to transmit through the air to a significant extent. Few bacterial cells are enough to infect human with tuberculosis or tularemia. These diseases could be fatal if untreated (Fernstrom & Goldblatt, 2013).

The air-decontaminating effect of the ultraviolet light (UV) was noticed as early as 1877 and not only explicitly proven itself effective against many airborne pathogens (e.g. tuberculosis or flu) but also served to prove that air was a vector for certain infectious agents (McDevitt et al., 2012; Sharp, 1939). There is evidence of SARS-CoV-2 susceptibility to UV, discussed below. Biosan offers a number of products exploiting UV for decontamination, as example, UV-cleaner boxes (Figure 1) purposed for operations with DNA and RNA (e.g. PCR) and UV cleaner-recirculators (Figure 2) for

room air disinfection. This article overviews the mechanism of UV germicidal effect, susceptibility of microbes, specifically of viruses including SARS-CoV-2, and describes the rationale for UV cleaner-recirculators.

Figure 1: UV-cleaner box UVC/T-M-AR by Biosan.

The germicidal effect of UV irradiation and theory

The UV irradiation is an electromagnetic wave with wavelength ranges from 100 to 400 nm. The UV range splits into three regions: 100–280 nm UVC, 280–320 nm UVB and 320–400 nm UVA. In the context of UV ability to inactivate pathogens reproduction, the irradiation is referred to as the UV Germicidal Irradiation (UVGI), where UVC waves cause the greatest damage to pathogens by impairing DNA and RNA structures at the highest efficiency peak around 260–265 nm (Kowalski, 2009). A wavelength of 253.7 nm is usually used as initially, low-pressure mercury lamps are used for UV disinfection. Their peak intensity was measured at 253.7 nm in most studies which, in turn, made their conclusions in favour of the lamp efficiency (Reed, 2010). Another factor that influences the UV absorption is relative humidity (RH). It was shown, that microbial inactivation efficiency is inversely proportional to RH: the higher is RH, the less efficient will be the UV-induced inactivation. Therefore, a dry room would be more efficiently disinfected (Woo et al., 2012; Peccia, 2001).

The ability of a molecule to absorb UV is described by a few parameters, including absorptivity, the degree of absorption, and the absorptive range. For example, DNA nucleotides have a range that peaks twice: at 265 nm at a nitrogenous base (for thymine) and 200 nm at phosphate and ribose. Absorbing UV, a molecule transmutes to the excited state with chemical and physical properties that may differ from its the ground state. Following excitation, a molecule may undergo a whole range of possible reactions from forming new bonds to isomerisation (Chatwal & Madhu, 2007).

UV irradiation distorts DNA or RNA structure by crosslinking two nucleotide bases — just one picosecond is enough to produce a dimer if the bases are suitably oriented. The individual hydrogen bonds two bases had before the UV-exposure are weaker than the crosslinking bond, which limits the spontaneous repairing possibilities and disrupts microorganism reproduction cycle (Figure 3).

Figure 2: UV cleaner-recirculators UVR-M (left) and UVR-Mi (right) by Biosan.

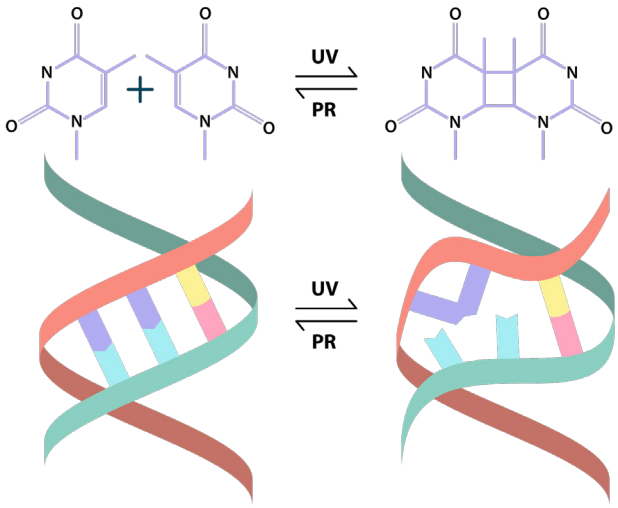


Figure 3: Thymine UV-induced dimerisation. The cartoon shows thymine (indicated by purple) dimerisation reaction stimulated by UV irradiation and the resulting DNA helix distortion. The reaction may be reversed by photoreaction (PR).

In most cases, the crosslink occurs between two thymines in DNA or uracils in RNA, but cytosine dimers also arrise. Purines are also able to absorb UV, but pyrimidines absorption ability is ten-fold more robust, and in practice, thymine dimers are the most often discovered photoproducts. Besides, in some pathogens, especially viruses, UV may be absorbed by proteins and then form a protein-DNA/RNA linkage, which is also damaging (Kowalski, 2009).

It is important to understand the relationship between joules (J) and watts (W) to understand the difference between UV dose [J/m^2] and UV intensity [W/m^2]. Power is the rate a which energy (J) is transferred per unit of time (seconds), and, in the International System of Units, power is quantified in W, equal to J per second. Therefore, W = J/s and J = W×s. In UV context, UV dose is quantified in J/m^2. Thus, the UV dose describes the overall amount of energy transferred per area (e.g. per square centimetre). Meanwhile, UV intensity units are W/m^2 equal to J s^{-1} m^{-2}. Thus, the UV intensity describes the amount of energy transferred per area per second. It is possible to calculate one parameter from another and vice versa if the time of exposure is known. For example, if in 30 seconds the received UV dose was 180 J/m^2, that means that UV intensity was 6 W/m^2 [(180 J/m^2)/(30 s)]. Opposite example: for 2 seconds an area was exposed to UV with intensity of 10 mW/cm^2, so the received dose was 20 mJ/cm^2 [(10 mW/cm^2)×(2 s)] (Figure 4).

$$W = J/s$$
$$J = W \times s$$

$$UV\ dose\ [J/cm^2] = UV\ intesity\ [W/cm^2] \times Time\ [s]$$

$$UV\ intesity\ [W/cm^2] = UV\ dose\ [J/cm^2] / Time\ [s]$$

$$10\ mJ/cm^2 = 0.01\ J/cm^2 = 100\ J/m^2$$
$$10\ mW/cm^2 = 0.01\ W/cm^2 = 100\ W/m^2$$

Figure 4: Relationship between UV intesity and UV dose units.

Microbial susceptibility to the UVGI

Microorganism susceptibility and resistance to the UV differ, but in most cases, it is a question of dosage. Bacteria can execute photoreactivation and recover using specific enzymes (e.g. photolyase) and repair mechanisms, but the ability to heal damage is negligible at high UV doses. A review by Hijnen et al. (2006) states that UV inactivated at least 99% of the initial amount of poliovirus, rotavirus, *Escherichia coli*, *Cryptosporidium parvum*, *Giardia muris* in examined studies, as well as *Yersinia* and *Salmonella* species were inactivated down to log 5 (99.999%) at a UV dose below 10 mJ/cm^2. A review by Chevrefils et al. (2006) summarises findings from over 60 experiments on the UV doses required to achieve a particular log reduction down to log 7 (99.99999%) for various bacteria, viruses, protozoa and protozoan spores, including *Legionella pneumophila*, *Staphylococcus aureus*, caliciviruses, adenoviruses, *Bacillus subtilis* spores and others.

Viruses are shown to be susceptible to UVGI. As Kowalski (2009) noted, 10 J/m^2 (1 mJ/cm^2) would be sufficient to inactivate most viruses with a 0.1 µm diameter significantly. Moreover, since viral nucleocapsid proteins also absorb UV rays, crosslinking may occur between the DNA/RNA and the capsid proteins, which leads both to impairment of genetic material and of capsid structure (Kowalski, 2009). Walker and Ko (2007) studied UV disinfection against viral aerosols of MS2 phage, adenovirus serotype 2 and murine hepatitis coronavirus and found that relatively low doses noticeably inactivated these viruses. In 2007, the authors made a predictive conclusion: "The high UV susceptibility of coronavirus aerosols suggests that UV air disinfection may be an effective tool for preventing important respiratory viral diseases such as SARS". In Table 1, some example doses are given for airborne pathogens.

COVID-19

Speaking about coronaviruses, a single-stranded RNA virus, such as SARS-CoV-2 (Romano, 2020), tends to be critically less resistant against the UV than a double-stranded one due to the lower stability (Kowalski, 2009). Heßling et al. (2020) summarised 30 papers on the UV inactivation of various coronaviruses and calculated an average UVC log-reduction dose of 11.9 ± 11.4 mJ/cm^2 for all coronaviruses. Still, authors suggest the corrected dose was 5.8 ± 5.5 mJ/cm^2, which would be effective against SARS-CoV-2 due to structural similarities among all the coronaviruses. On practice, Bianco et al. (2020) experiment reported 3.7 mJ/cm^2 dose to be the threshold for virus eradication. Similarly, Heilingloh et al. (2020) reported complete inactivation of the virus after 9 minutes of exposure to UV intensity of 1.94 mW/cm^2 UVC and 0.54 mW/cm^2 UVA. Finally, Inagaki et al. (2020) irradiated 87.4% (log 0.94) of the virus stock

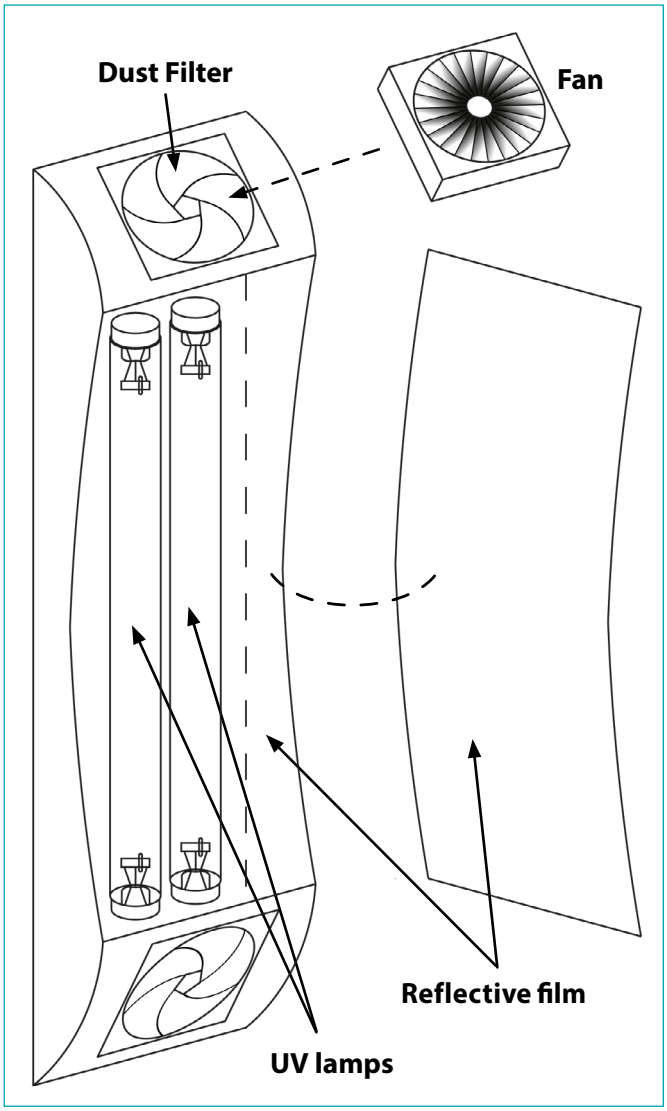
Table 1: UV inactivation doses chart. Doses are averaged from two reviews and ranges given according to standard deviation. * — One study determined dose.
[Source: ClorDiSys (2019); Chevrefils (2006). For SARS-CoV-2: Bianco (2020) and Inagaki (2020)]

Num.	Pathogen Class	Species	**Average dose, mJ/cm^2**	**Inactivation, %**
1	Bacteria	*Mycobacterium tuberculosis*	**10.0–12.2**	**99**
2		*Escherichia coli* ATCC 11229	**8.2–11.0**	**99.999**
3		*Legionella pneumophila*	**6.6–9.0**	**99.99**
4		*Bacillus subtilis ATCC6633* spores	**48.4–60.6**	**99.9**
5		*Pseudomonas aeruginosa*	**10.5***	**99**
6		*Staphylococcus aureus*	**5.6–6.6**	**99**
7	Fungi	*Aspergillius niger*	**132***	**90**
8	Virus	Adenovirus serotype 2 (The most resistant known virus)	**97.1–149.5**	**99.99**
9		Calcivirus feline	**15.9–25.5**	**99.9**
10		Influenza	**6.6–6.8**	**99**
11		SARS-CoV-2	**3.70–3.75**	**87.5**

after exposure to 3.75 mJ/cm^2 and irradiated the virus to 99.9% (log 3) after 37.5 mJ/cm^2. Therefore, UVGI was shown to be effective against the susceptible COVID-19 pathogen, SARS-CoV-2.

UV air recirculators

Biosan produces devices for air decontamination by UVGI. Air re-circulators UVR-M and UVR-Mi have a simple construction and principle. Two fans force air-flow through a chamber installed with a UV lamp (TUV 25 W 1SL/25 by Philips) emitting UV at 253.7 nm. To increase the efficiency of irradiation, inner chamber walls are coated with reflective surface. UVR-Mi is different from UVR-M by having two lamps, meaning higher efficiency, and digital time control. Air flows through the chamber, where UVGI damages aerosolized microorganisms as described in previous sections (Figure 5).



Overall, the efficiency of the UVR-Mi in an irre-circulated room could be described by a few values. As measured: (1) the air-flow productivity was measured at 14 m^3 of air forced in an hour; (2) the UV intensity within the chamber ranged from 18.6 (MIN intensity) to 36 mW/cm^2 (MAX intensity) dependent on the distance from lamps but not taking the reflective surface into account; (3) the inner chamber volume was 2,233.721 cm^3 considering volume-occupying factors, such as lamps and corpus shape irregularities.

Using these values a mathematical model was created for two cases, MIN and MAX intensity. We assumed no diffraction, interference or reflection of light (e.g. due to RH). Thus, it was calculated that in one cycle, received UV dose would range from 10.7 to 22.4 mJ/cm^2 (Figure 6). Therefore, just one cycle should be enough to inactivate many pathogens and cause critical damage to SARS-CoV-2. In addition, 23 minutes of a single UVR-Mi work noticeably reduces the number of colony-forming units (Figure 7).

The presence of an air conditioner in a room affects the recirculation efficiency. One UVR-Mi is able to effectively process a 9 m^2 ventilated room or an 18 m^2 unventilated one, while UVR-M effective room area is 6 and 12 m^2 respectively (Table 2). The area might seem small, however, it is essential to consider: the received dose in one cycle is inversely proportional against the flow-rate. Increasing fan output to process air faster or process a larger area room would shorten the exposure time of passing particles and, therefore, decrease the UV dose received in one air-flow cycle (Figure 8). A way to overcome this limitation is to increase both the fan power and UV lamps intensity, which makes the device noisy and more energy-consuming. Nevertheless, having several re-circulators increases effective volume without lowering doses or creating disturbing fan noise.

Figure 5: Construction schematics of a UV cleaner-recirculator UVR-Mi by Biosan. Forced by a fan, air passed through one filter into the chamber where it gets exposed to the UV emitted by the lamps then, decontaminated air leaves the chamber.

Conclusions

UV irradiation was already used against epidemic agents and, as discussed above, evidence shows that COVID-19 pathogen is also susceptible to UV. Therefore, air disinfection would not only be a good preventive technique but also an essential strategic step in fighting the 2020 pandemics. To note, the UV susceptibility of SARS-CoV-2 is not studied extensively yet. Still, it is very likely the inactivation dose would remain as low as it is detected so far due to similarities between all coronaviruses.

$$UV\ dose = UV\ intensity \times Exposure\ time = UV\ intensity \times \frac{Chamber\ volume}{Air - flow\ rate} =$$

$$= 36\ mW/cm^2 \times \frac{2.25 \times 10^{-3}\ m^3}{3.61 \times 10^{-3}\ m^3/s} \approx \mathbf{22.4\ mJ/cm^2}$$

$$UV\ dose = UV\ intensity \times Exposure\ time = UV\ intensity \times \frac{Chamber\ volume}{Air - flow\ rate} =$$

$$= 18.6\ mW/cm^2 \times \frac{2.25 \times 10^{-3}\ m^3}{3.61 \times 10^{-3}\ m^3/s} \approx \mathbf{10.7\ mJ/cm^2}$$

Figure 6: UV dose produced by UVR-Mi by Biosan: equation and calculations.

Figure 7: Air contamination before and after short-term recirculator UVR-Mi operation.

Table 2: Effective volume of room decontamination by UVR-M and UVR-Mi UV-cleaners recirculators. Number of units increases the effective decontamination volume. Room sizes are shown as area (m^2) and volume (m^3) Abbreviations: Unvent. — unventilated; Vent. — ventilated.

Model	UVR-M			UVR-Mi		
Num of units	1	2	3	1	2	3
Vent. room	**6 m^2 (18 m^3)**	**12 m^2 (36 m^3)**	**18 m^2 (54 m^3)**	**9 m^2 (27 m^3)**	**18 m^2 (54 m^3)**	**27 m^2 (81 m^3)**
Unvent. room	**12 m^2 (36 m^3)**	**24 m^2 (72 m^3)**	**36 m^2 (108 m^3)**	**18 m^2 (54 m^3)**	**36 m^2 (108 m^3)**	**54 m^2 (162 m^3)**

Biosan has produced devices that exploit UV for disinfection since 2004. These devices are time-tested, debugged and suitable for air decontamination in laboratory rooms, hospitals (e.g. examination rooms, delivery rooms, outpatient departments), schools and any other public places. According to the mathematical model described, UV recirculators expose air to UV dose sufficient to cause serious damage to airborne pathogens including SARS-CoV-2. Biosan box UVT-S-AR is suitable for work with sensitive techniques, such as PCR. Please, refer to Bankovsky et al. (2018) case study of our UV-cleaner boxes for more information about that method.

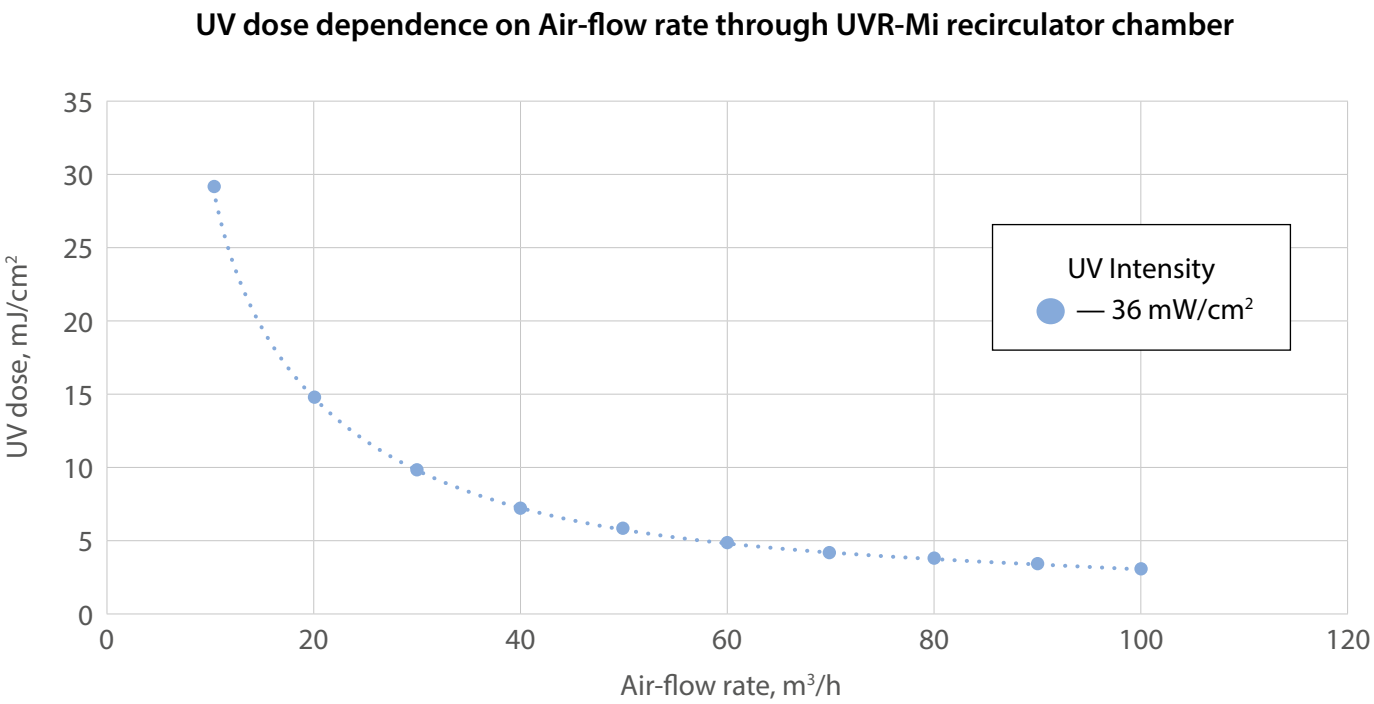


Figure 8: The relatioship between the air-flow rate of UVR-Mi by Biosan and the UV dose received within it per one cycle.

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