A Review of Recent Evidence for Utilizing Ultraviolet Irradiation Technology to Disinfect Both Indoor Air and Surfaces

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About

Abstract

Background: The implementation of "no-touch" technologies such as ultraviolet (UV)-based sanitizers to effectively disinfect the air and high-touch surfaces may be important to keeping working environments and indoor public gathering places, where there may be a higher risk of infection from specific agents, safe for all occupants, particularly with the emergence of highly communicable diseases. UV technologies have been used for many years and are being revisited as one of disinfecting technology to address the SARS-CoV-2 virus that causes COVID-19.

Methods: We selected over 20 relevant source documents from approximately 80 papers dating between 1985 and the present (2020) to evaluate the applicability, safety and relative contribution of ultraviolet to disinfect air and surfaces in the built environment. UV-based sanitizers have the potential for effective application when used in conjunction with other disinfecting means.

Results: The efficacy of UV-based sanitizer technologies are promising but are dependent on numerous environmental, physical and technical factors.

Conclusions: We believe that UV technologies should not be utilized in isolation and should be considered as an adjunct to protocol-driven standard operating procedures for cleaning and disinfection, had hygiene practices, and appropriate use of personal protective equipment (PPE).

Introduction

Cleaning and disinfection of public spaces are salient matters because contaminated built environments have been implicated in pathogen transmission.[1,2] This is because contaminated surfaces and objects, also called fomites, play a key role in the transmission of some infectious agents. Fomites are generally contaminated by infective respiratory droplets, which are usually considered to be >5 μm in diameter. When persons touch a contaminated fomite, the microorganism is transferred to their hand (a transmission process known as indirect contact).

From there, it can be transferred to susceptible sites on the body, creating the opportunity for infection.[3]

Pathogens can also be transmitted through aerosol. Aerosol transmission refers to the presence of microbes within droplet nuclei, which are generally considered to be particles <5 µm in diameter and that result from the evaporation of larger droplets or exist within dust particles.[4] These nuclei may remain in the air for long periods of time and be transmitted to others over distances >1 m.[4] The intent of this article is to provide evidence that no-touch technologies such as ultraviolet (UV)-based sanitizers have the potential for effective application, and should be considered an adjunct to protocol-driven standard operating procedures for surface cleaning and disinfection, hand hygiene practices, and appropriate use of personal protective equipment (PPE). Furthermore, it is crucial to keep in mind that the efficacy of these technologies is heavily dependent on a range of situational factors including temperature, humidity, distance from the radiation source, dwell time, UV intensity, and UV resistance of microorganisms.

Ultraviolet Radiation

UV technology is a nonchemical approach to disinfection. UV technology is also advantageous because it does not require changes in room ventilation, does not leave a residue after treatment, and has a broad spectrum of action.[5] UV light has been successfully used to reduce the bioburden of a room enough to stop outbreaks associated with environmental contamination[6] and healthcare-associated infections (HAIs) transmitted from high-touch surfaces.[7]

UV radiation is electromagnetic radiation with a wavelength of 100–400 nm—shorter than that of visible light (400–700 nm), but longer than X-rays (<100 nm). UV radiation is classified into three bands, UV-A, UV-B, and UV-C, along with a subset of UV-C known as far UV-C. These four categories are defined as follows:

1. UV-A—wavelength: 315–400 nm.[8] Not absorbed by the ozone layer. Reaches earth's surface.

2. UV-B—wavelength: 280–315 nm.[8] Mostly absorbed by the ozone layer, but some does reach the earth's surface.

3. UV-C—wavelength: 100–280 nm.[8]Completely absorbed by the ozone layer and atmosphere.

a. Far UV-C—wavelength: 207–222 nm. A subset of UV-C, which can be used to inactivate bacteria and viruses without causing harm to acutely exposed mammalian skin.[9]

UV-A and UV-B wavelengths are harmful to humans and animals because they penetrate the upper layers of skin and can cause skin cancer, cataracts, suppression of the immune system and premature aging of the skin.[10] UV-C causes DNA damage in mammalian cells[11] through photohydration, photosplitting, photodimerization, and photo-cross-linking,[5] thereby inhibiting cellular replication. UV-C light damages the genetic nuclear material (DNA or RNA) in biological cells and viruses.[12] Ozone may be produced from UV-C lamps emitting UV-C at wavelengths <240 nm. Exposure to ozone, above threshold levels, may cause adverse effects to the eyes, skin, and respiratory tract in humans.[13] The Environmental Protection Agency advises that the UV-C lamps that emit ozone should not be used in closed premises without ventilation.[14] Far UV-C radiation devices also generate some ozone, however, it is not a significant level to provide an antimicrobial effect to aerosolized viruses.[15] According to the International Ultraviolet Association, the risk posed by this generation depends on the UV power, air flow/stagnation, operation duty cycle, UV spectrum, etc. A risk assessment should be conducted for ozone exposure from far UV-C to evaluate the safety for far UV-C irradiation in the presence of humans. There has not yet been sufficient consensus on its safety.[16]

UV-C can be generated by man-made electrical sources such as low-pressure mercury vapor lamps, excimer lamps (using a krypton–chlorine gas mixture),[17] or special lamps that emit continuous low doses of the desired wavelength of UV light, such as far-UV-C lights as researched by the Center for Radiological Research at Columbia University.[18] The most lethal range of UV-C is 250–270 nm, with 262 nm being the optimal wavelength for germicidal action[19]; 254 nm, which is close to this optimal wavelength, is easily produced by a low-pressure mercury vapor lamp.[11]

Types of UV-C Decontamination

Ultraviolet germicidal irradiation (UVGI) is a method of disinfection that uses the 254 nm radiation from low-pressure mercury vapor lamps to inactivate or kill microorganisms and pathogens on surfaces, in air, and in water. UVGI is commonly used as a germicidal UV-C light in the upper part of a room to inactivate airborne microorganisms. This method uses louvers to prevent direct exposure of potentially occupied room areas.[20] A Lancet study showed that UVGI lights installed in ventilation systems led to a 99% reduction of microbial and endotoxin concentrations, resulting in significantly fewer work-related respiratory and mucosal symptoms.[21]This makes ventilation installment a promising alternative or supplement to the upper room method.

A different method, far-UV-C light, is a new technology that has been shown to inactivate bacteria without harming acutely exposed mammalian skin.[9] Far-UV-C light is generated by filtered 222 nm excimer lamps at a wavelength of 207–222 nm; this wavelength is unable to penetrate the outer (nonliving) layers of human skin, the eye, or other organs and is, therefore, proposed safe for acute human exposure.[22] Bacteria and viruses are so much smaller than the depth of the human skin layer that far-UV-C can still penetrate and inactivate these microorganisms.

Assuming sufficient air dwell time in the light to achieve fluence (and, therefore, pathogen inactivation), study has provided some evidence that a continuous very low dose rate of far-UV-C light in indoor public locations may be a promising, safe, and inexpensive tool to reduce the spread of airborne-mediated microbial diseases.[17] In general, the use of low-level far-UV-C fixtures could provide the desired antimicrobial benefits without the accompanying human health concerns of conventional UVGI lamp. The challenge lies in designing the far-UV-C light solutions to fit existing fixtures and building/room configurations.

General Considerations for UV-C Decontamination

No-touch surface decontamination technologies that use automated disinfection devices as a complement to other infection control precautions (e.g., appropriate use of PPE, surface disinfection strategies, environmental cleaning and disinfection strategies, and hand hygiene practices) serve to reduce HAIs from high-touch surfaces[7] as well as to reduce the bioburden in the air. UV-C decontamination may be an effective no-touch technology that, depending on its application, can be automated to meet facility needs.[23]

UV-C's germicidal effectiveness (meaning its ability to destroy the organism's ability to multiply and cause disease) and use are influenced by the presence of organic matter, wavelength, type of suspension, temperature, humidity, type of microorganism, and UV intensity, which is affected by distance and tube cleanliness.[24] The effectiveness of UV lights also depends on the exposure time and the ability of the UV light to reach the viruses in folds, crevices, and undersurfaces of materials and surfaces where the UV light cannot reach.[25]

No-touch UV technology is dependent on the distance between the lamp and the surface being disinfected; for a point source, the inverse square law states that doubling the distance between the lamp and the surface being disinfected will quadruple the time required for disinfection.[5]

UV-C light disinfection systems using low-pressure mercury lamps including portable and rolling units and strategically placed stationary fixtures that produce continuous UV-C with a wavelength of 254 nm must be used judiciously in normally occupied spaces; because of the potential health risks, UV light disinfection must only take place when rooms are unoccupied to avoid injury to occupants. Other necessary safety measures include warning signage, timers, and motion sensors that shut off the device if any movement is detected inside the room being disinfected. In addition to health risks, some materials, such as high-pressure acrylic material, may show degradation with prolonged periods of exposure to UV light and must be covered during the UV-C application to avoid these effects.[5]

Although many UVGI technologies are approved by the FDA,[26] far UV-C light has not yet been approved.[18] All UV-C decontamination should follow existing guidance for safe human and animal exposure. The National Institute for Occupational Safety and Health recommends that the maximum exposure should not exceed 6 mJ/cm^2 for an 8-hour period.[27] The American Conference of Governmental Industrial Hygienists threshold limit values (TLVs) for occupational exposure to UV refer to UV radiation in the spectral region between 180 and 400 nm. TLVs represent conditions to which workers may be repeatedly exposed without adverse health effects; the TLVs for occupational exposure to UV radiation incident upon skin or eye are based on the irradiance and time of exposure.[28]

UV-C Light Decontamination Applications

A key advantage of the UV-C approach is that UV-C light has the potential to be effective against all airborne microbes before they enter the body.[12] Contaminated droplets from sneezing, coughing, and talking may be expelled into the “local” air and travel through air currents. Some of these droplets may drop onto surfaces and remain infective for varying periods of time, depending on factors such as temperature, humidity, air currents, organism viability, and stability of microorganisms.

By appropriately applying UV-C lamp system devices in air handling systems and in room settings, both the breathing air and the surfaces (onto which contaminated particles may fall from the air) can be disinfected. Upper room air disinfection devices with UVGI can be installed in occupied spaces (above eye level) to control bioaerosols, as well as in air handling units (AHUs) or ducts to disinfect circulated air and to control microbial growth on cooling coils and other surfaces.[29-31] The in-duct air disinfection system has the potential to deliver and uniformly distribute the appropriate UV-C dose with the requisite dwell time to the air moving in the irradiated zone.[29,31]

Other examples where UV-C strategies may be used effectively for disinfection needs, as identified by a risk assessment, include cooling coils, drain pans, air filters, insulation, plenum walls, and humidifiers; point-of-use drinking water applications; pharmaceutical production, laboratories, hospitals, and clinics; hospital treatment areas and patient rooms; common areas of congregation such as kitchenettes, lobbies, and stairwells; and animal husbandry areas.

UV disinfection strategies can include a variety of individual and combined elements. Among these are specific installations such as point-of-care UV that may be installed to disinfect high-touch surfaces such as keyboards, portable medical equipment, computers on carts, kitchen areas, and stairwells[23]; cell phone and small equipment disinfection stations; in terminal heating, ventilation, and air conditioning (HVAC) ducts; and in other HVAC system components and in public places such as transportation terminals and common use spaces in office buildings.

Safety features of UV disinfection strategies include built-in motion sensors that enable the unit to safely emit UV-C light for disinfection when in-room workstations and stationary[5] or moveable equipment are not in use and no motion is detected. For this application, device settings must be established to determine clean time (the period of time the device is producing UV-C light; no motion time (the length of time the device will allow to pass after the motion sensor has last registered movement before producing UV-C such as 1 to 4 min, depending on sensitivity); wait time (downtime scheduled between cleaning cycles that are unrelated to motion sensor activity such as 1 hour)[23]; door interlocks; and a building management system card for each unit.

UV-C Decontamination and Coronavirus Disease 2019 (COVID-19)

To most efficaciously respond to the current pandemic, it is necessary to determine routes of virus transmission to develop effective measures to protect the public. To date, scientists have established that the severe acute respiratory syndrome coronavirus (SARS-CoV-2)—the virus that causes coronavirus disease 2019 (COVID-19)—can be transmitted in two ways, with a third potential route under investigation:

1. Inhalation of virus-laden liquid droplets (from coughing or sneezing of an infected person)

2. Contact with surfaces that contain the virus—*lower transmission risk*

3. Aerosol transmission—*research pending.*

A recent study in China recognized that, although aerosols may be an additional transmission route for SARS-CoV-2, further research is needed to determine the infectivity of the aerosolized virus.[32] Although a scientific brief posted on the World Health Organization (WHO) website on March 29, 2020, cited that there is insufficient evidence to suggest that airborne SARS-CoV-2 is infectious,[4] WHO has since revised their position (on July 9, 2020) to note that there is evidence to suggest that COVID-19 is spread from person to person by direct, indirect (through contaminated objects or surfaces), or close contact with infected people through small droplets expelled from the mouth and nose when an infected or asymptomatic person coughs, sneezes, or speaks. These droplets are relatively heavy, do not travel far, and quickly sink to the ground. People can catch COVID-19 if they breathe in these droplets from a person infected with the virus.[33] A CDC COVID alert similarly warns that COVID-19 is thought to spread mainly from person to person, through respiratory droplets from an infected person who coughs or sneezes. These droplets can land in the mouths or noses of people who are nearby or possibly be inhaled into the lungs. Spread is more likely when people are in close contact with one another (within ~6 feet).[34]Doremalen et al. provide scientific evidence that the half-lives of SARS-CoV-2 and SARS-CoV-1 are similar in aerosols and on copper, and the half-life of SARS-CoV-2 is longer than that of SARS-CoV-1 on cardboard. Both viruses show a longer viability on stainless steel and plastic with an estimated median half-life for SARS-CoV-2 of 5.6 hours on stainless steel and 6.8 hours on plastic. They conclude that aerosol and fomite transmission of SARS-CoV-2 is plausible, since the virus can remain viable and infectious in aerosols for hours and on surfaces up to days under certain conditions.[35]

The science on this subject is evolving rapidly as data are generated and analyzed. There is currently no scientific evidence that there is a health risk due to aerosol transmission. If, however, further research does find a proven health risk in airborne SARS-CoV-2, recirculated building air systems may be a source of distribution and transmission within buildings. In this case, in addition to the cleaning and decontamination of high-touch surfaces and other standard hygiene and social distancing practices, the use of UV-based sanitizers in air ducts or AHUs to decontaminate recirculated air may be an effective method of infection control by reducing the bioburden in the air.

Conclusion

In this era of newly emerging highly communicable diseases, there is an urgent need to keep work environments and public spaces safe for the occupants. UV-C light disinfection systems at a peak wavelength of 254 nm have been used to disinfect fomites and HVAC systems for many years, but they can have deleterious effects on humans and animals who are directly exposed to the UV-C light. Understanding these restrictions, UV light still holds promise and has been shown in specific instances to reduce bioburden and disease incidence.

It is crucial to keep in mind that the efficacy of these technologies is heavily dependent on a range of situational factors including temperature, humidity, distance from the radiation source, UV intensity, dwell time, and virulence of microorganisms. However, such technologies have the potential for effective application and should be considered an adjunct to protocol-driven standard operating procedures for surface cleaning and disinfection, hand hygiene practices, and appropriate use of PPE. With further evaluation and scientific research, it may also prove effective and practical to utilize UV-C light disinfection as a method to reduce the risk of COVID-19 airborne transmission.

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