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Understanding UVC Ultraviolet Light Disinfection

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History of Ultraviolet Light Disinfection

As early as 1877 scientists Downes and Blunt observed that ultraviolet light could prevent the growth of microorganisms. Between 1904 and 1905, Hertel used arc lamps and a prism to determine disinfection effectiveness for different wavelengths of light. He determined that UVC ultraviolet light was the most effective, although the reasons were not yet understood.

In 1929 and 1930 Gates was able to show that UVC light had maximum disinfection effectiveness at 265nm wavelength. This was fortuitous because low-pressure mercury vapor lamps emit energy at 254nm, near the peak of disinfection effectiveness.

In the 1950s UVC light was demonstrated to be effective at reducing the spread of tuberculosis and influenza. However, UVC was largely abandoned in subsequent years due to the introduction of new antibiotics and widespread immunization with vaccines. Additionally, concern was being raised regarding the health impact of human UVC exposure and ozone production by UVC lamps. More details regarding the history of UVC disinfection can be found in reference [1].

Mitigating Infections in Hospitals

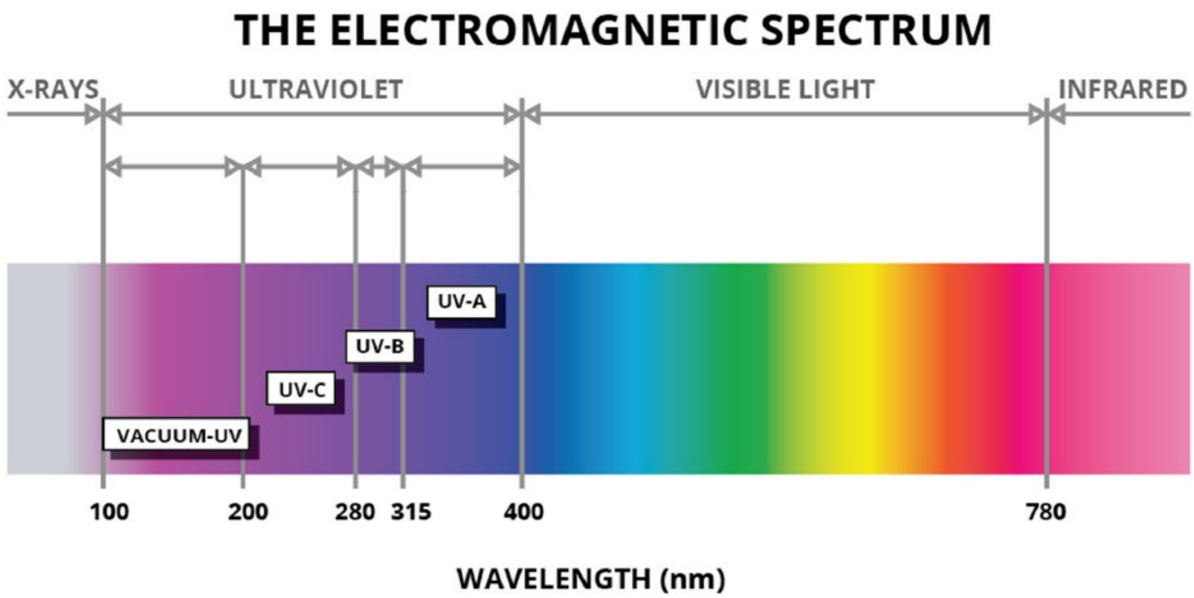
During the last decade, UVC disinfection in hospitals has had a resurgence in order to mitigate healthcare-associated infections (HAIs). The U.S. Centers for Disease Control and Prevention (CDC) estimates that roughly 1 in 25 U.S. hospital patients is diagnosed with at least one infection related to hospital care alone.[2] The CDC also estimates that HAIs are responsible for nearly 100,000 deaths per year in the U.S.[3]

COVID-19 Drives UVC Demand

The COVID-19 pandemic immediately boosted demand for UVC disinfection equipment in hospitals. At the same time, hundreds of companies began introducing UVC disinfection products for home and office use. Even though these products give users confidence they are killing pathogens, many provide little if any actual disinfection. Buyer beware, for many of these products are merely high-tech versions of “snake oil”. The only practical way to validate disinfection efficacy of these products is by using a UVC dosimeter.

Understanding the Light Spectrum

The Sun produces a broad spectrum of radiation, some of which is in the form of light. But light can be further categorized into various types as shown in the figure below:



Types of Ultraviolet Light

Ultraviolet light is divided into four categories: UV-A, UV-B, UV-C and Vacuum-UV. UV-A and UV-B reach the Earth's surface and are responsible for skin tans and sunburns. However, because of the Earth's ionosphere, virtually no UV-C or Vacuum-UV reach the Earth's surface. The ionosphere is a natural radiation shield – without it, intense UV-C radiation (often written as just UVC) and other high-energy radiation would have prevented most life as we know it!

The shorter the light wavelength, the higher the energy of the light photons. Consequently, UV-B ultraviolet photons have more energy than visible light photons, and that's why UV-B causes biological damage and can create skin cancer while visible light does not. UV-C photons are even more energetic and capable of doing more biological damage.

How UVC Neutralizes Pathogens

The high-energy photons of UVC ultraviolet light damage the RNA or DNA in pathogens. This doesn't necessarily kill pathogens, but it eliminates their ability to reproduce. Pathogens generally fall into one of three categories: viruses, bacteria and fungi. In sufficient doses, UVC ultraviolet light can effectively neutralize any pathogen.

How UVC Dose is Measured

First, it's important to understand the difference between power and energy. Joules (J) is a unit of energy, while Watts (W) is unit of power (rate of energy delivery). Expressed as a formula:

1 Joule = 1 Watt x 1 second

UVC "dose" is a measurement of UVC energy delivered per unit area (typically one square centimeter or cm^2). That total dose can be the result of low UVC power for a long duration, or a high UVC power for a short duration. For example:

- $50mJ/cm^2$ can be produced by $50mW/cm^2$ for 1 second
- $50mJ/cm^2$ can be produced by $1mW/cm^2$ for 50 seconds

In the above example milli-Joules (mJ) and milli-Watts (mW) are used because typical UVC dose energy and power measurements are in this range.

<u>Neutralizing Pathogens is Probabilistic</u>

Neutralizing pathogens with UVC is probabilistic in nature; as the dose increases, the percentage of pathogens neutralized increases. The UVC industry defines the degree of disinfection by a Log Reduction Value (LRV), referring to what power of 10 neutralization has been achieved.[4] The table below shows how LRV values translate to neutralization percentages:

Log Reduction Value (LRV)	Reduction Factor	Percent Neutralized
1	10	90%
2	100	99%
3	1,000	99.9%
4	10,000	99.99%
5	100,000	99.999%

Required UVC Dose Levels for Disinfection

Each pathogen has its own unique characteristics and LRV profile for neutralization, and an ever-growing list of pathogen characteristics is being collected.[5] Staphylococcus aureus is a bacteria pathogen commonly found in HAIs. The table below shows the LRV dose values for this particular pathogen using 254nm UVC light:

LRV	1	2	3	4	5
Dose in mJ/cm^2	4.4	5.8	6.4	7.3	9.0

254nm UVC Dose Levels by LRV for Staphylococcus aureus[5]

As shown, Staphylococcus aureus requires a UVC dose of $7.3mJ/cm^2$ in order to achieve 99.99% neutralization (a commonly used disinfection target). As shown in reference 5, some pathogens require substantially higher dose to achieve an LRV of 4; however, most common pathogens will achieve an LRV of at least 4 with a dose of $50mJ/cm^2$. Consequently, $50mJ/cm^2$ is often used by hospitals as a UVC dose target in operating rooms and patient rooms.

UVC Effectiveness on COVID-19

Although experiments are still being conducted on COVID-19, it is presently believed to have characteristics similar to other coronaviruses. Based on laboratory data for other coronaviruses, a 254nm dose of $50mJ/cm^2$ should neutralize the COVID-19 virus to at least an LRV of 4 (99.99% reduction).

Real-world UVC Disinfection Challenges

All of the dose data above relate to disinfection of pathogens that are located on a surface. Surface-contact is known to be a common means of pathogen transmission between people, so this data is certainly relevant. However, some additional real-world situations must be considered.

Light Angle and Distance

UVC light rays perpendicular to a surface (0° angle) will have maximum effectiveness, while UVC rays hitting the surface at an angle will be less effective. Accurate measurements of UVC dose must take the light angle into account by applying what is termed cosine correction. We're all intuitively familiar with cosine correction in the real world – when facing the Sun your forehead will get sunburned, but the sides of your face will be less burned because of the angle of the Sun's rays.

Surface angle and distance from the UVC lamp both have a significant impact on the dose received by a surface. In the case of room disinfection equipment, perpendicular surfaces close to the lamp may receive ample dose, but distant surfaces not directly facing the lamp may receive a small percentage of the desired dose and still contain active pathogens. The only way to know for sure what dose is being received at different locations is by using a UVC dosimeter with excellent cosine correction.

Shadows Present Challenges

Shadows present another real-world challenge. Some of the most frequently touched surfaces are shadowed from whole-room disinfection equipment. For example, the undersides of door handles, light switches and handrails are often touched in locations that are shadowed from a whole-room disinfection lamp. Handheld UVC wands can be used to manually disinfect these shadowed surfaces, but the low power of most handheld devices means that considerable time must be spent on each shadowed area to deliver sufficient dose.

UVC Penetration Depth

UVC light penetration into most biological substances is very shallow, typically only a few microns (millionths of a meter), and this has both good and bad implications. For instance, if a pathogen resides in some spilled food, the UVC may neutralize any pathogens on the surface of the film, but it can't reach into the bulk of the film. This is one of the reasons hospitals generally use a combination of wiping with disinfectants followed by UVC irradiation to increase disinfection efficacy. The same technique should be used in non-hospital environments where thorough disinfection is important.

Disinfecting Masks and Fabrics

Porous materials such as face masks and fabrics present yet another challenge. As explained above, UVC light doesn't penetrate very far into surfaces, so cavities in porous materials receive very little of the surface UVC energy. This means that UVC dose levels must be dramatically increased to disinfect such materials. For instance, some experts are recommending over $1W/cm^2$ UVC dose to disinfect face masks – this is 20 times the dose generally used for surfaces – and this high UVC dose may also degrade the mask material itself.

Creating UVC Light

Today, most UVC light is produced by low-pressure mercury vapor lamps. These lamps are similar to normal fluorescent lamps but without the white phosphor coating on the inside. These lamps are relatively inexpensive, can produce significant UVC power and are roughly 33% efficient at converting electrical power into UVC light.

UVC LEDs Now Available

Another option for generating UVC light has recently become available – UVC LEDs. However, these LEDs are still very expensive and inefficient compared with mercury vapor lamps. For example, a UVC LED that emits 50mW of UVC power today costs approximately $15 in volume. This means that a piece of UVC disinfection equipment producing only 1W of UVC power would contain roughly $300 of LEDs! This limits UVC LEDs to medical and industrial applications that cannot use mercury vapor lamps and can support very high prices.

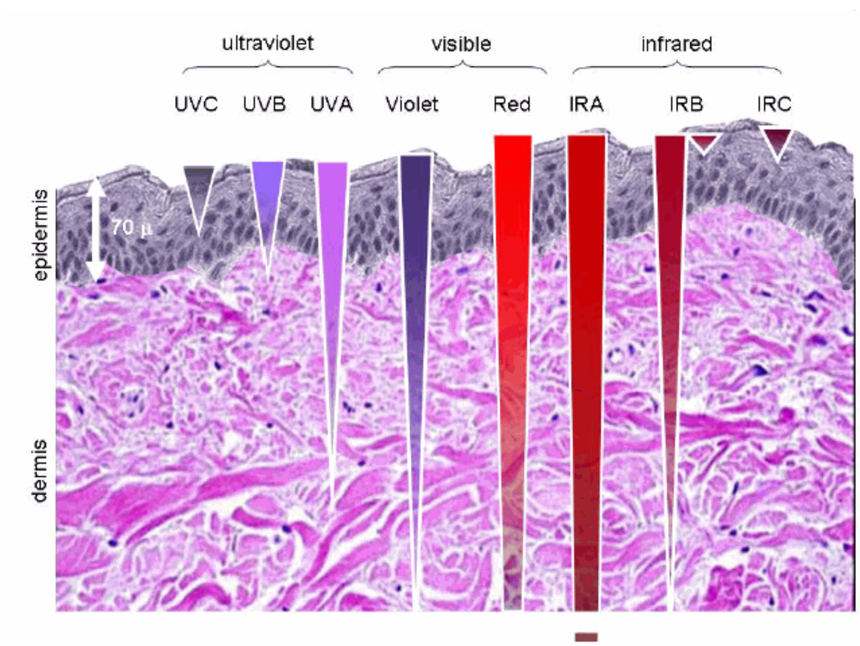
This leads to another case where buyers should beware. If you see an advertisement for a low-cost UVC disinfection wand that uses LEDs, it's highly unlikely that it uses actual UVC LEDs.

Such a device most likely uses standard blue LEDs that produce a blue glow similar to that of a mercury vapor lamp but with absolutely no disinfection capability. A UVC dosimeter must be used to determine if the disinfection wand is actually delivering UVC or just pretty blue light.

Human Exposure Hazards

Human exposure to UVC ultraviolet light poses health risks. As shown in the figure below, UVC light does not penetrate beyond the skin's epidermis, the protective layer of dead skin cells. Exposure to high doses of UVC light can still produce an itchy feeling with excessive dry flaking skin, but seldom any redness because the UVC does not penetrate to living cells.

However, open wounds don't have a protective layer of dead skin cells and directly expose living cells. UVC exposure can kill these exposed cells and prevent normal healing. Eyes can also be damaged by UVC, creating irritation, and in extreme cases, cataracts. One should always wear UV-blocking protective glasses whenever being directly exposed to high-intensity UVC light.



Light Penetration Depths in Human Skin[6]

<u>Maximum Permissible Human Dose</u>

The International Standard Organization has published ISO 15858 "UV-C Devices – Safety Information – Permissible Human Exposure". This standard recommends human exposure to no more than 6mJ/cm^2 UVC total dose per day. Health risks exist for UVC exposure above this level.

“Far UVC” Looks Promising

In recent years, testing has been performed on 222nm UVC, often referred to as “Far UVC”. Although slightly further away from the most effective disinfection wavelength of 265nm, it appears to create little if any human health risks. This creates the potential for environments that are continuously bathed in 222nm UVC light without any risk to humans. However, such UVC lights are still expensive, and it will likely take many years before various governmental safety approvals are granted for continuous exposure applications.

Beware of Ozone

Ozone is a highly reactive gas composed of three oxygen atoms and is shown by the chemical formula O_3. (The air we breathe contains O_2 composed of two oxygen atoms bonded together.) Ozone in the Earth’s ionosphere is created by the Sun’s UV radiation reacting with oxygen, and it provides a critical radiation shield for life on Earth. Ozone can be produced here on Earth with both good and bad consequences.

Ozone is naturally produced by ultraviolet light with wavelengths in the range of 100nm – 240nm. Two types of mercury vapor lamps are commonly available: “germicidal” lamps that deliver energy at 254nm and do not produce ozone, and “ozone producing” lamps that deliver UVC light at both 254nm and 185nm.[7] Ozone has a distinctive pungent odor reminiscent of chlorine and can be detected by many people at concentrations as low as 0.1ppm in air.[8]

Ozone Reacts with Pathogens and Humans

Since the onset of the COVID-19 pandemic, an increased number of ozone-producing lamps are being sold. Sellers generally tout the ability for ozone to permeate a room, disinfecting areas shadowed from UVC light disinfection systems. While these claims may be true, serious risks exist with using ozone-producing products.

The same chemical properties that allow high concentrations of ozone to react with organic material outside the body give it the ability to react with similar organic material that makes up the body, and potentially causing harmful health consequences. When inhaled, ozone can damage the lungs. Relatively low amounts can cause chest pain, coughing, shortness of breath and throat irritation. Ozone may also worsen chronic respiratory diseases such as asthma and compromise the ability of the body to fight respiratory infections.[9] Although not a health risk, ozone is also known to deteriorate some plastics and fabrics.

Because of these risks, buyers should refrain from purchasing UVC disinfection products that produce ozone.

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