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Basics of ultraviolet C (UV-C) light: considerations for use at livestock production facilities

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Abstract

Ultraviolet (UV) light is the range of electromagnetic radiation immediately more energetic than the visible range. UVC light has been found useful for disinfection in a variety of areas, including but not limited to air disinfection, water (and wastewater) treatment, laboratory disinfection (especially inside biosecurity cabinets), food and beverage preservation, and medical applications. UVC light has limitations as a disinfectant, mainly due to the need for adequate photon flux over the surface or atmosphere of interest. A common source of UVC in commercial applications is the standard “germicidal” lamp. The application in livestock production is a recent development and may be of increasingly higher interest for farmers to implement to defend the farms from infectious diseases such as African swine fever (ASF). However, the knowledge gap exists for producers and veterinarians in terms of the physics/mechanisms of UVC, the doses required to inactivate swine pathogens, and practical conditions under which UVC can operate effectively and practically on swine farms. To address this issue, this paper incorporates the overview of UVC light that is applicable for germicidal purposes, mechanisms of inactivation, UVC dose calculation, measurement of UVC, factors affecting UVC germicidal effectiveness, UVC light system components, and UVC light bulb selection to better inform the operator to effectively apply UV technologies in animal production.

Keywords

animal production, ultraviolet light, livestock health, livestock biosecurity, swine diseases

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Basics of ultraviolet C (UV-C) light: considerations for use at livestock production facilities

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ABSTRACT. *Ultraviolet (UV) light is the range of electromagnetic radiation immediately more energetic than the visible range. UVC light has been found useful for disinfection in a variety of areas, including but not limited to air disinfection, water (and wastewater) treatment, laboratory disinfection (especially inside biosecurity cabinets), food and beverage preservation, and medical applications. UVC light has limitations as a disinfectant, mainly due to the need for adequate photon flux over the surface or atmosphere of interest. A common source of UVC in commercial applications is the standard "germicidal" lamp. The application in livestock production is a recent development and may be of increasingly higher interest for farmers to implement to defend the farms from infectious diseases such as African swine fever (ASF). However, the knowledge gap exists for producers and veterinarians in terms of the physics/mechanisms of UVC, the doses required to inactivate swine pathogens, and practical conditions under which UVC can operate effectively and practically on swine farms. To address this issue, this paper incorporates the overview of UVC light that is applicable for germicidal purposes, mechanisms of inactivation, UVC dose calculation, measurement of UVC, factors affecting UVC germicidal effectiveness, UVC light system components, and UVC light bulb selection to better inform the operator to effectively apply UV technologies in animal production.*

Keywords. *animal production, ultraviolet light, livestock health, livestock biosecurity, swine diseases*

Introduction

Ultraviolet (UV) light is the range of electromagnetic radiation immediately more energetic than the visible range; this placement in the spectrum is the basis for that name. The generally accepted range of UV wavelength lies from 100 to 400 nm, which is shorter than the visible light spectrum (400 to 800 nm) seen by humans. The most essential physical consequence of the shorter wavelengths is that the photon energy meets or exceeds the energies of chemical bonds, ionization potentials, and band gaps of most materials, although this varies with the exact wavelengths under consideration. In short, there are four UV categories defined based on the wavelength range (Bolton and Cotton, 2008):

1) vacuum ultraviolet (VUV), 100 – 200 nm, so named because it is strongly absorbed by the components of the air;
2) ultraviolet C (UVC), 200 – 280 nm;
3) ultraviolet B (UVB), 280 – 315 nm;
4) ultraviolet A (UVA), 315 – 400 nm.

The natural source of UV light is the sun, but the spectrum at the surface differs from that which strikes the outer atmosphere. The distribution of UV light reaching the Earth's surface depends primarily on the concentration of particular atmospheric constituents and latitude, due to absorption and scattering of light as it travels through the gases surrounding the Earth. Almost all UVC light reaching the surface is blocked by the stratospheric ozone, while a portion of UVB and UVA can reach the Earth's surface. The consequences of overexposure to UV light for humans are often reported in the literature; they include sunburn, cataracts in eyes, and skin cancer. Fundamentally, these effects derive from chemical changes induced by absorption of the UV light by various biological molecules.

UVC light, which is absorbed by both nucleic acids and proteins, has been found useful for disinfection in a variety of areas, including but not limited to air disinfection, water (and wastewater) treatment, laboratory disinfection (especially inside biosecurity cabinets), food and beverage preservation, and medical applications (such as wound care, Gupta et al. 2013) (Cutler et al. 2011). The first commercial application of UV light was to treat water in Marseilles, France, as early as 1909 (AWWA, 1971). In 1916, the first UV application in the US was also initiated for water disinfection (AWWA, 1971).

UVC light has limitations as a disinfectant, mainly due to the need for adequate photon flux over the surface or atmosphere of interest. The disinfection effect reduces dramatically as the distance from the UV source increases; UVC light can only disinfect the surface under direct radiation and the performance pales in shadow areas; UVC cannot penetrate through common glass or any non-transparent materials. Quartz glass is needed if a transparent shield is required. Quartz is thus also used to manufacture UV light bulbs.

Overview of UVC light

A common source of UVC in commercial applications is the standard "germicidal" lamp. These are identical to the common fluorescent lamp, in that the primary light source is the emission from a low pressure of mercury (Hg) atoms within the tube. The major Hg emission line is at 254 nm, with smaller intensity lines at 185 nm, 313 nm, 365 nm, and a few more in the visible. Fluorescent lamps for common lighting purposes are made with glass housings (that do not transmit UV) with interior coatings of phosphors that absorb the UV and re-emit in the visible, providing white light. By contrast, the germicidal bulb is made of clear quartz, thus transmitting the major 254 nm line. There are a few other common types of UVC lights in the market, including both medium-pressure Hg and high-pressure Hg bulbs. Low-pressure bulbs have an internal pressure of less than 1 bar and low surface temperature (Cutler et al. 2011) Medium- and high-pressure bulbs are considerably more hazardous, with much higher operating pressures and temperatures; they generally require cooling and protective housings.

UVC LEDs are also commercially available. They tend to have a much longer lifespan and use less electric energy compared with conventional fluorescent lamps. However, while lamp costs are trending down, the initial cost is higher compared to mercury-vapor UVC as of this writing in early 2020.

There is renewed interest in the far-UVC (207 – 222 nm) 'excimer' lamps and their use for germicidal applications, as shown specifically for MSRA (Buonanno et al., 2017) and the H1N1 influenza virus (Welch et al., 2018).

Mechanism of inactivation

The effect of UVC varies for different materials and microorganisms. Protein has a peak absorption of UV light energy at about 280 nm, while for DNA (and RNA), the peak is 260-265 nm (Harm 1980; Kowalski, 2009), where the germicidal effectiveness is at its maximum. The common 254 nm lamp is sufficiently close to this maximum to be quite effective. UVC irradiation can induce photochemical reactions of pi systems (multiple bonds) in many organic molecules. Of particular relevance here is the formation of a cyclobutane ring that covalently joins two previously separate moieties that each contained a C=C double bond. Along DNA (or RNA) strands, adjacent thymine (uracil) residues are particularly susceptible to such photodimerization, although other destructive photochemical reactions can also occur in biological molecules. The dimerization along with the DNA (RNA) strand causes that particular section of the biopolymer to no longer be recognized correctly, and changes or ends its biological function. Bacteria and fungi use DNA for genetic material, while the virus may contain either DNA or RNA. These compounds are essential for cells to function and reproduce. (Cutler et al. 2011)

Six possible photodimers are formed during UVC irradiation, including multiple isomers of the thymine-thymine and uracil-cytosine dimers (Kowalski et al., 2009). Although biological systems generally contain repair mechanisms for DNA/RNA photodimers, required for natural exposure to sunlight, the intense radiation overwhelms the natural reversal and cell death, or reproduction failure eventually results. (Kuluncsics et al. 1999; Kowalski, 2009) (**Figure 1**).

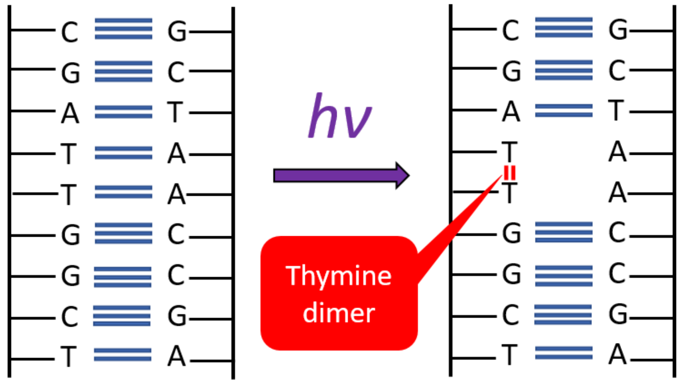

Figure 1. Thymine (T) dimers are formed after UVC irradiation on a DNA double strand. Dimerization inhibits cell replication. The *red* bonds are covalent. The *blue* ones are the hydrogen bonds holding the two strands together. (Figure drawn by the authors.)

UV dose calculation

Bolton and Linden (2003) suggest using the term "ultraviolet dose" to describe the total energy absorbed by the object(s) of study. The Bunsen-Roscoe Reciprocity Law has been used for calculating UV dose, which shows that the dose is the product of UV intensity and treatment (exposure) time. The Equation is an empirical equation introduced in 1862, and it was validated by Riley and Kaufman (1972) in the application of UV lights.

$$D = I \times T \quad [1]$$

where D = UV dose (mJ/cm^2),

I = light intensity or irradiance (mW/cm^2),

T = treatment time or exposure time (s).

The Equation shows treatment time and light intensity are proportional to UV dose and thus means that either variable can be used to increase (or decrease) dose. In idealized conditions, i.e., assuming that UV light comes from a point or line source (a simplified version of a UV bulb), light intensity (irradiance) decreases with the square of the distance from that point or line source, and the relationship is known as the inverse square law.

$$\frac{I_1}{I_2} = \frac{{d_2}^2}{{d_1}^2} \quad [2]$$

where I_1= light intensity (irradiance) measured at point 1,

I_2 = light intensity (irradiance) measured at point 2,

d_1 = distance between the light source and point 1 (where the sensor resides),

d_2= distance between the light source and point 2 (where the sensor resides),

This Equation shows that light intensity (irradiance) decreases very fast as distance increases. It is vital to keep an appropriate distance between the UV light source and the targeted objects to ensure treatment.

Measurement of UVC: how to use UV meter (radiometer)

UV light intensity (also known as irradiance) and dosage can be measured by using UV light meters (radiometers). A radiometer is a device with wavelength-specific sensors that can measure UV intensity emitted by the sources (e.g., UV lamps). Most UV sensors use solar-blind semiconductors so that they are not activated by sunlight (> 300 nm) to reduce errors in measurements (Bolton and Cotton, 2008). Some UV radiometers incorporate time as a built-in function so that UV dosage (time × intensity, Equation [1]) can be directly displayed on the screen or stored in memory cards.

Figure 2 shows a simple UV light meter, UV254SD (General Tools & Instruments LLC., New York, NY, USA), with a plugged-in sensor that can measure either UVA or UVC wavelengths, and it is equipped with a data-logging SD card. As of May 2020, this device sells at a price below $600. Other more advanced devices such as ILT 5000 research/Lab radiometer (International Light Technologies, Peabody, MA, USA) is also available, but it is more expensive (over $1,000). (Photo credit: PL)

Periodic measurements of lamp output with radiometers can help to ensure that the UV light bulbs are functioning well. A relatively lower UV intensity reading could signal an operator that it might be time to replace the ill-performing bulbs. To maintain accurate UV measurements, some manufacturers recommend the annual calibration of the radiometers and the sensors. Table 1 summarizes some examples of portable and low-cost UV light meters that are available in the market.

The consistency of units is essential when comparing different measurements. The default unit of light intensity may differ from one sensor to another. In some UV meters, the unit is mJ/cm^2, while in others, the unit may be J/cm^2.

Table 1. Examples of portable, low-cost UVC light meters.

Name	Model #	Spectral range	Manufacturer	Price*	Website
UVA-UVC light meter with data logging SD card	UV254SD	240~390 nm	General Tools & Instruments LLC.	$688 (Amazon)	www.generaltools.com/uva-uvc-light-meter-with-excel-formatted-data-logging-sd-card-and-k-j-port
Solarmeter® Model 8.0-RP UVC meter with a remote probe	8.0-RP	246~262 nm	Solarlight Inc.	$425	www.solarmeter.com/model8rp.html
UVC light meter	UV512C	220~275 nm	General Tools & Instruments LLC.	$471 (Home Depot)	www.generaltools.com/uvc-light-meter
UVA, UVC light meter	HHUV254SD	240~390 nm	Omega Engineering	$874	www.omega.com/en-us/sensors-and-sensing-equipment/visual-inspection-equipment/light-meters/p/HHUV254SD-Series

*Price: the price of the devices was recorded as of mid-May 2020.

Factors affecting UV germicidal effectiveness

The germicidal effectiveness of UVC lamps is affected by several of the following factors (refer to Definitions section for additional information):

- Light intensity (irradiance) and time: Both factors directly correlate to the calculation of UV dose, needed for inactivation. A higher dose can be achieved with a higher irradiance or more time.
- Angle: The best scenario for UV treatment is to put objects directly under UV irradiation (perpendicular to the lamps).
- Distance: The distance directly affects the UV light intensity (irradiance). The longer the distance, the weaker the light intensity.
- Microbe susceptibility: Different microbes need different levels of UV dose to be inactivated. A list of susceptibilities of common microbes can be found in Appendix A, Tables 1 and 2.
- Relative Humidity (RH): Two trends of inactivation related to RH were observed by researchers. (1) inactivation of pathogens decreases as RH increases (Tseng and Li, 2005; McDevitt et al., 2008); (2) inactivation of pathogens peaks between 25% to 79% and decreases on both ends (Cutler et al. 2012).

- UV light surface reflectiveness/cleanliness: The bulb surface and reflective surfaces need to be cleaned using dry cloth or alcohol wipes regularly to allow for more UVC irradiation. Dust or fingerprints on the UVC lightbulbs limits the effective lamp output.
- Temperature: inactivation of pathogens increases as temperature increases from 15 °C to 30 °C (Cutler et al. 2012).
- UV bulb lifespan: The rated lifespan could be 8000 hours for mercury bulbs, and for LED, it is much longer; however, the real lifespan would be much lower than the rated value because of frequent short-time operations (on and off).

UV light system components

A UV light (system) typically consists of four main components:

(i) a chamber (fixture),
(ii) the UV lamps
(iii) quartz sleeve for the bulb (optional),
(iv) the controller unit (ballast).

A UV chamber is where the UV lamp and sleeve house in, and it is usually made of stainless steel or other metals to reflect and direct light to enhance more uniform irradiation. The UV lamp refers to different types of lights that the operators prefer to use. Sometimes an additional layer of quartz sleeve is used for sealing and protecting the bulb beside the original structure. A controller unit is where the operator controls the UV system by adjusting the voltage or current output to the light.

The first step to set up a UV treatment chamber is to estimate the necessary UV dose for the target pathogens. The susceptibility of different pathogens to UVC light may vary and should be used with caution. Some common swine bacteria and viruses are listed in Appendix A, Table 1 and Table 2.

Below is an example of how this information can be used for practical applications for *E. coli*. Lets assume that a UV treatment is to be conducted inside a 1.0-m box cube planned to be used for UVC disinfection.

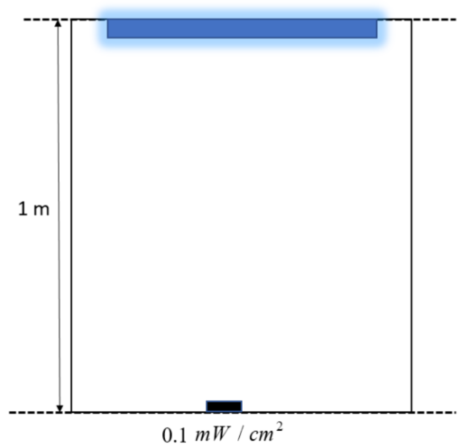

Figure 3. Diagram of UVC chamber box for disinfection on *E. coli* contaminated surface irradiated from 1 m distance in Example 1. (Schematics drawn by PL)

Example 1. To find out the appropriate treatment time to achieve 4-long deduction *for E. coli*:

Assume that at the bottom of the box, the UV light intensity is 0.1 mW/cm^2 (shown in **Figure 3**), i.e., the actual light intensity should be confirmed in two ways:

- Lamp selection from reputable suppliers that provides lamp output specs (typically at 1 m distance from the lamp). Equation [2] could be used to estimate irradiation at a distance of 1 m if the specs are for a different distance. Note that many lamp manufacturers do not publicize the information on light intensity (irradiance) at a certain distance. In that case, the actual values need to be measured and verified by the operators. Additional details regarding UV bulb selection can be found in the next section.
- Measurement of UV light intensity at desired distance with an appropriate UV light meter suitable for a bactericidal UV.

Once the light intensity (I) is verified, then the time needed to inactivate *E. coli* is:

$$T = \frac{D}{I} = \frac{10\ mJ/cm^2}{0.1\ mW/cm^2} = 100\ s \quad [3]$$

However, calculated T is an estimation in the ideal case. It is recommended to treat estimations with caution. The actual treatment time required might be longer than 100 s, if the contaminated surface is less than ideal (e.g., porous), and other factors such as shadow, reflection, sub-surface contamination are present.

UVC light bulb selection

There are a variety of UV bulbs available in the market. Some prominent UVC light manufacturers/retailers are listed in **Table 2** below.

Table 2. Common sources of UVC lamps and applications.

Manufacturer/ retailer name	Related products	Web address
Once Inc.	UVC chamber (various types and sizes)	www.once.lighting/uv-c-lighting-products/
Ushio America Inc.,	UV bulbs (germicidal, excimer, LED)	www.ushio.com/products/uv/
CureUV	UV bulbs, sensors, and a variety of applications	www.cureuv.com/
Atlantic Ultraviolet Corp.	UV bulbs, UV systems (air, surface, water, etc.), and accessories (ballasts, quartz tubes, etc.)	https://ultraviolet.com/product-directory/
American Ultraviolet	Germicidal solutions (HVAC, air, water, food, lab, etc.)	www.americanultraviolet.com/

The producers/operators need to select the types that fit their demand. Low-pressure germicidal UVC (200-280 nm) lights are commonly used for disinfection. In appearance, UVC bulbs usually come with transparent quartz tube cover, while UVA blacklight (BL) or black light blue (BLB) sometimes have white or blue cover. Common types of UVC lamps are shown in **Figure 4**.

Figure 4. Common types of UVC lights available in the market. (Photo courtesy of Atlanta Light Bulb Inc., 2020)

Commercially available UVC lamps are usually labeled with model/catalog numbers, which consist of the following parts (some may not have all the information listed) (**Tables 3-9**).

Indicator (first 1~4 letters of the model number)

Table 3. Lamp label indicators and their significance.

Acronyms	Significance
G	Germicidal
F	Fluorescent (usually not labeled for UVC lamp)
PH	Pre-heating
HO	High Output
CL	Cell lamp
U	U lamp
PHA	Pre-heat amalgam
PHHA	Pre-heat amalgam horizontal high output
PHVA	Pre-heat amalgam horizontal or vertical

For UVC lamps, the model number starting with the letter "G (germicidal)" to denote that this is a germicidal lamp (254 nm). If a name begins with letter "F ('fluorescent')," then the lamp is not UVC but more likely a UVA lamp or a general fluorescent non-UV bulb.

Lamp power consumption (wattage)

The nominal power consumption of the lamp is expressed in *Watts (*W*)*. This part follows the indicator letter(s) in the order of the lamp model number.

Bulb size (diameter): Table 4 explains the meaning of common tubular labels

Table 4. Tubular label with bulb size information.

Tubular Label	Diameter
T	1/8 in (3.2 mm)
T5	5/8 in (15 mm)
T6	3/4 in (19 mm)
T8	1.0 in (25 mm)
T10	1.25 in (32 mm)
T12	1.5 in (38 mm)

Ozone level

Table 5. Acronyms annotating ozone levels and their meanings

Acronyms	Ozone level
L	Low level (or ‘ozone-free’), often refers to lamps at 254 nm
VH	Very high level (or ozone-generating), often refers to lamps at 185 nm

Base type

Table 6. Acronyms of base types and their meanings are shown in the table below. Diagrams of two common base types are shown in **Figure 5.**

Acronyms	Base type
4P	4-pin circline base
MDBP	medium bi-pin* base (G13, 12.7 mm)
MNBP	miniature bi-pin (G5, 5mm)
SL	slimline
SP	single pin

*bi-pin: two terminal pins that fit into corresponding sockets

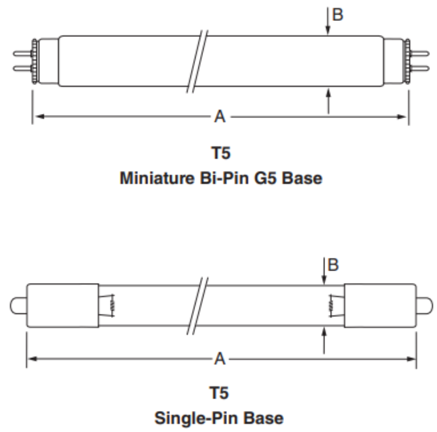

Figure 5. Miniature bi-pin base vs. single pin base for T5. (Photo: Online Spec Sheet from Ushio America Inc., 2020)

Connection type:

Table 7. Acronyms of connection types and their meanings

Acronyms	Connection type
SE	Single-ended
DE	Double-ended

Length of the lamp:

The full length of the lamp follows the first letter(s) and is usually expressed in either inch (2 digits) or millimeters (3 digits).

Below are two examples (**Tables 8** and **9**) of labels that can be commonly found on UV bulbs. The purpose is to help operators understand the names and model/catalog numbers on UVC lights and to lower the risk of selecting non-germicidal lamps.

Table 8. Example 1: an explanation of the model number "G30T8".

Section of the model number (in order)	Meaning
G	This is a germicidal UV bulb (usually refers to 254 nm)
30	The nominal power consumption is 30 W.
T8	The connection pin type is T8 (bulb diameter = 1 inch).

Comment: double-check the pin type on the fixture before installation.

Table 9. Example 2: an explanation of the model number "F15T8BLB".

Section of the model number (in order)	Meaning
F	This is a fluorescent UVA bulb (wavelength >315 nm)
15	The nominal power consumption is 15 W.
T8	The connection pin type is T8 (bulb diameter = 1 inch).
BLB	BLB refers to "blacklight blue", which is a type of UVA light that has a purple color bulb.

Comment: this is NOT a UVC light, and it does not have a germicidal effect. Applications of UVA include artificial sun tanning, forensic detection, etc.

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