Ultraviolet C (UVC) Standards and Best Practices for the Swine Industry

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Executive Summary

What Is UVC Light?

UV light is a type of electromagnetic energy that is invisible to humans. There are four categories based on wavelength range. In particular, UVC light (200–280 nanometers (nm)) is useful for disinfection in swine field settings. Inactivation of microorganisms by UVC is a function of the dose of radiation, which is determined by the intensity (irradiance) of radiation and time.

UVC inactivation varies by material and microorganism type. The peak absorption of UV light energy is 280 nm for proteins and 260-265 nm for DNA/RNA. Low-pressure mercury (Hg) bulbs (254 nm) are commonly used and quite effective for most microorganisms. Other UV lamp types are available, but are either more hazardous (e.g., medium- and high-pressure Hg) or more costly (e.g., LED).

UVC Applications in Swine Settings

UVC germicidal chambers are used in swine settings to reduce the microbial load on surface items. Chambers, which may be commercial or homemade, are usually constructed so items to be disinfected are passed through from the dirty side (entry/hallway) to the clean side (office/break room).

UVC germicidal chambers are mostly used for small to medium items like lunch boxes, cell phones, small tools, and medications. Food and semen bags can also be passed through the chamber without negative effects. Repeat exposure of plastics to UVC light may lead to a change in the color or smell of the object. Paper and cardboard cannot be disinfected in a UVC germicidal chamber. Larger UVC chambers, or UVC rooms, can be built for larger items.

Implementing UVC Disinfection in Your Facility

To start using UVC disinfection at your facility, follow these steps.

Step 1. Set Up UVC Germicidal Chamber and Choose UV Lamp

The UVC germicidal chamber is composed of four parts.

1. **Chamber** (fixture): contains the UV lamp and sleeve; must be lined with a reflective surface like stainless steel or aluminum to enhance the effect of UVC light.
2. **UVC lamps**: select to fit producer needs; low-pressure germicidal UVC commonly used. Bulbs should be labeled as germicidal (not fluorescent). Options may include power consumption (watts), bulb size (diameter), ozone level, base type, connection type, and length of lamp.
3. **Quartz sleeve** for UVC lamp: optional to seal and protect the UVC lamp.
4. **Controller unit** (ballast): used to adjust voltage or current output to the UVC lamp.

Step 2. Estimate the Necessary UVC Dose for Target Pathogens

Published information on UV dose is available only for porcine reproductive and respiratory syndrome virus (PRRSV), porcine epidemic diarrhea virus (PEDV), and foot-and-mouth disease virus (FMDV). For PRRSV and PEDV, studies showed the UVC dose required for a 3 $\log_{10}$ reduction was well below the range delivered by a commercially available chamber (150–190 mJ/cm^2, BioShift® Pass-Through UV-C Chamber, Once^{TM}). For FMDV, the UVC dose required for a 5 $\log_{10}$ reduction was also below the range delivered by a commercially available chamber (150–190 mJ/cm^2, BioShift® Pass-Through UV-C Chamber, Once^{TM}).

For other swine pathogens, UVC dose must be extrapolated from members of the same genus (bacteria) or family (virus). Most pathogens are inactivated at 190 mJ/cm^2, but some require doses greater than 150 mJ/cm^2. A significant gap in the literature exists for many swine pathogens.

Step 3. Use and Maintain the UVC Germicidal Chamber Properly

Follow these guidelines when using a UVC germicidal chamber on your farm. Remember, items to be disinfected must have direct exposure to UVC light.

- Remove organic matter (dirt) from items by wiping the surface prior to disinfection
- Place items in single layer with space between them
- Check for shadows and adjust item placement/spacing if necessary
- Do not use secondary containers such as Tupperware or plastic baggies to contain items in the chamber; UVC light cannot penetrate these even if they are transparent
- Rotate items in the chamber after the first cycle if needed to ensure that all sides are exposed to UVC light, or use a grid shelf
- Cycle UV lamps prior to first use for disinfection on cold days to bring bulb energy up

Maintenance of a UVC germicidal chamber involves cleaning and monitoring. Follow these guidelines to maintain your chamber.

- Clean the chamber interior with a non-abrasive cleaner when dirty
- Check and clean the UV lamps every three months; make sure to wear gloves and use an alcohol-based disinfectant on a soft cloth or gauze
- Monitor UVC lamp intensity with a light meter (radiometer); place face-up in chamber for five minutes and record, then place face-down and record a second time in the same spot
- Change UVC lamps and ballast once per year or after 1000 cycles (minimum)
- Check intensity after installing new lamps

In addition, develop a checklist for farm personnel to ensure they know how to operate the chamber. Run time and UVC intensity should be recorded. Item placement within the chamber can be monitored through the window or via cell phone video from within. Regular audits are recommended.

Step 4. Train Staff on Safety Precautions

UVC light is mutagenic and carcinogenic; however, UVC germicidal chambers are safe when operated and maintained properly. Follow these recommendations to keep farm personnel safe.

- Install warning labels and properly train all personnel
- Do not expose skin or eyes to UVC light; make sure the chamber is completely enclosed
- Use a radiometer to ensure that UVC light cannot penetrate the chamber windows or seams
- Connect a hard-wired safety shutoff to doors and latches
- Discontinue use and contact manufacturer if there is any malfunction in the safety controls
- Consider use of personal protective equipment including goggles or face shields designed for UV exposure, clothing, and sunblock

Ultraviolet C (UVC) Standards and Best Practices for the Swine Industry

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Funding

Funding for the project titled “UVC standards and best practices for the swine industry,” Project #19-237 SHIC, was provided by the Swine Health Information Center (SHIC).

Acknowledgements

Thank you to Maria Agustina Eizmendi, an undergraduate student at Iowa State University, for providing assistance with organizing the one-day workshop.

Contents

Definitions

Angle of irradiation: the angle between the UV rays and the target of irradiation.

Distance: the distance between the UV light and the target/object of irradiation. The distance directly affects the UV light intensity (irradiance). The longer the distance, the weaker the light intensity.

Light intensity (irradiance): the optical power (radiant flux) per unit area on the surface of the target, often expressed in units of illuminating power per area (e.g., miliWatts per square centimeter, mW/cm^2).

Microbial susceptibility: The susceptibility of different microbes with respect to UV treatment.

Radiometer: A device with wavelength-specific sensors that can measure UV intensity emitted by the sources (e.g., UV lamps).

Treatment time: The time needed to inactivate a particular type of microbe (bacteria, virus, fungi, etc.). To achieve a higher log reduction, longer treatment time is required.

UV dose: The amount of UV radiation that a surface or target is exposed and is often expressed in mJ/cm^2. UV dose is calculated by multiplying UV light intensity and the treatment time.

Ultraviolet (UV) light: The range of electromagnetic radiation that is 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, including vacuum ultraviolet (VUV, 100 – 200 nm), ultraviolet C (UVC, 200 – 280 nm), ultraviolet B (UVB, 280 – 315 nm), ultraviolet A (UVA, 315 – 400 nm). UVC is considered to be germicidal to many bacteria and viruses.

Introduction

Ultraviolet C (UVC) light has been widely used for disinfection for a long time in many industries, including human medicine and food processing. The practical application of this technology in livestock production is a more recent development and is increasingly being used on swine farms as producers look for ways to improve biosecurity in response to endemic diseases and the threat of transboundary and foreign animal diseases, such as African swine fever virus (ASFV). However, many swine producers and veterinarians are unfamiliar with 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. Safety and maintenance requirements regarding the application are also not widely known. The pork industry lacks standards and best practices to apply this technology effectively and safely.

To address this need, subject matter experts were convened for a one-day workshop to define standards and best practices for the use of UVC in the swine industry. The members of the working group included practicing swine veterinarians as well as academics with expertise in epidemiology, infectious disease, biosecurity, chemistry, and engineering. This white paper is the outcome of the workshop. In addition, the content of the white paper may be used to develop fact sheets, brochures and/or tutorial videos for swine producers and veterinarians.

Physics of Ultraviolet C (UVC) Light

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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 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 the 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 spectrum. 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 spectrum, 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 one bar and low surface temperature (Cutler et al. 2011). Medium-pressure 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 micro-organisms. 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**).

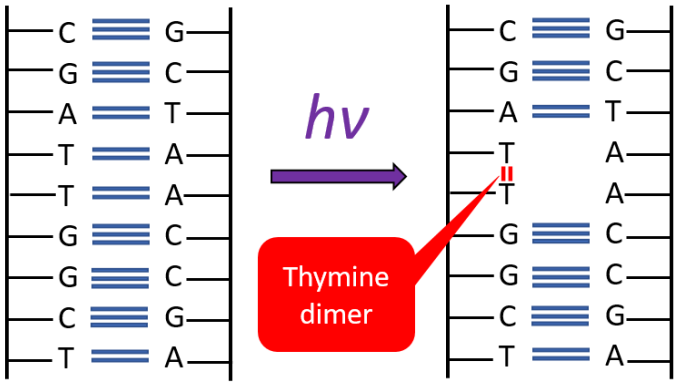

Figure 1. Thymine (T) dimers are formed after UVC irradiation on a DNA double strand. Dimerization inhibits cell replication. The *red* bonds are covalent. The *blue* ones are the hydrogen bonds holding the two strands together.

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.

$D = I \times T$ [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 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 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: Peiyang Li)

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.

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 summarizes some examples of portable and low-cost UV light meters that are available in the market.

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

*Devices listed in this table are examples. It is not an exhaustive list of all that are available.
†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 application for *E. coli*. Let's assume a UV treatment is to be conducted inside a 1.0-m box cube planned to be used for UVC disinfection.

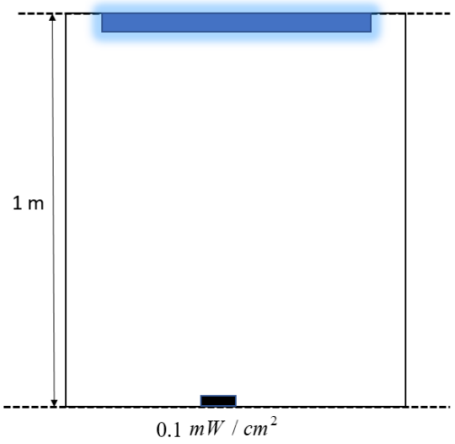

Figure 3. Diagram of UVC chamber box for disinfection on *E. coli* contaminated surface irradiated from 1 m distance in Example 1.

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:

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

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/

*Sources listed in this table are examples. It is not an exhaustive list of all sources.

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**).

1. 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)" denotes this is a germicidal lamp (254 nm). If a name begins with the letter "F (fluorescent)," then the lamp is not UVC but more likely a UVA lamp or a general fluorescent non-UV bulb.

2. 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.

3. 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)

4. 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.

5. 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

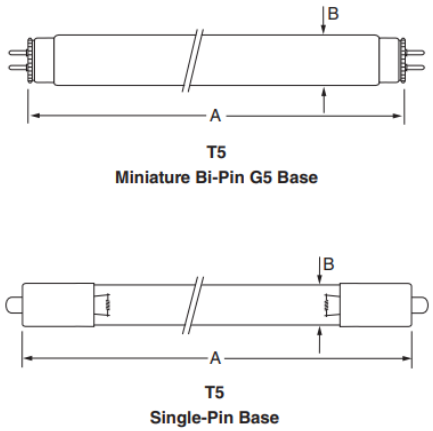

Figure 5. Miniature bi-pin base vs. single pin base for T5.
(Photo: Online Spec Sheet from Ushio America Inc., 2020)

6. Connection type:

Table 7. Acronyms of connection types and their meanings

Acronyms	**Connection type**
SE	Single-ended
DE	Double-ended

7. 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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UVC Dose Requirements for Swine Pathogens

Derald Holtkamp, Amanda V. Anderson, Madison Durflinger, Chelsea Ruston

Introduction and Methods

Inactivation of pathogens by UVC is a function of the dose of radiation. The dose is a function of the irradiance or intensity of radiation on the pathogen-contaminated surface and time. The dose of UVC is measured in millijoules per square centimeter (mJ/cm^2).

Summaries from companies such as Once Incorporated (Plymouth, Minnesota), Clordisys Solutions, Incorporated (Lebanon, New Jersey), and ECO Scope (Amtzell, Germany) were used to identify primary references for the UVC dose requirements to inactivate viruses and bacteria, nearly all of which were not swine pathogens, but many were in the same genus of swine bacteria or same family of swine viruses. The summaries included studies applying UVC for the physical disinfection of organic and non-organic surfaces, as well as the disinfection of air and water. In addition, a review of the literature for information on doses for swine pathogens was conducted. Only peer-reviewed journal articles discussing the UVC dosage for the disinfection of non-organic surfaces were included since this is the primary purpose for which UVC would be applied as a bio-security control measure on swine farms. PubMed, Journal of Swine Health and Production and Google Scholar were used to identify papers. Only studies related to surface disinfection in the United States and Europe were included. The review was conducted for both endemic and foreign swine viral and bacterial pathogens, which were deemed important to pork production in the United States, including those on the Swine Health Information Center's Swine Disease Matrix (www.swinehealth.org/swine-disease-matrix/), accessed August 1, 2020).

Results and Discussion

The results presented in Appendix A, Table 1 provide a summary of the information in the literature on the dose of UVC required to achieve alternative log reductions of bacteria. The results in Appendix A, Table 2 provide the same information for viruses. Swine bacteria and swine viruses are indicated with a shaded background in Tables 1 and 2. For context, the dose of UVC radiation delivered to a surface was measured in a recent study to evaluate the efficacy of UVC radiation for inactivating Senecavirus A (SVA) on contaminated surfaces (Ruston, et al. 2020. Efficacy of Ultraviolet C disinfection for inactivating Senecavirus A on contaminated surfaces commonly found on swine farms. The device used in the study was a commercially available UCV chamber (Bioshift® Pass-through Germicidal UV-C chamber, OnceTM, Plymouth, MN) commonly used in the swine industry. The exterior measurements of the pass-through chamber are 23 ½ inches (in) long x 29 ¾ in wide x 24 in high. The interior of the chamber was approximately 20 inches x 20 inches x 20 in. and there are 4 UVC bulbs at the wavelength of 254 nm, approximately 18 in long, located at each corner of the chamber. One corrugated metal wire shelf is located approximately 1 in from the bottom of the UVC chamber. The unit operates on a timer that is fixed at five minutes. There was some variation in the irradiance recordings taken during the study, but the total measured dose of UVC radiation ranged from 150 to 190 mJ/cm^2 for the 5-minute exposure.

For applications of UVC radiation on swine farms to exclude pathogens from being introduced into a herd (i.e., for bio-exclusion), the pathogens of greatest concern are those that are not currently present or can be eliminated from herds. For herds that are free of those pathogens, bio-exclusion becomes the primary line of defense for excluding the pathogen from the herd. The summary provided here is for the swine bacterial and viral pathogens for which bio-exclusion on swine farms is a concern.

- Published studies with information on UVC dose of swine bacteria and viruses
    - Porcine reproductive and respiratory syndrome virus (PRRSV)
    - Porcine epidemic diarrhea virus (PEDV)
    - Foot and mouth disease virus (FMDV)
- No published studies with information on UVC dose of swine bacteria and viruses, but published studies with information on UVC dose for other bacteria in the same genus or viruses in the same family
    - Transmissible gastroenteritis virus (TGEV)
    - Porcine delta coronavirus (PDCoV)
    - Pseudorabies virus (PRV)
    - Swine influenza virus
    - Seneca virus A (SVA)
- No published studies with information on UVC dose of swine bacteria and viruses, and no published studies with information on UVC dose for other bacteria in the same genus or viruses in the same family
    - African swine fever virus (ASFV)
    - Classical swine fever virus (CSFV)
    - Actinobacillus pleuropneumoniae
    - Swine dysentery (SD)
    - Non-dysentery Brachyspira spp.
    - Mycoplasma hyopneumoniea

For the swine bacteria and viruses where published studies with information on UVC dose is available, all of the doses are less than the 150 to 190 mJ/cm^2 delivered by the Once UCV chamber. However, for PRRSV and PEDV, doses required for more than a 3 log reduction were not reported. For the swine bacteria and viruses where published studies with information on UVC dose is not available, but information is available for bacteria in the same genus or viruses in the same family, the doses required are less than 190 mJ/cm^2, but some are greater than 150 mJ/cm^2. For example, the dose for a 5 log reduction of SARS coronavirus in the coronavirus family with TGEV and PDCoV, is 114.0 to 162 mJ/cm^2. A significant gap in the literature exists for the swine bacteria and viruses where no information is published for them or other bacteria in the same genus or viruses in the same family. Foremost among them is ASFV and CSFV, two important foreign animal diseases.

References available at the end of Appendix A.

Maintenance Requirements of UVC Germicidal Chambers

Tina Loesekann and Aaron Stephan

Introduction

Regular maintenance of UVC chambers is imperative if they are to perform optimally. Maintenance includes regular cleaning of the interior of the chamber as well as checking, replacing, and cleaning the germicidal bulbs. Ensure it is in proper operating condition by monitoring UVC intensity.

Maintaining UVC germicidal bulbs and chambers

UVC bulbs should be checked periodically (approximately every three months) and can be cleaned when wearing gloves and applying an alcohol-based disinfectant on soft cotton cloth or gauze. Do not touch bulbs with bare hands, because skin oils block the light and its efficiency. Regular cleaning will also maximize the life of the bulb.

The reflective aluminum panels on the inside of the chamber should also be cleaned with non-abrasive cleaners when dirty. The chamber will be less efficient at distributing UVC light when the panels have dull spots.

More frequent cleaning is advised during an active outbreak or if workers live with people that work at other swine farms. Monitoring the UVC intensity in the chamber on a regular basis (e.g. weekly, see below for instructions) and changing the bulbs and ballasts on a schedule is recommended.

The temperate of the UV bulbs has a major impact on the disinfection efficiency of UVC chambers. On cold days the first cycle on the bulbs will be of a lower overall energy transfer. It is recommended that the bulbs be cycled once in the morning to bring the bulb energy level up before the first disinfection cycle. If the relative humidity is high, condensation may form on the bulbs. Condensation on the bulbs is a safety concern and should be monitored closely in high humidity environments. (Refer to the section titled Physics of Ultraviolet C (UVC) Light for additional information.)

Changing germicidal UVC bulbs

Some commercial UVC germicidal chambers (e.g. the BioShift series from ONCE Inc.) come equipped with a built-in bulb change timer on their models. Generally, the number of cycles is the main factor shortening the life of the bulbs, more so than the hours of runtime. For example, running five minute cycles is estimated to reduce the overall relative lamp life to 4.2%, i.e., the life of a bulb rated for 8,000 hours is reduced to 336 hours or about 4,000 five minute cycles. At a minimum, bulbs and ballasts should be changed once a year or every 1,000 cycles, whatever is earlier. Generally, bulbs and the ballast should be replaced at the same time. As a rule of thumb, if replacing the bulb alone does not resolve flickering, buzzing, or low output, the ballast should be replaced as well. Be sure to check that UVC intensity is at the desired level after the replacement. If bulbs and ballasts are changed at the same time, the rotation of bulbs is not

necessary. Replacement bulbs can be purchased through the manufacturer of commercially available devices.

Monitoring UVC intensity

It is of utmost importance to monitor the UVC intensity in the chamber to ensure it is in proper operating condition. Blue light is the result of a phosphor and only serves as a visual safety indicator that the light is on. The blue light intensity may **NOT** correlate with UVC intensity. Moreover, the illumination with visible light in the chamber can be misleading as to what areas are illuminated by the UVC light since the reflective, and refractive properties of UVC differ from visible light. UVC light may not fully illuminate fomites and tools in the chamber, even if visible light can be seen.

UVC intensity may be monitored using a NIST-traceable calibrated UVC meter (e.g. solar meter from Solarlight Inc. $425 with remote probe or UV512C digital UVC meter from General Tools on Amazon $472.38 and others), recording the UVC intensity after five minutes in the chamber. Always record the same spot with the probe facing up and then down for a second measurement.

UVC dosimeters (e.g. www.once.lighting/uv-cdosimeter/) are paper coupons that change color according to the UVC dose they were exposed to. They are placed in the chamber for a set amount of time, and the color is immediately compared to a reference color. The color readout has to be done immediately after the light exposure, as the UVC dosimeter color may revert back toward yellow over time. The use of UVC dosimeters is generally not recommended.

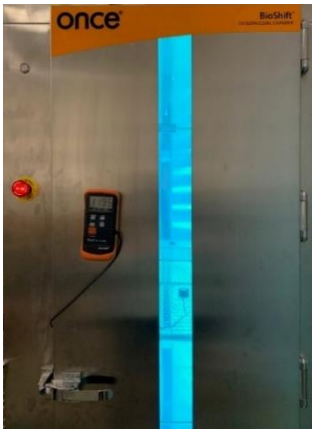

Figure 1. (A) UV meter measurement taken with probe inside the chamber.

Figure 2. Example of calibrated UVC dosimeter color changes with increasing UVC dose.

Safety Requirements of UVC Germicidal Chambers

Tina Loesekann and Aaron Stephan

Introduction

UVC germicidal chambers are very safe when operated and maintained properly. Potential risks can be mitigated through proper training of personnel and adherence to safety measures during operation.

The potential danger to eyes and skin

UVC is mutagenic and carcinogenic. Avoid exposure to any part of a person's or an animal's body or eyes. Exposure to the eyes may result in the development of cataracts and/or actinic keritinosis. Short-term effects of exposure to skin include sunburn while long-term effects could include cancer. Risk for cancer is cumulative.

Safety practices

- Never allow UVC exposure to skin or eyes.
- Ensure complete enclosure of the UVC chamber without any light leakages.
- Verify with an UVC meter that there is no UVC penetration through the window. Glass windows are okay, quartz windows are not.
- Connect a hard-wired safety shutoff to doors and latches.
- Install warning labels for human safety.
- Properly train all personnel; refresh training annually.
- Consider using personal protective equipment (PPE) as secondary protection which may include goggles or face shields (such as American Ultraviolet's Ultra-Spec 100 Safety Goggles and Ultra-Shield Face Shields designed for ultraviolet exposure), and clothing or sun block.
- Discontinue use and contact manufacturer if there is any malfunctioning in the safety controls.

Common misconceptions

- Food is not altered by short UVC exposure and is safe for consumption.
- UVC exposure of plastics may produce low amounts of volatile compounds, such as mercaptans and sulfhydryls, that some people can smell. The longer the exposure, the more plastics are broken down and the stronger the odor. Limit run cycles to a maximum of 10 minutes.

And remember: NO PRRS

- ✓ **N**ew bulbs
- ✓ **O**rganize
- ✓ **P**lace items in direct exposure
- ✓ **R**otate
- ✓ **R**eflective sidewall
- ✓ **S**afety first

UVC Application in Swine Field Settings and Best Practices

Montse Torremorell, Derald Holtkamp, Deb Murray, Clayton Johnson, Katie Wedel

Introduction

The use of UVC chambers to treat surfaces of items prior to entering them into swine farms, as part of comprehensive biosecurity programs, has increased in the last few years. While UVC light can also be used to decontaminate water, air, prevent microbial growth in air conditioning systems, and to decontaminate surfaces in general, those applications are uncommon in swine farms. Both commercial and homemade chambers exist, and both can be effective if they are constructed and used properly. UVC chambers are an effective method to reduce the microbial load on surfaces of items; however, total inactivation is not commonly achieved.

Applications under field settings

In swine farms, UVC chambers are commonly located at the interface between the outside farm entry or hallway, also considered the dirty side, and the office/breakroom considered the clean side of the farm. These chambers are designed as pass-through chambers where items from one side are placed into the chamber and retrieved from the other side of the chamber after being treated. Because of chamber capacity, UVC chambers are mostly used to treat small and medium-size items such as lunch boxes, cell phones, small tools, medications, etc. that are relatively clean on their exterior. There are also large UVC chambers and UVC rooms, where larger items can also be treated. Such items include medications, feed bags, maintenance tools, etc. Having to treat all items that employees may need, such as lunch boxes, may create a bottleneck in the system at specific times of the day. Staggering of personnel access to farms or specific protocols to reduce the frequency of introduction of materials may be necessary.

Food placed inside UVC chambers is safe to eat. In addition, treatment of semen bags should not affect the viability of the semen. However, repeat UVC exposure of certain plastics may result in a change in color and emission of smells. Lastly, treatment of paper or cardboard material tends to be ineffective due to the limited exposure capabilities of the UVC light into porous materials.

UVC chambers are mostly installed in sow farms where biosecurity is considered a priority and are part of comprehensive biosecurity programs that include multiple biosecurity measures. It is recommended to have simple on-site instructions or checklists highlighting how UVC chambers should be used. In addition, it is recommended to have regular audits conducted either by farm personnel or an external party to ensure that the chambers are being used properly. Auditing compliance should include records for run time, ensuring that timers work properly, and measuring UVC intensity or dose using a UVC meter. If a chamber does not have a window, a suggestion is to have a video recording device such as a cell phone inside the chamber to observe how items are placed.

Best practices for using UVC chambers in swine farms

The effectiveness of the UVC light depends mostly on the time of UVC exposure and UVC light intensity. To be effective, UVC rays must directly strike the micro-organisms. If organisms are

shielded by a coating of organic material, the UV light will be ineffective. UVC light has limited ability to penetrate into materials, so it will not go through materials such as plastics, containers, cloth, etc.

The following includes recommendations for using UVC chambers. See section titled Maintenance Requirements of UVC Germicidal Chambers for additional information on chamber maintenance.

- Place items in direct exposure to the UVC light. Since UVC light works by directly striking the micro-organisms, it is very important that: a) items are placed into the UVC chamber in a single layer, b) there are no shadows between the items, c) no secondary containers are used, and d) there is no dirt or organic material coating the items.
- If items are placed on top of each other, not all of the surfaces will come in contact with the UVC light, presenting a risk for pathogens to enter the farm. Items should be placed one at a time or leave enough space between items to get maximum UVC light exposure avoiding shadows between items. In addition, if there are no lights on a side or sides of the UVC chamber, rotate items after a first treatment cycle in order to ensure that all sides of an item are exposed to UVC light. The items should also be placed on a grid shelf to allow UVC light to shine on the items in particular if there are lights on the bottom of the chamber.
- In order to obtain the maximal effect of the UVC bulbs in the chamber, it is important to ensure that the chamber walls contain a reflective material such as aluminum. This helps to enhance the effect of the UVC bulbs by reflecting and redirecting the UVC light.
- The UV light will not be able to penetrate the containers such as plastic bags or Tupperware containers, even if they are transparent.
- If an item has dirt or is coated with organic material, it is recommended that first this organic material is removed by wiping the surface of the item.

Summary

When utilized and maintained properly, UVC light germicidal chambers can be an effective component of comprehensive biosecurity programs. However, proper construction and use of the chambers is necessary to obtain the full benefit of using the chambers. Ensure that the UVC lights are working properly to provide the intensity of light exposure or dose necessary to inactivate the micro-organism. Placement of the items for maximum exposure and time in a way that the light can impact all surfaces of the items is essential to prevent the introduction of pathogens into farms. In addition, safety should be a top priority when utilizing UVC chambers.

Appendix A Table 1. Ultraviolet-C Dose (mJ/cm2) Required for a given log10 reduction of bacteria. Swine pathogens are those with shaded background.

			Log_{10} Reduction						
Genus	***Bacteria***		**1**	**2**	**3**	**4**	**5**	**6**	**Reference**
			Dose (mJ/cm^2)	**Dose (mJ/cm^2)**	**Dose (mJ/cm^2)**	**Dose (mJ/cm^2)**	**Dose (mJ/cm^2)**	**Dose (mJ/cm^2)**	
Actinobacillus	Actinobacillus pleuropneumoniae		No information						
	Actinobacillus suis		No information						
	Range of dose for bacteria in genus		**No information**						
Aeromonas	*Aeromonas salmonicida*		1.5	2.7	3.1	5.9			Liltved and Landfald 1996
	Aeromonas hydrophila ATCC7966		1.1	2.6	3.9	5.0	6.7	8.6	Wilson et al. 1992
	Range of dose for bacteria in genus		**1.1 - 1.5**	**2.6-2.7**	**3.1-3.9**	**5.0-5.9**	**6.70**	**8.60**	
Bacillus	Bacillus anthracis - Anthrax		4.5	8.7					UV-Light.co.UK
	Bacillus magaterium sp. (veg.)		1.3	2.5					UV-Light.co.UK
	Bacillus paratyphusus		3.2	6.1					UV-Light.co.UK
	Bacillus subtilis		5.8	11.0					UV-Light.co.UK
	Range of dose for swine bacteria in genus		**1.3 - 5.8**	**2.5 - 11.0**					
Bordetella	Bordetella bronchiseptica		No information						
	Range of dose for swine bacteria in genus		**No information**						
Brachyspira	Brachyspira hyodysenteriae		No information						

	Brachyspira pilosicoli	No information					
	Brachyspira murdochii	No information					
	Range of dose for swine bacteria in genus	**No information**					
Brucella	Brucella melitensis	2.8 - 3.7	5.3 - 5.8	7.8			Rose LJ, O'Connell H. 2009
	Brucells suis	1.7 - 2.7	3.6 - 5.3	5.6 - 7.9	7.5 - 10.5		Rose LJ, O'Connell H. 2009
	Range of dose for bacteria in genus	**1.7 - 3.7**	**3.6 - 5.8**	**5.6 - 7.9**	**7.5 - 10.5**		
Burkholderia	Burkholderia mallei	1.0-1.2	2.4-2.7	3.8-4.1	5.2-5.5		Rose LJ, O'Connell H. 2009
	Burkholderia pseudomallei	1.4-4.4	2.8-3.5	4.3-5.5	5.7-13		Rose LJ, O'Connell H. 2009
	Range of dose for bacteria in genus	**1.0 - 4.4**	**2.4 - 3.5**	**3.8 - 5.5**	**5.2 - 13**		
Campylobacter	*Campylobacter jejuni* ATCC 43429	1.6	3.4	4	4.6	5.9	Wilson et al. 1992
	Range of dose for bacteria in genus	**1.6**	**3.4**	**4**	**4.6**	**5.9**	
Citrobacter	*Citrobacter diversus*	5.0	7.0	9.0	11.5	13.0	Giese and Darby 2000
	Citrobacter freundii	5.0	9.0	13.0			Giese and Darby 2001
	Range of dose for bacteria in genus	**5.0 - 7.0**	**7.0 - 9.0**	**9.0 - 13.0**	**11.5**	**13.0**	
Clostridium	Clostridium tetani	13.0	22.0				UV-Light.co.UK
	Range of dose for bacteria in genus	**13.0**	**22.0**				
Corynebacterium	Corynebacterium diphtheriae	3.4	6.5				UV-Light.co.UK
	Range of dose for bacteria in genus	3.4	6.5				

Deinococcus	Deinococcus radiodurans ATCC13939	91.0						Arrage, et al.,1993
	Range of dose for bacteria in genus	**91.0**						
Ebertelia	Ebertelia typhosa	2.1	4.1					UV-Light.co.UK
	Ebertelia typhosa	2.1	4.2					UV-Light.co.UK
	Range of dose for bacteria in genus	**2.1**	**4.1 - 4.2**					
Erysipelothrix	Erysipelothrix rhysiopathiae	No information						
	Range of dose for swine bacteria in genus	**No information**						
Escherichia	*Escherichia coli* O157:H7 CCUG 29193	3.5	4.7	5.5	7.0			Sommer et al. 2000
	Escherichia coli O157:H7 CCUG 29197	2.5	3.0	4.6	5.0	5.5		Sommer et al. 2001
	Escherichia coli O157:H7 CCUG 29199	0.4	0.7	1.0	1.1	1.3	1.4	Sommer et al. 2002
	Escherichia coli O157:H7 ATCC 43894	1.5	2.8	4.1	5.6	6.8		Wilson et al. 1992
	Escherichia coli O157:H7		0.6 - 1.2	2.4 - 6.0				Mukhopadhyay et al., 2014
	Escherichia coli	3.0	6.6					ClorDiSys Solutions Inc. 2018
	Escherichia coli			9.0				Peschel Ultraviolet Inc., 2018.
	Escherichia coli ATCC 11229	7.0	8.0	9.0	11.0	12.0		Hoyer 1998
	Escherichia coli ATCC 11303	4.0	6.0	9.0	10.0	13.0	15.0	Wu et al. 2005
	Escherichia coli ATCC 25922	6.0	6.5	7.0	8.0	9.0	10.0	ClorDiSys Solutions Inc. 2018
	Escherichia coli B	4.0						Arrage, et al.,1993
	Escherichia coli K-12 IFO3301	2.2	4.4	6.7	8.9	11.0		Oguma et al. 2004
	Escherichia coli O157:H7	2.0	2.0	2.5	4.0	8.0	17.0	Yaun et al. 2003

	Range of dose for bacteria in genus	**0.4 - 7.0**	**0.7 - 8.0**	**1.0 - 9.0**	**1.1 - 11**	**1.3 - 13.0**	**1.4 - 17.0**	
	Range of dose for swine bacteria in genus	**3.0**	**6.6**	**9.0**				
Francisella	Francisella tularensis	1.3 - 1.4	3.1 - 3.8	4.8 - 6.3	6.6 - 8.7			Rose LJ, O'Connell H. 2009
	Range of dose for bacteria in genus	**1.3 - 1.4**	**3.1 - 3.8**	**4.8 - 6.3**	**6.6 - 8.7**			
Haemophilus	Haemophilus parasuis	No information						
	Range of dose for swine bacteria in genus	**No information**						
Halobacterium	*Halobacterium elongate* ATCC33173	0.4	0.7	1.0				Martin et. al 2000
	Halobacterium salinarum ATCC43214	12.0	15.00	17.5	20.0			Martin et. al 2000
	Range of dose for bacteria in genus	**0.4 - 12.0**	**0.7 - 15.0**	**1.0 - 17.5**	**20.0**			
Klebsiella	*Klebsiella pneumoniae*	12.0	15.0	17.5	20.0			Giese and Darby 2000
	Klebsiella terrigena ATCC33257	4.6	6.7	8.9	11.0			Wilson et al. 1992
	Range of dose for bacteria in genus	**4.6 - 12.0**	**6.7 - 15.0**	**8.9 - 17.5**	**11.0 - 20.0**			
Lawsonia	Lawsonia intracellularis	No information						
	Range of dose for swine bacteria in genus	**No information**						
Legionella	*Legionella pneumophila* ATCC33152	1.9	3.8	5.8	7.7	9.6		Oguma et al. 2004
	Legionella pneumophila ATCC 43660	3.1	5.0	6.9	9.4			Wilson et al. 1992
	Legionella pneumophila ATCC33152	1.6	3.2	4.8	6.4	8.0		Oguma et al. 2004

	Range of dose for bacteria in genus	**1.6 - 3.1**	**3.2 - 5.0**	**4.8 - 6.9**	**6.4 - 9.4**	**8.0 - 9.6**	
Leptospira	Leptospira species	No information					
	Range of dose for swine bacteria in genus	**No information**					
Leptospiracanicola	Leptospiracanicola - Infectious Jaundice	3.2	6.0				UV-Light.co.UK
	Range of dose for bacteria in genus	**3.2**	**6.0**				
Listeria	Listeria monocytogenes	0.8 - 11.9					Adhikari et al., 2015
	Range of dose for bacteria in genus	**0.8 - 11.9**					
Micrococcus	Micrococcus candidus	6.1	12.3				UV-Light.co.UK
	Micrococcus sphaeroides	1.0	15.4				UV-Light.co.UK
	Range of dose for bacteria in genus	**1.0 - 6.1**	**12.3 - 15.4**				
Mycobacterium	Mycobacterium tuberculosis	6.2	10.0				UV-Light.co.UK
	Mycobacterium avium	5.7 - 6.4	7.9 - 9.4	10.0 - 12.0	12.0 - 24.0		Shin GA. et al. 2008
	Mycobacterium intracellulare	7.4 - 7.8	11.0	13.0 - 15.0	16.0 - 19.0		Shin GA. et al. 2008
	Mycobacterium terrae		10.5				Ko G. et al. 2005
	Range of dose for bacteria in genus	**5.7 - 7.8**	**7.9 - 11.0**	**10.0 - 15.0**	**12.0 - 24.0**		
Mycoplasma	Mycoplasma hyopneumoniae	No information					
	Mycoplasma hyorhinis	No information					
	Mycoplasma hyosynoviae	No information					
	Range of dose for swine bacteria in genus	**No information**					

Neisseria	Neisseria catarrhalis	4.4	8.5				UV-Light.co.Uk
	Range of dose for bacteria in genus	**4.4**	**8.5**				
Pasturella	Pasturella multocida	No information					
	Range of dose for swine bacteria in genus	**No information**					
Phytomonas	Phytomonas tumefaciens	4.4	8.0				UV-Light.co.UK
	Range of dose for bacteria in genus	**4.4**	**8.0**				
Proteus	Proteus mirabilis	0.9	1.8	2.7	3.6	4.5	Hofemeister J, Bohme H. 1975
	Proteus vulgaris	3.0	6.6				UV-Light.co.UK
	Range of dose for bacteria in genus	**0.9 - 3.0**	**1.8 - 6.6**	**2.7**	**3.6**	**4.5**	
Pseudomonas	Pseudomonas aeruginosa	5.5	10.5				UV-Light.co.UK
	Pseudomonas fluorescens	3.5	6.6				UV-Light.co.UK
	Pseudomonas fluorescens ATCC13525	3.6					UV-Light.co.UK
	Range of dose for bacteria in genus	**3.5 - 5.5**	**6.6 - 10.5**				
Salmonella	Salmonella paratyphi - Enteric fever	3.2	6.1				UV-Light.co.UK
	Salmonella anatum (from human feces)	7.5	12.0	15.0			Tosa and Hirata 1998
	Salmonella derby (from human feces)	3.5	7.5				Tosa and Hirata 1998
	Salmonella enterica		0.6 - 4.8	6.0			Mukhopadhyay et al., 2014
	Salmonella enteritidis (from human feces)	5.0	7.0	9.0	10.0		Tosa and Hirata 1998

	Salmonella infantis (from human feces)	2.0	4.0	6.0				Tosa and Hirata 1998
	Salmonella spp.		0.2	5.0				
	Salmonella spp.	2.0	2.0	3.5	7.0	14.0	29.0	Yaun et al. 2003
	Salmonella typhi ATCC 19430	1.8	4.8	6.4	8.2			Wilson et al. 1992
	Salmonella typhi ATCC 6539	2.7	4.1	5.5	7.1	8.5		Chang et al. 1985
	Salmonella typhimurium (from human feces)	2.0	3.5	5.0	9.0			Tosa and Hirata 1998
	Salmonella enteritidis	4.0	7.6					UV-Light.co.UK
	Salmonella typhimurium	8.0	15.2					UV-Light.co.UK
	Salmonella typhosa - Typhoid fever	2.2	4.1					UV-Light.co.UK
	Range of dose for bacteria in genus	**1.8 - 8.0**	**2.0 - 12.0**	**3.5 - 15.0**	**7.0 - 10.0**	**8.5 - 14.0**	**29.0**	
	Range of dose for swine bacteria in genus	**8.0**	**15.2**					
Shigella	*Shigella dysenteriae* ATCC29027	0.5	1.2	2.0	3.0	4.0	5.1	Wilson et al. 1992
	Shigella dyseteriae - Dysentery	2.2	4.2					UV-Light.co.UK
	Shigella flexneri - Dysentery	1.7	3.4					UV-Light.co.UK
	Shigella paradysenteriae	1.7	3.4					UV-Light.co.UK
	Shigella sonnei ATCC9290	3.2	4.9	6.5	8.2			Chang et al. 1985
	Range of dose for bacteria in genus	**0.5 - 3.2**	**1.2 - 4.9**	**2.0 - 6.5**	**3.0 - 8.2**	**4.0**	**5.1**	
Spirillum	Spirillum rubrum	4.4	6.2					UV-Light.co.UK
	Range of dose for bacteria in genus	**4.4**	**6.2**					
Staphylococcus	*Staphylococcus aureus* ATCC25923	3.9	5.4	6.5	10.4			Chang et al. 1985
	Staphylococcus albus	1.8	5.7					UV-Light.co.UK
	Staphylococcus aureus	2.6	6.6					UV-Light.co.UK
	Staphylococcus aureus ATCC 12600							

	Staphylococcus hemolyticus	2.2	5.5					UV-Light.co.UK
	Staphylococcus lactis	6.2	8.8					UV-Light.co.UK
	Staphylococcus hyicus							
	Range of dose for bacteria in genus	**1.8 - 6.2**	**5.4 - 8.8**	**6.5**	**10.4**			
	Range of dose for swine bacteria in genus	**2.6**	**6.6**					
Steptococcus	*Streptococcus faecalis* (secondary effluent)	5.5	6.5	8.0	9.0	12.0		Harris et al. 1987
	Streptococcus faecalis ATCC29212	6.6	8.8	9.9	11.2			Chang et al. 1985
	Streptococcus viridans	2.0	3.8					UV-Light.co.UK
	Steptococcus suis	No information						
	Range of dose for bacteria in genus	**2.0 - 6.6**	**3.8 - 8.8**	**8.0 - 9.9**	**9.0 - 11.2**	**12.0**		
	Range of dose for swine bacteria in genus	**No information**						
Vibrio	*Vibrio anguillarum*	0.5	1.2	1.5	2.0			UV-Light.co.UK
	Vibrio cholerae ATCC25872	0.8	1.4	2.2	2.9	3.6	4.3	UV-Light.co.UK
	Vibrio comma - Cholera	3.4	6.5					UV-Light.co.UK
	Range of dose for bacteria in genus	**0.5 - 3.4**	**1.2 - 6.5**	**1.5 - 2.2**	**2.0 - 2.9**	**3.6**	**4.3**	
Yersinia	*Yersinia enterocolitica* ATCC27729	1.7	2.8	3.7	4.6			Wilson et al. 1992
	Yersinia ruckeri	1.0	2.0	3.0	5.0			Liltved and Landfald 1996
	Yersinia pestis	1.3 - 1.4	2.2 - 2.6	3.2 - 3.7	4.1 - 4.9			Rose LJ, O'Connell H. 2009
	Range of dose for bacteria in genus	**1.0 - 1.7**	**2.0 - 2.8**	**3.0 - 3.7**	**4.1 - 5.0**			

Appendix A Table 2. Ultraviolet-C Dose (mJ/cm2) Required for a given log10 reduction of viruses. Swine pathogens are those with shaded background.

			Log_{10} Reduction						
Family	***Virus***	***Host / Cell Line***	**1**	**2**	**3**	**4**	**5**	**6**	**Reference**
			Dose (mJ/cm^2)	**Dose (mJ/cm^2)**	**Dose (mJ/cm^2)**	**Dose (mJ/cm^2)**	**Dose (mJ/cm^2)**	**Dose (mJ/cm^2)**	
Adenoviridae	Adenovirus type 15	A549 cell line (ATCC CCL-185)	40.0	80.0	122.0	165.0	210.0		Thompson et al. 2003
	Adenovirus 1		35.0	69.0	103.0	138.0			1327-30
	Adenovirus type 2	A549 cell line	20.0	45.0	80.0	110.0			Shin et al. 2005
	Adenovirus type 2	Human lung cell line	35.0	55.0	75.0	100.0			Ballester and Malley 2004
	Adenovirus type 2	PLC / PRF/ 5 cell line	40.0	78.0	119.0	160.0	195.0	235.0	Gerba et al. 2002
	Adenovirus type 4		10.0	34.0	69.0	116.0			Gerrity D. et al. 2008
	Adenovirus type 5					216.0 - 240.0			Kallenbach NR. et al. 1989
	Adenovirus type 6		39.0	77.0	115.0	154.0			Nwachuku N. et al. 2005
	Adenovirus type 40	PLC / PRF / 5 cell line	55.0	105.0	155.0				ClorDiSys Solutions Inc. 2018
	Adenovirus type 41	PLC / PRF / 5 cell line	23.6			111.8			ClorDiSys Solutions Inc. 2018
	Porcine adenovirus 1, 2, 3 (PAdV-1, 2, 3)		No information						
	Range of dose for virus in family		**10.0 - 55.0**	**34.0 - 105.0**	**69.0 - 155.0**	**100.0 - 165.0**	**195.0 - 210.0**	**235.0**	
	Range of dose for swine virus in family		**No information**						
Asfaviridae	African swine fever virus (ASFV)		No information						
	Range of dose for swine virus in family		**No information**						

Astroviridae	Porcine astrovirus 1 (PAstV-1)		10.0 - 12.0						Lytle CD, Sagripanti JL. 2005
	Range of dose for swine virus in family		**10.0 - 12.0**						
Arenaviridae			3.5						Lytle CD, Sagripanti JL. 2005
	Range of dose for virus in family		**3.5**						
Arteriviridae	Porcine respiratory and reproductive syndrome virus (PRRSV)	MARC-145 cells	3.9	4.5	>4.9				Stephan, 2017
	Range of dose for swine virus in family		**3.9**	**4.5**	**>4.9**				
Bunyaviridae			2.0 - 3.5						Lytle CD, Sagripanti JL. 2005
	Range of dose for virus in family		**2.0 - 3.5**						
Caliciviridae	Calicivirus canine	MDCK cell line	7.0	15.0	22.0	30.0	36.0		Husman et al. 2004
	Calicivirus feline	CRFK cell line	5.0	15.0	23.0	30.0	39.0		Enriquez et al. 2003
	Murine norovirus					25.0	30.0		Lee J. et al. 2008
	Vesicular exanthema of swine virus (VESV)		No information						
	Porcine sapovirus (historically porcine enteric calicivirus)		No information						
	Porcine circovirus 2 (PCV2)		No information						
	Porcine circovirus 3 (PCV3)		No information						

	Range of dose for virus in family		**5.0 - 7.0**	**15.0**	**22.0 - 23.0**	**25.0 - 30.0**	**30.0 - 39.0**		
	Range of dose for swine virus in family		**No information**						
Coronaviridae	Transmissible gastroenteritis virus (TGEV)		No information						
	Porcine respiratory coronavirus (PRCV)		No information						
	Porcine hemagglutinating encephalomyelitis virus (pHEV)		No information						
	Porcine deltacoronavirus (PDCoV)		No information						
	SARS coronavirus					91.0	114.0 - 162.0		Duan SM et al. 2003
	Berne virus					5.0			Weiss M, Horzinek MC. 1986
	Porcine Epidemic Diarrhea Virus (PEDV)	Vero 76 Cells	0.7	2.7	2.9				Stephan, 2017
	Range of dose for virus in family		**0.7**	**2.7**	**2.9**	**5.0 - 91.0**	**114.0 - 162.0**		
	Range of dose for swine virus in family		**0.7**	**2.7**	**2.9**				
Deltaviridae			22.0						Lytle CD, Sagripanti JL. 2005
	Range of dose for virus in family		**22.0**						
Filoviridae	Reston virus (RESTV)		2.0						Lytle CD, Sagripanti JL. 2005
	Range of dose for swine virus in family		**2.0**						
Flaviviridae	Japanese encephalitis virus (JEV)		No information						

	Classical swine fever virus (CSFV)		No information						
	Atypical porcine pestivirus (APPV)		No information						
	Range of dose for swine virus in family		**No information**						
Hepadnaviridae			3.8 - 4.1						Lytle CD, Sagripanti JL. 2005
	Range of dose for virus in family		**3.8 - 4.1**						
Herpesviridae	Epstein Barr virus		16.0 - 23.0						
	Herpes simplex virus 1		3.7 - 10.0	7.4 - 20.0	11.0	24.0	37.0		Henderson E. et al. 1978
	Herpes simplex virus 2		0.4	0.7	11.0	13.0			Wolff MH, Schneweis KE 1973
	Equine herpes virus				7.5				Weiss M, Horzinek MC. 1986
	Pseudorabies virus (PRV) or Aujeszky's disease virus		No information						
	Porcine cytomegalovirus (PCMV)		No information						
	Range of dose for virus in family		**0.4 - 23.0**	**0.7 - 20.0**	**7.5 - 11.0**	**13.0 - 24.0**	**37.0**		
	Range of dose for swine virus in family		**No information**						
Hepeviridae	Hepatitis E virus (HEV)		No information						
	Range of dose for swine virus in family		**No information**						
Leviviridae	*MS2 (Phage)*	Salmonella typhimurium WG49	16.3	35.0	57.0	83.0	114.0	152.0	Nieuwstad and Havelaar 1994

	MS2 (Phage)	*E. coli* ATCC 15597	20.0	42.0	70.0	98.0	133.0		Lazarova and Savoye 2004
	MS2 (Phage)	*E. coli* HS(pFamp)R		45.0	75.0	100.0	125.0	155.0	Thompson et al. 2003
	MS2 ATCC 15977-B1 (Phage)	*E. coli* ATCC 15977–B1	15.9	34.0	52.0	71.0	90.0	109.0	Wilson et al. 1992
	MS2 DSM 5694 (Phage)	*E. coli* NCIB 9481	4.0	16.0	38.0	68.0	110.0		Wiedenmann et al. 1993
	MS2 NCIMB 10108 (Phage)	*Salmonella typhimurium* WG49	12.1	30.1					Tree et al. 1997
	Range of dose for virus in family		**4.0 - 20.0**	**16.0 - 45.0**	**38.0 - 75.0**	**68.0 - 100.0**	**90.0 - 133.0**	**109.0 - 155.0**	
Microviridae	PHI X 174 (Phage)	*E. coli* C3000	2.1	4.2	6.4	8.5	10.6	12.7	Battigelli et al. 1993
	PHI X 174 (Phage)	*E. coli* WG 5	3.0	5.0	7.5	10.0	12.5	15.0	Sommer et al. 1998
	Range of dose for virus in family		**2.1 - 3.0**	**4.2 - 5.0**	**6.4 - 7.5**	**8.5 - 10.0**	**10.6 - 12.5**	**12.7 - 15.0**	
Orthomyxoviridae	Influenza		3.4	6.6					UV-Light.co.UK
	Influenza A virus in swine (IAV-S)		No information						
	Influenza B		No information						
	Influenza C		No information						
	Influenza D		No information						
	Range of dose for swine virus in family		**3.4**	**6.6**					
Papillomaviridae	Swine papillomavirus (SPV)		No information						
	Range of dose for swine virus in family		**No information**						
Papovaviridae	Polyomavirus		47.0	43.0 - 94.0	141.0				Larzarona V, Savoys P. 2004

	Simian virus 40		105.0 - 300.0	130.0 - 261.0		440.0	551.0		Abrahams PJ, Van der Eb AJ. 1976
	Range of dose for virus in family		**47.0 - 300.0**	**43.0 - 261.0**	**141.0**	**440.0**	**551.0**		
Paramyxoviridae	Menangle virus		3.0						Lytle CD, Sagripanti JL. 2005
	Blue eye paramyxovirus (BEPV)		No information						
	Nipah virus (NiV)		No information						
	Porcine parainfluenza virus 1 (PPIV-1)		No information						
	Sendai virus		No information						
	Range of dose for swine virus in family		**3.0**						
Parvoviridae	Parvovirus H-1, hamster osteolytic virus		23.0	46.0					Cornelis JJ et al. 1982
	Porcine parvovirus						83.0		Chin S et al. 1997
	Murine Parvovirus						<20		Lytle CD, Sagripanti JL 2005
	Porcine parvovirus 1 (PPV1)		No information						
	Porcine parvovirus 2 (PPV2)		No information						
	Porcine parvovirus 3 (PPV3), or porcine hokovirus, or PARV4-like		No information						
	Porcine parvovirus 4 (PPV4)		No information						
	Porcine parvovirus 5 (PPV5)		No information						
	Porcine parvovirus 6 (PPV6)		No information						
	Porcine parvovirus 7 (PPV7)		No information						

	Encephalomyocarditis virus		7.6	15.0	23.0	16.0 - 113.0	25.0 - 141.0		Caillet-Fauquet P et al. 2004
	Range of dose for virus in family		**7.6 - 23.0**	**15.0 - 46.0**	**23.0**	**16.0 - 113.0**	**<20 - 141.0**		
	Range of dose for swine virus in family						**83.0**		
Picornaviridae	Coxsackievirus B3	BGM cell line	8.0	16.0	24.5	32.5			Gerba et al. 2002
	Coxsackievirus B5	Buffalo Green Monkey cell line	6.9	13.7	20.6				Battigelli et al. 1993
	Coxsackievirus B5	BGM cell line	9.5	18.0	27.0	36.0			Gerba et al. 2002
	Echovirus I	BGM cell line	8.0	16.5	25.0	33.0			Gerba et al. 2002
	Echovirus II	BGM cell line	7.0	14.0	20.5	28.0			Gerba et al. 2002
	Hepatitis A	HAV/HFS/GBM	5.5	9.8	15.0	21.0			Wiedenmann et al. 1993
	Hepatitis A HM175	FRhK-4 cell	5.1	13.7	22.0	29.6			Wilson et al. 1992
	Hepatitis A HM175	FRhK-4 cell	4.1	8.2	12.3	16.4			Battigelli et al. 1993
	Infectious Hepatitis	N/A	5.8	8.0					UV-Light.co.UK
	Poliovirus - Poliomyelitis	N/A	3.2	6.6					UV-Light.co.UK
	Poliovirus 1	BGM cell line	5.0	11.0	18.0	27.0			Tree et al. 2005
	Poliovirus 1	CaCo2 cell-line (ATCC HTB37)	7.0	17.0	28.0	37.0			Thompson et al. 2003
	Poliovirus Type Mahoney	Monkey kidney cell line Vero	3.0	7.0	14.0	40.0			Sommer et al. 1989
	Foot-and-mouth disease virus (FMDV)		24.0	48.0	72.0	96.0	120.0		Nicholson WL, Galeano B. 2003
	Encephalomyocarditis virus (EMCV)		No information						
	Coxsackievirus B4 (including swine vesicular disease virus 2 [SVDV-2])		No information						
	Coxsackievirus B5 (including SVDV-1)		No information						
	Porcine kobuvirus (PKV)		No information						

	Porcine sapelovirus (PSV)		No information						
	Seneca Valley virus (SVV)		No information						
	Porcine teschovirus (PTV) 1–13		No information						
	Poliovirus Type 1 LSc2ab ()	MA104 cell	5.6	11.0	16.5	21.5			Chang et al. 1985
	Poliovirus Type 1 LSc2ab	BGM cell	5.7	11.0	17.6	23.3	32.0	41.0	Wilson et al. 1992
	Range of dose for virus in family		**3.0 - 24.0**	**6.6 - 48.0**	**12.3 - 72.0**	**16.4 - 96.0**	**32.0 - 120.0**	**41.0**	
	Range of dose for swine virus in family		**24.0**	**48.0**	**72.0**	**96.0**	**120.0**		
Poxviridae	Vaccinia virus		1.5 - 3.5	3.0 - 7.1	4.5 - 11.0	6.1	7.6		Kowalski WJ et al. 2000
	Swinepox virus		No information						
	Range of dose for virus in family		**1.5 - 3.5**	**3.0 - 7.1**	**4.5 - 11.0**	**6.1**	**7.6**		
	Range of dose for swine virus in family		**No information**						
Reoviridae	Rotavirus A (RVA)		No information						
	Rotavirus B (RVB)		No information						
	Rotavirus C (RVC)		No information						
	Rotavirus E (RVE)		No information						
	Rotavirus H (RVH)		No information						
	Porcine reovirus		No information						
	Getah virus (GETV)		No information						
	Chikungunya virus (CHIKV)		No information						

	Reovirus Type 1 Lang strain	N/A	16.0	36.0					Harris et al. 1987
	Reovirus-3	Mouse L-60	11.2	22.4					Rauth 1965
	Simian Rotavirus		29.0	58.0	87.0	117.0			Li D. et al. 2009
	Rotavirus	MA104 cells	20.0	80.0	140.0	200.0			Caballero et al. 2004
	Rotavirus SA-11	MA-104 cell line	9.1	19.0	26.0	36.0	48.0		Wilson et al. 1992
	Range of dose for virus in family		**9.1 - 29.0**	**19.0 - 80.0**	**26.0 - 140.0**	**36.0 - 200.0**	**48.0**		
	Range of dose for swine virus in family		**No information**						
Retroviridae	Rous sarcoma virus						300.0		Kariwa H. et al. 2004
	HTLV-III/LAV			200.0			360.0		Nakashima H. et al. 1986
	Range of dose for virus in family			**200.0**			**300.0 - 360.0**		
Rhabdoviridae	Vesicular stomatitis virus					19.0	<75		Kariwa H et al. 2004
	Vesicular stomatitis Indiana virus (VSIV)		No information						
	Vesicular stomatitis New Jersey virus (VSNJV)		No information						
	Rabies virus					5.0			Weiss M, Horzinek MC. 1986
	Range of dose for swine virus in family					**5.0 - 19.0**	**<75**		
Siphoviridae	*B40-8 (Phage)*	B. Fragilis	11.0	17.0	23.0	29.0	35.0	41.0	Sommer et al. 2001
	Range of dose for virus in family		**11.0**	**17.0**	**23.0**	**29.0**	**35.0**	**41.0**	
Tectiviridae	*PRD-1 (Phage)*	S. typhimurium Lt2	9.9	17.2	23.5	30.1			Meng and Gerba 1996

	Range of dose for virus in family		**9.9**	**17.2**	**23.5**	**30.1**			
Togaviridae	Sindbis virus				15.0 - 30.0	40.0	24.0 - 50.0		Wang J. et al. 2004
	Semliki forest virus				7.5				Weiss M, Horzinek MC. 1986
	Venezuelan equine encephalomyelitis virus					22.0	33.0		Smirnov Yu et al. 1992
	Range of dose for virus in family				**7.5 - 30.0**	**22.0 - 40.0**	**24.0 - 50.0**		

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