Upper room Ultraviolet Germicidal Irradiation (UVGI)

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Since the 1950s Upper room Ultraviolet Germicidal Irradiation (UVGI) has been used to combat pathogens on surfaces and in the air (Wells, 1955; Riley 1976). In those days it was a control measure against Tuberculosis and Measles.

In buildings UVGI can be applied in different ways:

1) UVGI in fixtures in the open air
2) in mobile robots with high intensity to destroy pathogens (the absence of humans is required)
3) in fixtures in air handling units and local air cleaning devices.

This article is directed to the UVGI in fixtures in the open air. It combats pathogens deposited on surface and floating in the air by irradiation with UVGI.

UVGI

Sunlight contains irradiation from the UV spectrum (see fig 1): long waves (UVA: 315 – 400 nm) and median waves (UVB: 280 – 315 nm). Outdoors viruses can be destroyed due to the high intensity of the UV present. The higher the UV-Index the better it can destroy the virus. Short waves are not present in natural light. It is filtered out by the atmosphere. A wavelength of 254 nm (UVC) has a relative high efficiency compared to a wavelength of 313 nm (UVB). This results in short range waves (UVC) is destroying pathogens more efficiently compared to long range waves (UVA/UVB). To obtain equal inactivation higher doses is required for UVA and UVB than UVC.

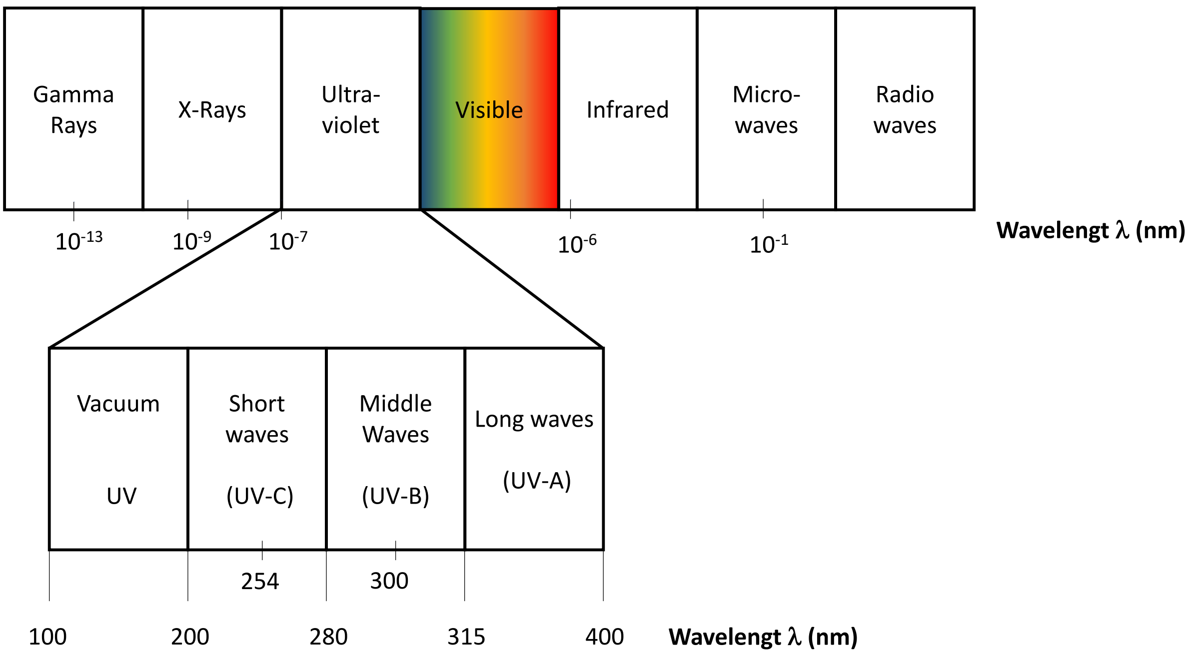

Figure 1. Solar radiation spectrum.

UVGI and Coronavirus

The UV-C photons are interacting with the genetic material (RNA) of the virus to destroy its structure. Harmed viruses can't be infectious. UVGI is more effective for ssRNA viruses compared to dsRNA viruses (Tseng & Li, 2007). SARS-CoV-2 is a ssRNA virus and belongs to *Coronaviridae*. To decode the sort: ss means single stranded, ds double stranded and RNA expresses the genetic material. In laboratory research from Tseng & Li relative humidity is affecting the efficacy in destroying the virus. For higher relative humidity's a higher dose of UVGI is required. The additional accumulated moist creates a better protection against UVGI.

Efficiency UVGI

The exposure of viruses towards UVGI (doses) is expressed in mJ/cm², the radiant energy per surface area. It is the product between irradiation intensity E per surface area (mW/cm²) and the exposure time t (s).

$$D = Et$$

The decay of virus concentration is a first order process with a constant value, called the k-value or susceptibility constant of pathogen k (cm²/mJ) (Noakes et al, 2015).

$$\varphi(t) = e^{-kD} = e^{-kEt}$$

For multiple viruses the dose to destroy 90% is studied (Tseng & Li, 2007; Malayeri et al, 2016), including the coronavirus.

The efficiency of UVC can be expressed in equivalent air changes per hour (ACH). Assuming a well-mixed ventilated room the equivalent is the log-reduction λ multiplied by the volume V of the room. The product λV can be used as sink to estimate the infection probability. An equivalent ACH of 6 to 8 is achievable. The sink terms used in infection probability models such as the Wells-Riley models are mechanism eliminating pathogens from the air, e.g. to ventilate indoor environments, deposition from pathogens as well as destroying pathogens by UVGI.

Far UVC (222 nm) versus traditional UVC (254 nm)

Novel lighting techniques are creating the potential to irradiate other wavelengths. Fluorescent lamps based on mercury is irradiating a wavelength of 254 nm. LED and fluorescent lamps based on excimer gases (Krypton Chloride), created opportunities to irradiate a wavelength of 222, called far UVC. Unfortunately, the supply of far UVC is limited yet.

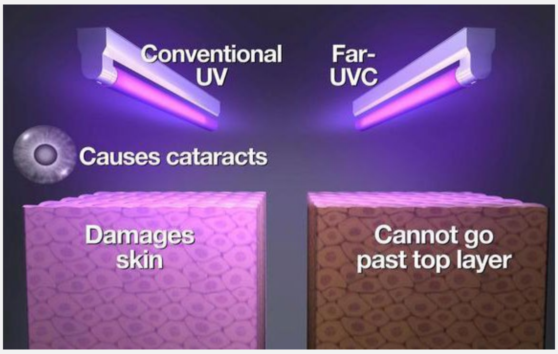

Figure source: CBS News

Table 1. *Dose for log-reduction of UVGI wavelengths 254 nm and 222 nm. For UVC 254 nm the median was taken based on a review article (Heßling et al, 2020), for UVC 222 nm a laboratory study has been used (Welch et al, 2020).*

	k-value [cm²/mJ]	Log 1-reduction D_{90} [mJ/cm²]	Log 2-reduction D_{99} [mJ/cm²]	Log 3-reduction $D_{99,9}$ [mJ/cm²]
UV-C (254 nm)	Not available	3,70	NA	NA
UV C (222 nm)				
HCoV-229E	4.1	0.56	1.10	1.70
HCoV-OC43	5.9	0.39	0.78	1.20

Positioning UVGI fixtures in rooms and environmental factors

For a high efficiency to destroy floating viruses a well-mixed ventilated room is required. Positioning depends on the wavelength of the used UVGI fixture. Especially UVC (254 nm) can harm humans if inappropriate positioned.

From a Health and Safety perspective UVC fixtures must be installed above 2,1 meters to avoid direct irradiation in the living zone (to protect eyes and skin of humans). This requirement is only needed for UVC with a wavelength of 254 nm. UVC with a wavelength of 222 nm can't harm eyes and skin due to the limited penetration of this irradiation on human tissues. Therefore, installing fixtures on ceiling is allowed for far UVC (222 nm).

Health and Safety and UVC

The current safety limit for UVC (254 nm) is set on 6 mJ/cm², the safe dose (ICNIRP, 2004). It prevents skin burning and consequently potential skin cancer as well is eye damage. Comparing UV irradiation caused by sun irradiation: at the safety limit of 6,0 mJ/cm² the dose is achieved after 10 minutes at a UV-index of 10 while it takes 8 hours indoors using UVC before the dose has been achieved.

The human exposure for upper room UVGI fixture has been set on 1/3 from the safety limit. By exchanging lamps, the UVGI should be switched off to avoid direct irradiation. For far UVC (222 nm) the limited penetration of UVC irradiation on human tissues seems very low and therefore it is thought no harmful (Welch et al, 2018). A dose of 24,0 mJ/cm² is the safety limit.

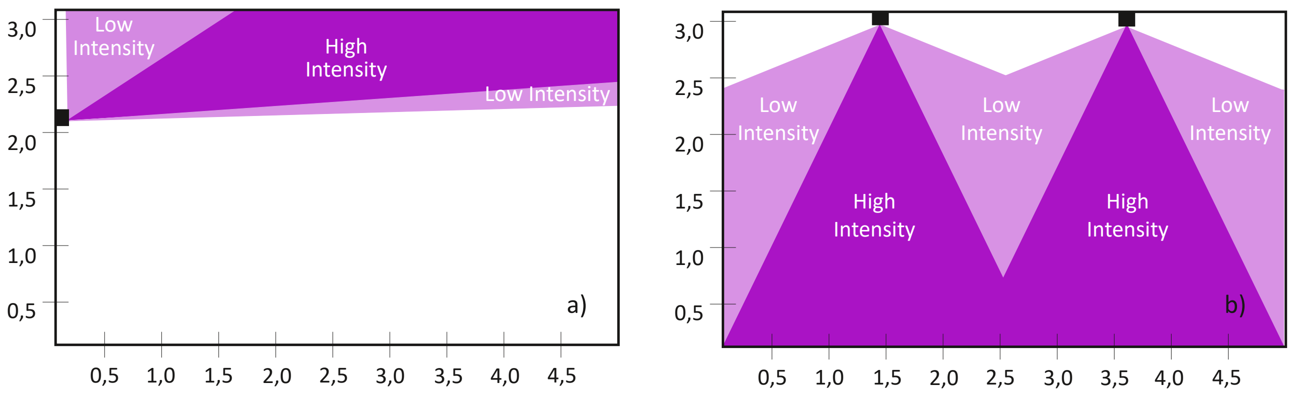

Figure 2. Positioning of UV-C fixtures. a) UV-C 254 nm, b) UV-C 222 nm

Figure 3. Example of application of UVC fixtures: Hospital ward room. [Source: Germicidal Lamps & Applications (GLA)]

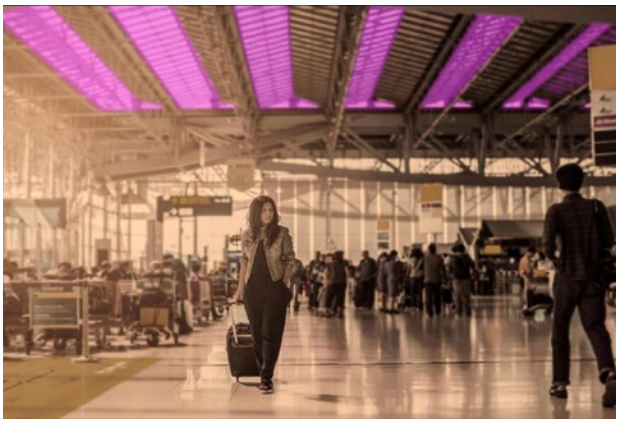

Figure 4. Example of application of UVC fixtures: Airport. [Source: Colombia University]

Based on the log 1, log 2 and log 3 -reductions due to far UVC (222 nm) no limitations on direct irradiations are required (ICNIRP, 2004).

Design and commissioning of UVGI fixtures

For design and commissioning this article is focused on the commercial wide available UVC lamps with a wavelength of 254 nm.

The reflection of ceiling should be considered to prevent excessing the safety limit of 6,0 mJ/cm^2 during 8 hours.

To compute the required irradiation intensity at different parts of the room based on the product specifications Computational Fluid Dynamics (CFD) simulations can be used. It shows intensity for every point in the room. This depends on the distance to the fixture and angle of the irradiation (Gilkeson & Noakes, 2012).

UVC irradiation can't cause harm when penetrating to glass. The wavelengths of UVC are filtered out.

To determine the required dose the irradiation intensity in order to destroy coronaviruses at different points in the room UVC radiometers can be used. This measurement also gain insight if the safety limits are not exceeded. A laboratorial calibrated radiometer complying the ISO/IEC 17025 is recommended. Consider if the radiometer is sensitive for far UVC (222 nm).

Conclusion

UVGI can be very effective to destroy coronaviruses. Especially in indoor environments with inappropriate ventilation, with a consequence to obtain an unacceptable infection probability. Good engineering practice and taking care of safety limits to protect eyes and skins is crucial for an effective and safe application of UVGI. ■

References

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