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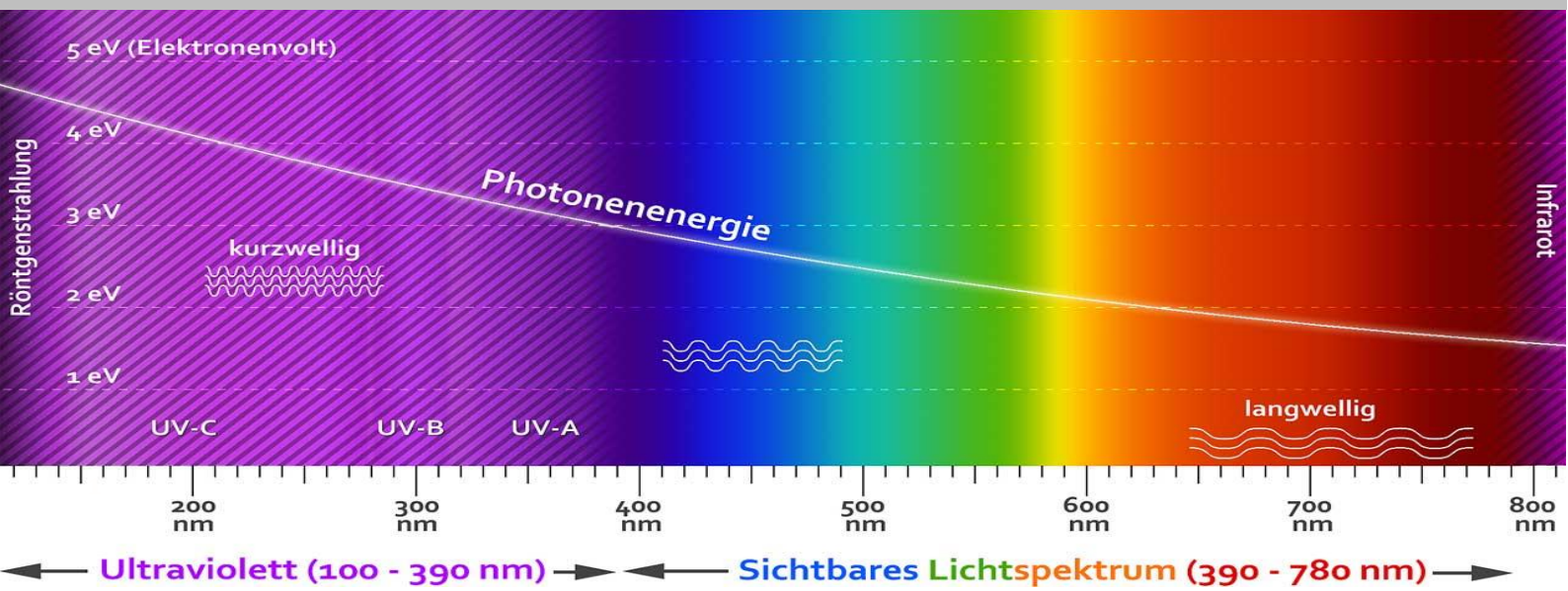

Far-UVC - potentials and weaknesses

Fraunhofer Institute of Optronics, System Technologies and Image Exploitation

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Introduction

Far-UVC is currently experiencing a real hype, especially in American UV specialist circles. Driven in particular by the corona pandemic, this wavelength range is therefore being postulated as a good solution for air disinfection. The purpose of this document is to take a critical look at the current state of research into far-UVC and the radiation sources currently available. It deals with the advantages and disadvantages compared to other wavelength ranges and technologies and considers both infectiological and economic aspects. All statements in this document refer to the status at the end of 2023.

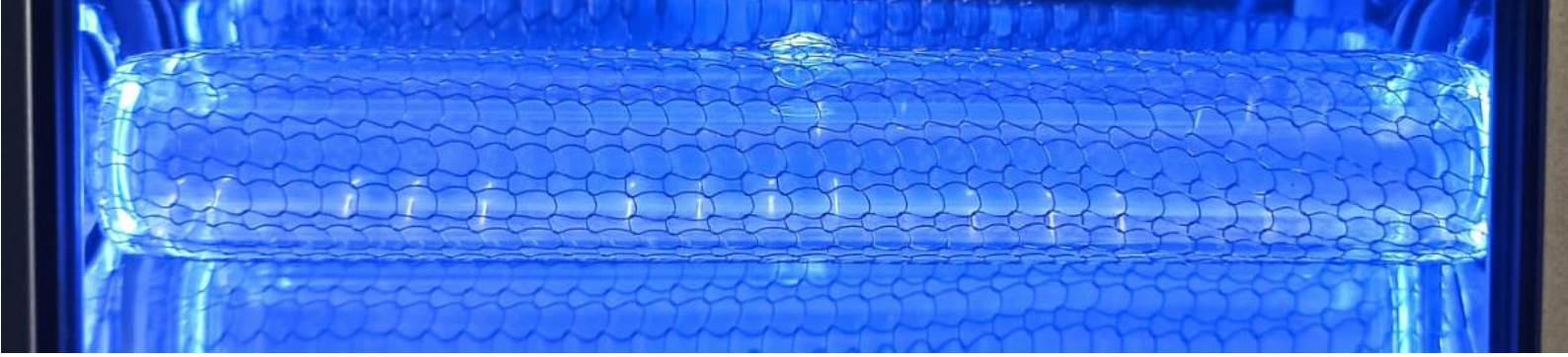
What is Far-UVC?

First of all, it should be noted that the term "far-UVC" has not yet been clearly defined. However, it has become common parlance to refer to the spectral sub-range of UVC radiation from 200 - 230 nm as far-UVC (or far-UVC). In contrast to the 254 nm UVC emission of mercury vapor lamps, far-UVC radiation can inactivate pathogens and cause less damage to humans. Despite promising studies to date, however, further scientific work is still required before a clear, well-founded statement can be made on the large-scale use of Far-UVC. In the long term, far-UVC radiation sources could very probably open up new areas of application due to their apparently lower risk to humans.

Since the start of the corona pandemic in December 2019, disinfection measures and the emergence of new ideas to contain (corona) infections have become part of everyday life worldwide. Some of the suggestions put forward are curious or even questionable and some sound too good to be true. For example, it has been discussed whether there is UVC radiation (ultraviolet radiation with a wavelength below 280 nm) that only inactivates pathogens such as coronaviruses but is harmless to humans.

To date, UVC radiation has mainly been generated by mercury vapor lamps that emit at 254 nm. It has been known for decades that this radiation has a very strong antimicrobial effect because it destroys the DNA and RNA of pathogens. Unfortunately, this radiation is also very harmful to human cells, which is why there are standards and guidelines that prohibit the use of UVC radiation if there is a risk that people could be directly exposed to this radiation or at least set very low limits for this. However, applications in closed systems such as water disinfection reactors are widespread.

The idea that there could be short-wave UVC radiation that damages microorganisms significantly more than cells of higher organisms was first presented in 2004 [1]. About 10 years later, the approach was taken up again and further investigated [2, 3], but received little attention outside the scientific community. The corona pandemic has brought increased attention to this proposal, as important new applications are conceivable, such as the irradiation of



rooms or elevators while people are present.

Mode of action

So why is the 254 nm radiation from the mercury vapor lamp more harmful than other wavelengths in the UVC range? As can be seen in Figure 1, the 254 nm emission peak is located near a DNA absorption maximum. This is the reason for the strong antimicrobial effect of this radiation. Compared to short-wave UV radiation, however, the absorption of proteins at 254 nm is low and the penetration depth into the skin is therefore quite high. The strongest radiation sources currently commercially available are krypton chloride excimer lamps with a peak wavelength of 222 nm (also Figure 1). DNA absorption is somewhat lower at this wavelength. However, the major difference lies in the significantly higher absorption of this radiation by proteins. The effect of this strong protein absorption is illustrated in Figure 2. Human skin consists of several layers. The uppermost layer (stratum corneum) of keratinized skin cells contains a high concentration of the protein keratin. Keratin absorbs far-UVC radiation so that only a very small proportion of it reaches the deeper skin layers with vital cells. In a self-experiment, British researchers irradiated their own skin with a Far-UVC dose of 18,000 mJ/cm² without observing any permanent skin damage [5]. This value is 6,000 times higher than the maximum permitted daily 254 nm irradiation, a dose of 3 mJ/cm² [6].

Even free human cells - without a high keratin content - are said to be less sensitive to Far-UVC than at 254 nm. The DNA-containing cell nucleus is usually surrounded by proteins that at least partially absorb the radiation, so that the DNA is exposed to a significantly reduced radiation intensity [7]. Another study investigated skin damage at wavelengths of 233 nm and came to the conclusion that hardly any damage to the skin can be detected here either [15].

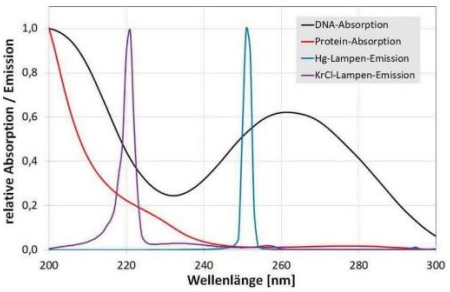


Figure 1: Emission spectra and absorption rates

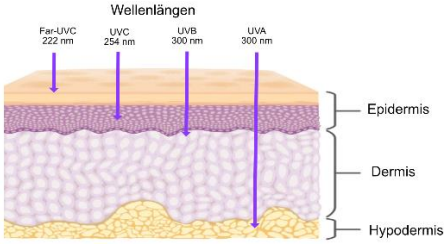


Figure 2: Penetration depths into the skin

Various pathogens generally also contain proteins and yet are not protected against Far-UVC. The reason for this is that they do not have a protective layer like the stratum corneum of human skin and, above all, that they are very small. The volume of a bacterium is on average approx. 10,000 times smaller than that of a human cell and the volume of a virus is another 1,000 times smaller than that of a bacterium. This means that there is hardly any far-UVC absorption by proteins. The microorganisms are simply irradiated, as with a wavelength of 254 nm, and their DNA and RNA are damaged.

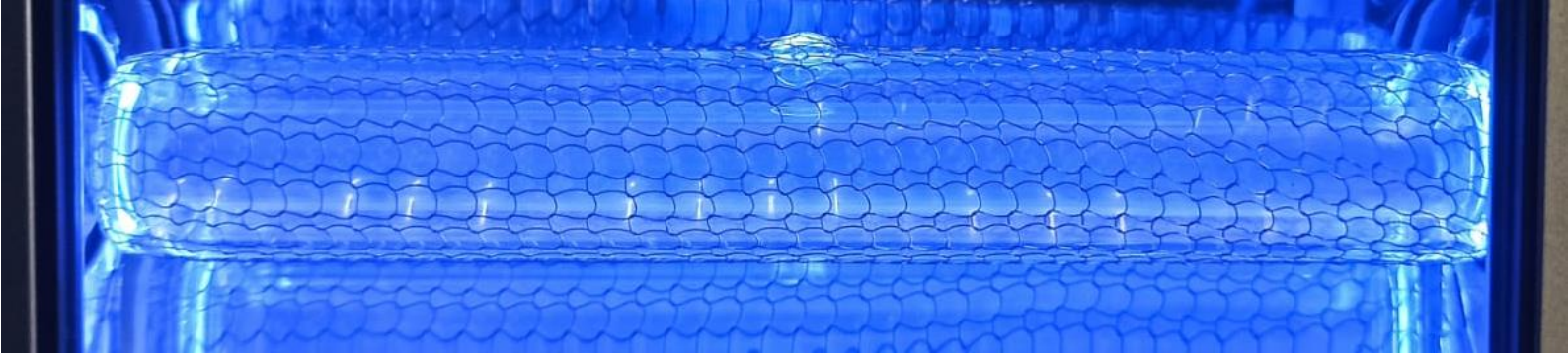
Relationship between irradiation intensity, irradiation dose and microbiological effect

The effectiveness of UVC irradiation is largely determined by the applied dose or fluence. The dose results from the irradiation intensity [W/m², mW/cm², µW/cm²] multiplied by the irradiation time over which this intensity acts on the microorganism. The dose is given in [Ws/m², J/m², mJ/cm², µJ/cm²...]. The higher the dose, the more microorganisms are inactivated by the irradiation. This inactivation is expressed as a decadic logarithm. An inactivation of one log level corresponds to 90%. This means that 10% of the microorganisms are still active after irradiation. Two log levels correspond to 99% inactivation and so on. Disinfection is said to have taken place from an inactivation of at least four log levels, i.e. 99.99%. Only from this inactivation rate is it ensured that there is hardly any danger from most pathogens. Sterilization is achieved when an inactivation of at least six log levels of all pathogen species present has been achieved (99.9999%). However, out of one million microorganisms, which can be found in this quantity on one square centimetre of human skin, one would still be active.

The required irradiation doses also vary depending on the microorganism. Viruses can usually be inactivated with very low doses of irradiation, as they lack DNA repair mechanisms such as photoreactivation. Bacteria require a higher irradiation dose and the upper end of the scale is formed by molds and yeasts, which sometimes require a thousand times the dose of a virus to be inactivated.

State of research

All the information mentioned so far suggests that antimicrobial Far-UVC radiation is possible in the presence of humans and that this radiation could also be used against coronaviruses or other aerosol-borne viruses (e.g. noroviruses, rhinoviruses or influenza viruses). In addition to the skin, the eyes in particular are exposed to possible far-UVC radiation. Based on studies on animals, it can be assumed that the radiation is absorbed by the tear film and the outer corneal layer without causing permanent damage [10]. However, there are also studies with primates and in some cases on the human eye, resulting in demonstrable eye damage from as little as 10 mJ/cm² [13]. The eyes of monkeys and humans are very similar in structure, which requires particular caution and further studies. In addition to these still open scientific questions, there are some regulatory aspects to consider. The current guidelines for protection against radiation [6] only allow a maximum daily 222 nm Far-UVC dose of approx. 23 mJ/cm² (230 J/m²)



within an 8-hour day. There is currently no test standard for Far-UVC irradiation devices that allows independent test facilities to carry out comparable testing of such devices to ensure the irradiation doses required to inactivate microorganisms and the necessary safety aspects for the end user.

Disadvantages?

In addition to the advantages and potential of Far-UVC, there are also disadvantages resulting from the wavelength and the current possibilities of radiation generation, which cannot be ignored.

Radiation sources

KrCl excimer lamps are currently the only radiation sources that can be used to generate far-UVC radiation at 222 nm. These are gas discharge lamps filled with a gas mixture of krypton and chlorine, which is stimulated to emit by an external high voltage pulsed at several 100 kHz. In contrast to mercury vapor lamps, there are only very few manufacturers worldwide, such as the Japanese company Ushio, whose devices were also used for almost all current studies. Ushio is the de facto market leader and monopolist in the field of KrCl excimer lamps. When new devices from other manufacturers come onto the market, it must be checked that they do not have any harmful effects on humans. Particularly critical are the undesirable emissions above 230 nm, which also occur with KrCl and could penetrate deeper into human skin and damage cells there [5, 8]. These undesirable spectral components must be blocked with suitable filters. As Ushio holds a patent for these filters, it is likely to be difficult or even unattractive for other suppliers to enter the KrCl excimer market. Although UV LEDs are increasingly penetrating the short-wave UVC range, they are currently nowhere near reaching the wavelengths (< 230 nm) and the necessary efficiencies to compete with KrCl excimers. However, this is likely to change in the future.

Efficiency of KrCl excimers

Basically, there are several types of efficiency to consider. Firstly, there is the so-called wall-plug efficiency (WPE) or electrical efficiency, which describes how much of the supplied electrical energy is converted into radiant energy and how much energy is lost in conversion losses during this process. If we look at the WPE in the case of KrCl excimer lamps, we see that these lamps are extremely inefficient. Only 1-2 percent of the electrical energy is converted into radiant energy. A good 99 percent is therefore lost in the form of heat. A low-pressure mercury lamp achieves WPEs of between 30 and 40 percent and even UVC LEDs currently achieve a good 7-8 percent WPE (at 270 nm). Current KrCl excimer lamps, e.g. for room disinfection, generally have optical output powers in the two to three-digit milliwatt range due to this low WPE and only achieve irradiation intensities of a few µW/cm². To achieve an inactivation-relevant dose of at least 4 log levels (99.99%), very long irradiation times of several hours in a room would therefore be necessary.

The second important efficiency is the microbiologically effective photon efficiency, i.e. how effectively the emitted photons of a specific wavelength damage the microorganism or other components of the microorganism to be inactivated. The picture here is twofold. The result is that many microorganisms can be better inactivated with 254 nm than with 222 nm [14]. Far-UVC therefore requires significantly higher irradiation doses than would be the case with conventional UV lamps. However, there are also microorganisms that have been investigated, such as Pseudomonas, for which 222 nm performs slightly better. In order to make a clear statement here as to which wavelength is more efficient, reference must be made to the corresponding microorganism. On average for all microorganisms investigated in [14], an irradiation dose 1.89 times higher was required at 222 nm for the same log inactivation rate.

Costs

Kr-Cl excimer lamps are extremely expensive compared to other UV radiation sources. Prices for a complete system comprising lamp and power supply for a filtered system start at around €2000. The low efficiency and high costs make the use of KrCl excimer lamps economically viable for very few applications.

Service life

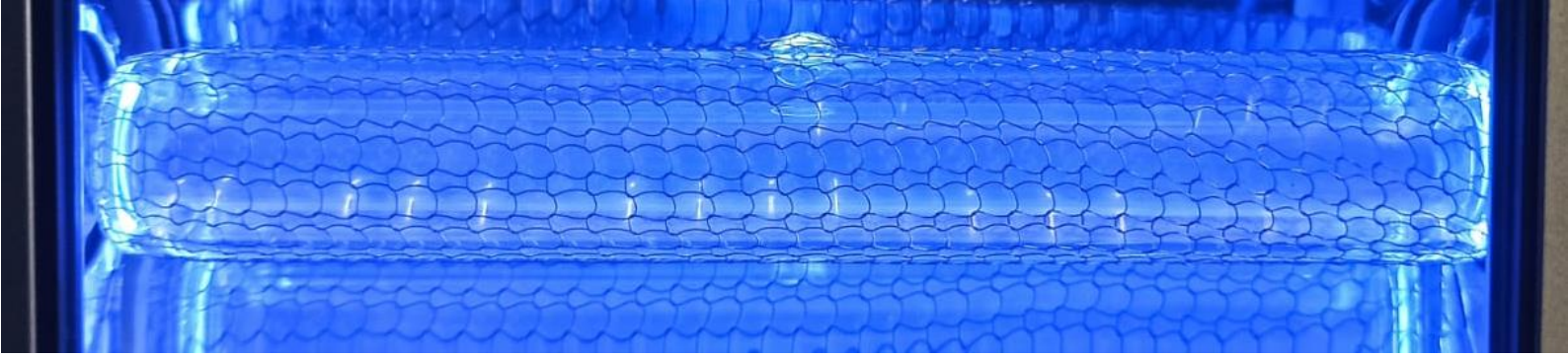
Information on the service life of KrCl excimer lamps compared to other UV radiation sources is quite difficult to find and also very vague. It is assumed that they can achieve a service life of more than 4000 hours [11]. Some other studies speak very unspecifically of "several thousand hours". If such a lamp is used in continuous operation, it would therefore have to be replaced about once or twice a year (equivalent to 8760 h). Due to the high price and this short replacement interval, it remains questionable whether this makes operation economically viable at all.

Ozone

When UV radiation below 242 nm is generated in an oxygen-containing atmosphere, ozone is produced by absorption of the photons in the atmospheric oxygen. The higher the power of the UV source and the lower the emission wavelength, the greater the amount of ozone produced. Metal oxides, light and heat accelerate the decomposition to oxygen. Ozone is oxidizing and also an irritant gas, which has a very low odour threshold and is therefore clearly and unpleasantly perceptible even at very low concentrations. The individual threshold of perceptibility varies greatly from 0.005 to 470 ppb, depending on the person. Ozone is absorbed through the mucous membranes of the respiratory tract (nose, throat, lungs) and eyes.

Possible health hazards are then:

- Irritation and damage to the mucous membranes of the respiratory tract (hoarseness, coughing, nosebleeds, bronchitis) and eyes;
- Change in lung function;



- Disruption of physical performance;
- in high concentrations: Pulmonary edema, headache, nausea, fatigue, dizziness, lack of concentration.

There is a well-founded suspicion of carcinogenic potential (carcinogenic category 2 according to TRGS 905) [16]. The MAK value for ozone was 0.2 mg/m³ or 0.1 ml/m³. As no OEL has yet been defined for ozone [17], the previous TLV [18] or international limit values of 0.12 mg/m³ (BG ETEM information sheet no. 526) serve as a guide for the concentration at the workplace. The DNEL can also serve as a guide [19]. It describes the exposure limit value below which a substance does not lead to any adverse effects on human health according to the current state of scientific knowledge. The DNEL for ozone is 0.024 mg/m³ (DNEL list of the DGUV). Ozone was already problematic in the past. Photocopiers and the first generations of laser printers in particular produced ozone, which led to health problems in offices. However, newer generations of these devices are ozone-free.

The ozone concentration over time produced by a KrCl lamp (Care222 80W electric) with two excimer lamps in a test room with a volume of 30 m³ was measured at the Fraunhofer IOSB-AST and is shown in Figure 3 below. The current MAK limit value of 120 µg/m³ is exceeded after just two hours.

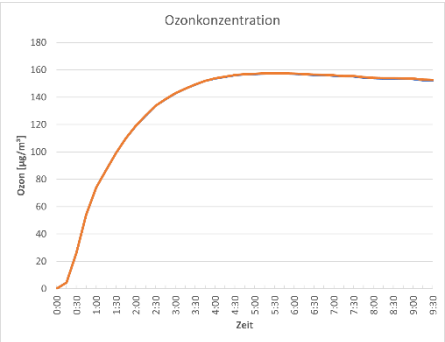


Figure 3: Ozone concentration

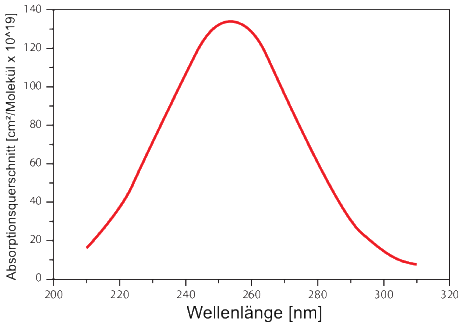


Figure 4: Wavelength-dependent absorption of ozone

In addition to the health aspects of ozone, it also has an influence on the radiation propagation itself. As ozone is not only produced by far-UV, but also absorbs UV itself in wide spectral ranges, the ozone produced at the lamp acts as an additional "filter" that further reduces the emitted UV radiation and thus the efficiency of the radiation source [Figure 4]. The drop in radiant power with distance is also greater than with other UV wavelengths, as the ozone reduces the UV transparency of the air due to its absorption properties.

Material damage

The photons of UV radiation have a much higher energy than those of visible light. The lower the wavelength, the higher the energy. If the photon energy corresponds to the binding energy of a chemical bond, the bond can be broken and the molecule destroyed. This can lead to damage such as discoloration, changes in surface structure or elasticity, particularly in polymers. Such damage to materials has also been demonstrated for Far-UVC [12].

Skin microbiome

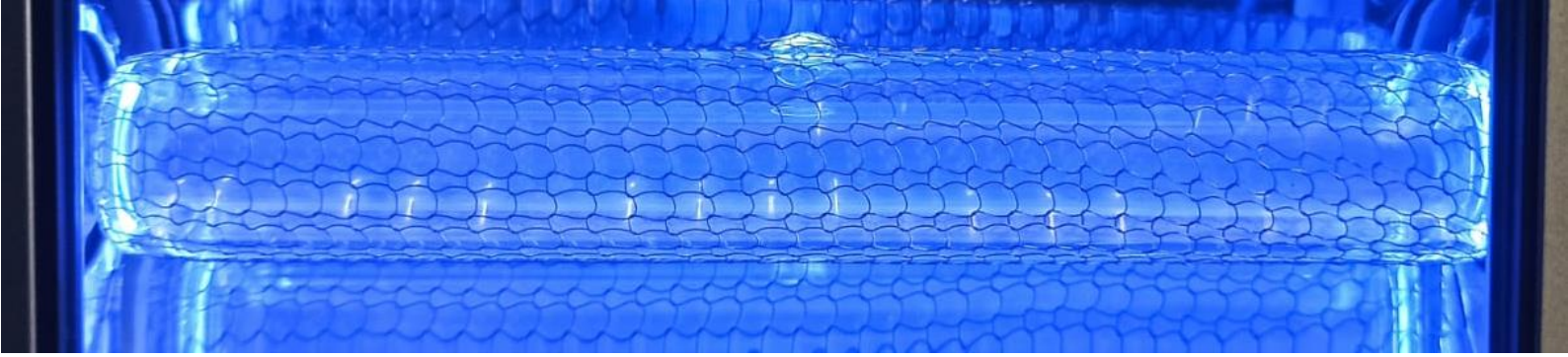
The human skin contains a microbiome consisting of a wide variety of microorganisms. The skin microbiome extends over the entire skin of the body and is divided into different zones. The composition of the bacteria in the microbiome is characterized according to the skin conditions and pH value. The microbiome forms a kind of protective shield for the skin. The skin is the connection between the body and the outside world and offers protection against harmful influences from the environment. A healthy skin flora functions in such a way that moisture can penetrate the skin and harmful substances such as pathogens must remain "outside". However, if there is an imbalance in the population of the microbiome, this protective function is impaired or disrupted. This can, for example, lead to pathogens entering the body. This can lead to increased skin sensitivity, faster skin ageing, loss of elasticity, wrinkling or even inflammation. Damage to the microbiome can be caused by excessive skin care or the use of the wrong cosmetic products, for example. Constantly disinfecting and washing hands also plays a major role. Irradiation of the skin with Far-UVC also leads to damage to the skin's microbiome, the effects of which have not yet been sufficiently researched. The effects of irradiation on the microbiome are also likely to depend on the size of the irradiated area. Perhaps hand disinfection or wound disinfection with Far-UVC is conceivable.

Conclusions

Far-UVC is gentler on humans than the 254 nm radiation from mercury vapor lamps used up to now, which is de facto pre-programmed to cause cell damage to the skin and especially the eyes.

Microbiologically, however, many pathogens are less sensitive to far-UVC than to 254 nm, resulting in longer irradiation times for log inactivation. There are also exceptions here.

The currently available Far-UVC sources are still so weak that irradiation times of several hours would be necessary to achieve sufficient inactivation of even extremely sensitive pathogens such as the SARS-CoV2 virus. Since pathogen transmission from the emitter to the recipient is usually much faster, a chain of infection cannot be interrupted quickly enough with the irradiation times of several hours currently required in Far-UVC. Irradiation therefore certainly results in a measurable reduction in the number of pathogens in the air and on surfaces, but has no influence on the infection process. Due to the low power,



however, relatively little ozone is produced. Unfortunately, the amount of ozone produced correlates with the effectiveness of disinfection.

If further studies confirm that eye damage can be safely ruled out, Far-UVC radiation sources could be used in areas where controlled irradiation is carried out under supervision (e.g. medical skin and wound disinfection). In order to ensure the safe use of Far-UVC, regulations still need to be adapted and a test standard for such devices developed to ensure sufficient inactivation of microorganisms.

Although existing problems such as the formation of ozone cannot be prevented due to physical reasons, they can at least be technically reduced.

For organizational and especially financial reasons, Far-UVC is unlikely to be suitable for the continuous irradiation of rooms due to the low power of the radiation sources and the comparatively high price. The irradiation doses required to effectively inactivate pathogens can only be achieved with a large number of lamps in a reasonable time. The development of more powerful far-UVC radiation sources will be necessary in the future.

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