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Surface disinfection in small rooms using optical radiation - Scenario: Ambulance

Fraunhofer Institute of Optronics, System Technologies and Image Exploitation

Innovation hub " Smart UV systems"

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Introduction

Microorganisms are ubiquitous, meaning they are found all around us. Every surface, the air, the soil and the water in our rivers and lakes contain a vast number of microorganisms such as viruses, bacteria and fungi. These microorganisms in their many different species fulfill countless important tasks that make life on earth possible in the first place. Even we humans could not survive without them. Each of us carries around 1-2 kg of bacteria with us, especially in our intestines. They break down components of our food and enable our body to absorb the nutrients released in the process. Their number exceeds the number of human cells in our body. There are also up to 1 million microorganisms per cm² on our skin, depending on the region of the body. The microorganisms of the skin biome are an important protective shield against pathogens.

Many products in our diet would be inconceivable without bacteria and fungi, and some things are only digestible thanks to them: yoghurt, kefir, beer, cheese and bread - yeasts are involved here.

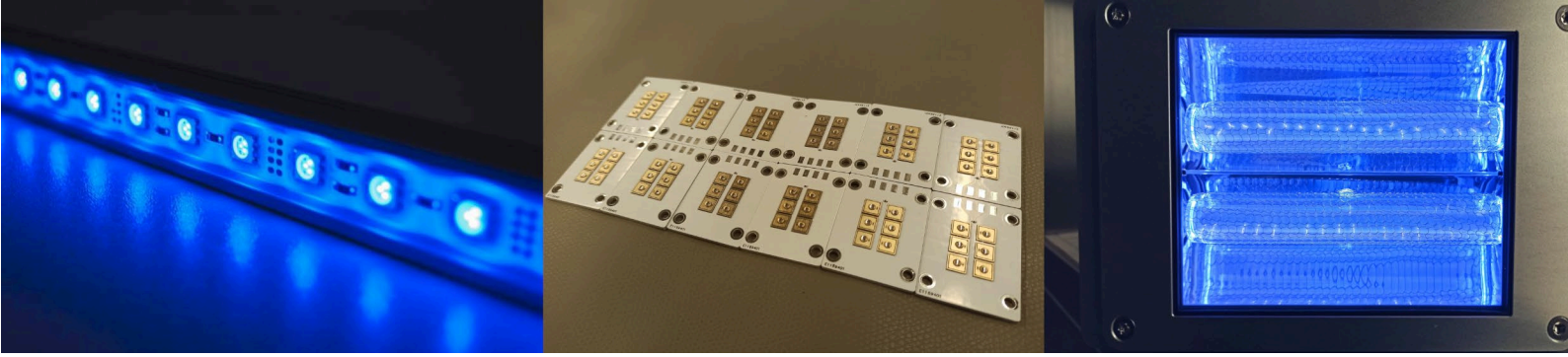
Pathogenic microorganisms

In addition to the beneficial microorganisms, there are some that are harmful to our organism or beneficial organisms that have a harmful effect when they get out of hand. They either damage our body by attacking it directly or by their metabolic end products having a toxic effect on our cells. Pathogenic microorganisms pose an increasing threat, as many of them have developed resistance to known antibiotics and their effectiveness is therefore increasingly limited.

One of the best known of these resistant pathogens is methicillin-resistant Staphylococcus aureus (MRSA). Bacteria of the Staphylococcus aureus species are found on the skin and mucous membranes of many healthy people. These bacteria can become resistant to the antibiotic methicillin as well as most other antibiotics [6, 20].

MRSA usually settles in the nasal vestibule, throat, armpits and groin without making people ill. Only when these bacteria enter the body through wounds or mucous membranes can an infection break out. As MRSA is insensitive to many antibiotics (multi-resistant), the disease can take a severe course.

MRSA is particularly prevalent in places where antibiotics are frequently used, such as hospitals. In Germany, around 20 % of all Staphylococcus aureus bacteria examined in hospitals were multi-resistant in earlier years. In recent years, there has been a decline in the proportion of MRSA in favor of other microorganisms.



Multi-resistant Gram-negative bacteria (MRGN bacteria) is a collective term for a large group of different bacteria, some of which have different characteristics, but which have one thing in common: they are resistant, i.e. insensitive to commonly used antibiotics. A distinction is made between bacteria that are resistant to four (4MRGN) or three (3MRGN) specific groups of antibiotics [35].

Depending on the group of bacteria, the pathogens are found in the gastrointestinal tract of animals and humans or on the skin; less frequently in the nasopharynx, in the anal area and also in or on raw food. Resistant bacteria occur particularly frequently in areas where many antibiotics are used. This is why they have become an increasing problem in the treatment of hospital patients in recent years. However, MRGN bacteria now also colonize around 5 out of 100 healthy people in the general population. Healthy people who are colonized with MRGN bacteria are referred to as MRGN carriers. However, the germs do not pose a problem for them because a healthy immune system protects them from becoming ill. Treatment is only necessary here too if MRGN bacteria, for example from the skin or intestines, enter wounds or the bloodstream and trigger an MRGN infection.

Recently, cases of infections with pathogens from another genus of microorganisms have been on the rise. Yeast fungi of the genus Candida are becoming a problem in some regions of the world, particularly in South East Asia, India and South Africa. Individual cases of infection with Candida auris have also been recorded in this country [9]. In contrast to all other Candida species, Candida auris is regularly transmitted from patient to patient in hospitals and causes nosocomial outbreaks. The cases in Germany were mostly imported by colonized persons. Nevertheless, experts assume that this fungus will also become a problem in Germany in the future, as it is resistant to fluconazole and can also develop resistance to other antimycotics (especially echinocandins). Candida auris is increasingly replacing the previously most common species Candida albicans and Candida glabrata, which generally cause endogenous infections (originating from colonization of the intestinal tract). Direct or indirect transmission from patient to patient is an absolute exception here [24] [15] [36] [26]. A major problem of the genus Candida in general is its longevity on surfaces.

Viruses are another group of pathogens against which no antibiotic is effective. Their infection mechanism is completely different from that of bacteria or fungi; they have no metabolism of their own and cannot reproduce themselves. They are de facto dead and consist of DNA or RNA strands that are often packaged in a protein envelope. They are dependent on host cells for their replication, into which they infiltrate and reprogram their metabolism in such a way that the host cell produces identical copies of the virus. Viruses are transmitted both through surfaces and via aerosols in the air.

An infection does not necessarily occur with every contact with a pathogenic agent. Infectivity varies depending on the pathogen. It is largely determined by the basic reproduction number (R_0 value) and the minimum infectious dose, i.e. the quantity of pathogens required to trigger an infection. In the case of viruses, the number of newly formed viruses per host cell ("burst size") also plays a role. A human norovirus, for example, can trigger an infection with just 10-100 virus particles.

Hygiene in medicine

Pathogenic antibiotic- and mycotoxin-resistant microorganisms are an increasing problem in the medical environment, in clinics, doctors' surgeries, nursing homes and in ambulances and rescue vehicles. The resistance of these pathogens to more and more drug classes and the decreasing research into new antibiotics are exacerbating the problem. Many patients have a weakened immune system due to their illness, which makes them vulnerable to attack. After organ transplants, for example, the immune system is deliberately switched off with medication to prevent rejection reactions in the body. Patients who are immunosuppressed in this way are particularly vulnerable. It is important to effectively prevent the transmission of potentially dangerous pathogens to these people. This can only be achieved through adequate hygiene and disinfection measures. In [30] it was shown that there is a correlation between contaminated surfaces and the frequency of nosocomial infections in the clinical environment.

The aim of every hygiene measure in the medical environment is therefore to effectively interrupt the chain of infection.

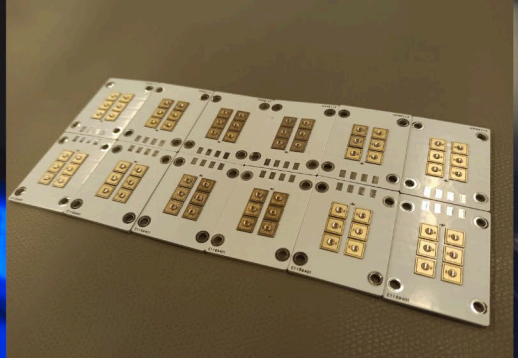
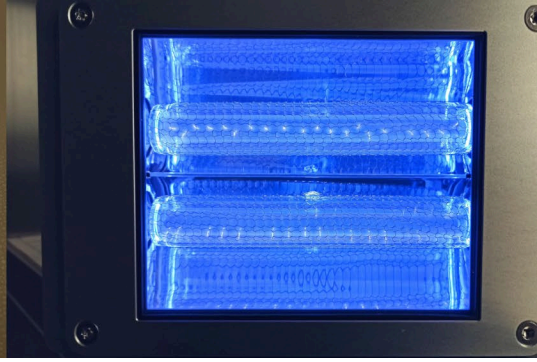
There are a wide range of options for this, such as general cleanliness, disinfection of surfaces and hands using disinfectants, thermal and chemical reprocessing of medical equipment or the spatial isolation of carriers of pathogens, as well as patient screening on admission.

Basics of disinfection using optical radiation

In addition to the aforementioned hygiene measures, research in recent years has also focused on methods that use optical radiation to inactivate pathogens [29]. These have the advantage that they do not require chemical agents and therefore have no impact on our environment and do not incur any consumable costs. The disadvantage is that they are only effective where the radiation actually reaches. However, this also applies to chemical disinfectants.

Optical radiation cannot develop its full effect in shaded regions.

The effectiveness of irradiation also depends on the irradiation dose or fluence. This results from the integral of the irradiation intensity over the irradiation time. How this dose is achieved also plays a decisive role. It makes a difference whether radiation is delivered at low intensity for a short time or at high intensity for a short

time. Another factor in the effectiveness of optical radiation is the wavelength used and the mechanism of action triggered by this wavelength. Different microorganisms also have different sensitivities to optical radiation. Viruses are the most sensitive, followed by bacteria and spore-forming bacteria. Yeasts and molds are the least sensitive. They require the highest radiation dose. The inactivation rate that optical radiation can achieve is usually specified in decadic log levels or as a percentage. An inactivation of 90 % corresponds to one log level (1-log), an inactivation of 99 % corresponds to two log levels (2-log) and so on. The achievable inactivation rate is proportional to the irradiation dose. There are clear definitions for the terms germ reduction, disinfection and sterilization. Disinfection is only achieved when at least 99.99 % of the pathogens have been inactivated (4-log). Anything less is merely a reduction of germs. Although this can reduce the risk of infection somewhat, it cannot eliminate it completely. Sterilization is required in the medical environment, especially when reprocessing medical devices. This is defined as the inactivation of all microorganisms present by at least 99.9999%, i.e. six log levels (6-log). This means that a maximum of one infectious pathogen in one million may remain infectious after sterilization.

Another important factor in the infection chain is the infection time, i.e. the time the pathogen passes from the emitter to the recipient. This should not be confused with the incubation period (time between infection and the appearance of the first symptoms). The infection time can often be very short. In most cases, touching a contaminated surface or walking past a person infected with an aerosol-borne virus is sufficient. Infection times of seconds to a few minutes are common.

The required irradiation dose also differs depending on where the pathogen is to be inactivated. While in air and water disinfection, the pathogens can be irradiated from all sides due to their own movement in the medium, the doses required to reach a certain log level are lower than when inactivating a pathogen on a surface, where it can only be irradiated from one side or it can shadow itself in recesses in the surface. Another problem with surface disinfection is multiple layers of pathogens on top of each other or if they are embedded in a film of grease, protein or dirt. By reducing the penetration depth of the radiation with decreasing wavelength, deeper regions of such contamination may not be reached or only insufficiently.

In this case, significantly higher radiation doses are usually required. It should be noted that the irradiation intensity decreases with the square of the distance from the radiation source. The further away a surface to be irradiated is from the radiation source, the longer it must be irradiated in order to achieve the same dose.

An irradiation dose must be at least high enough to reduce the number of pathogens to a level at which infection can no longer occur within the time required for a pathogen to spread to another patient.

These times can be very short for surface and air disinfection. In principle, pathogen transfer can take place immediately after contamination of a surface or the air. Short disinfection times are therefore always more sensible than long ones. An exception to this is the reprocessing of medical devices, which are cleaned and sterilized in a separate room after patient contact. The time until the device is next used on the patient is generally a purely economic factor for the medical facility.

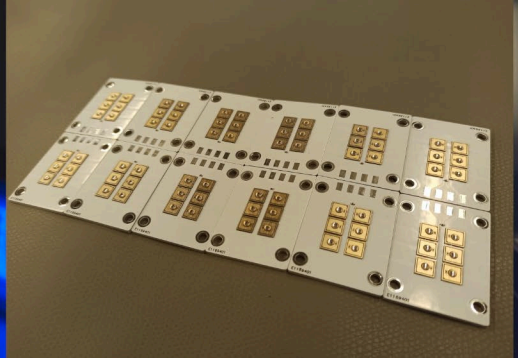
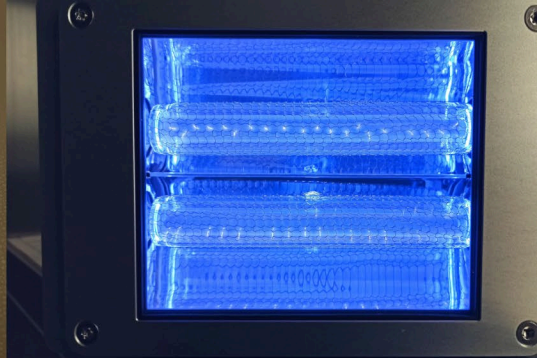
Wavelength *ranges*

Research has shown that large parts of the electromagnetic spectrum are suitable for inactivating microorganisms. The wavelength range here extends from the infrared to the ultraviolet range. In the infrared, however, the effects are very small and long-lasting, which is why three areas with shorter wavelengths will be discussed in more detail. It is known that irradiation with **blue-violet light** (400-450 nm) and ultraviolet radiation in the UVC range (200-280 nm) can inhibit the growth of microorganisms or inactivate them completely. In the UVC range, a distinction is also made between **germicidal UV** (250-280 nm) and **far-UV** (200-230 nm).

Mechanisms of action

In contrast to chemical disinfectants or antibiotics, the disinfecting effect of optical radiation is based on physical principles. Although it is known that blue light irradiation has a microbiocidal effect, the underlying mechanism of action has not yet been fully deciphered. In the UVC area, various mechanisms are quite well known. Basically, all these mechanisms are based on the splitting of chemical bonds. The energy of a photon depends on its wavelength. The shorter the wavelength, the higher the photon energy. If the photon energy corresponds approximately to the binding energy of a chemical bond, this bond can be broken by these photons. For example, the hydrogen bond between the nucleic base thymine, which has a pyrimidine backbone, and adenine in DNA or uracil and adenine in RNA can be easily broken in the UVC range. Furthermore, the UVC radiation is absorbed by the double bond in the pyrimidine ring and enables reactions to take place with neighboring molecules. As a result, if present in the DNA strand at this point, neighboring thymines combine to form a thymine dimer. This dimer is much more strongly bound and is no longer cleaved. As a result, duplication of the DNA or RNA is no longer possible and the microorganism is inactivated. This mechanism is very efficient. Damage to proteins and enzymes is also known to occur at other wavelengths [10], [17], [19].

The advantage of using optical radiation for disinfection is that, according to current scientific knowledge, microorganisms cannot develop resistance, unlike antibiotics.

Is dose equal to dose?

As already mentioned, the irradiation dose is defined as the integral of the irradiation intensity over the irradiation time. This leads to the question of whether it makes no difference whether you irradiate with a high intensity for a short time or with a low intensity for a long time. Depending on the type of pathogen, the answer here is a clear "no". Nature has equipped many microorganisms, apart from viruses, with some very efficient repair mechanisms. One of these repair mechanisms is photoreactivation.

Many pathogens with their own metabolism, such as Escherichia coli, are able to repair radiation-induced DNA damage under the influence of light in the range between 300-500 nm using the enzyme DNA photolyase (also known as photoreactivation enzymes). The excess methyl group created during pyrimidine dimer formation is bound by methyltransferases so that the DNA base is restored to its original state. This process counteracts the effects of microbiocidal irradiation. If the irradiation intensity is too low, DNA damage may be repaired faster than new damage is created. Inactivation of the microorganisms via the mechanism of action of DNA damage is then no longer efficient.

According to current knowledge, other mechanisms of action such as protein damage are not affected by this. In the case of viruses in particular, damage to the spike proteins with which they infiltrate the host cell often has a greater effect than damage to the DNA. Due to both mechanisms of action and the small size of viruses, they can generally be inactivated with significantly lower radiation doses than would be the case with bacteria or even molds.

Short irradiation times with high intensity are usually much more efficient than long irradiation times with low intensity.

Furthermore, only partial damage to the DNA of a microorganism means that there may be the potential for mutation. The mechanism of the photoreaction clearly shows that the duration of the required irradiation can have a major influence not only with regard to the transmission speed of a pathogen to the patient, but also due to possible regeneration processes of the microorganism. Long irradiation times usually only lead to satisfactory results in laboratory environments without exposure to external light and therefore without photoreactivation.

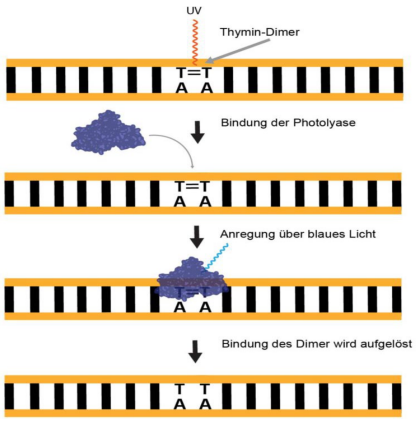


Illustration 1 Mechanism of action of photoreactivation

Efficiencies

When talking about disinfection using optical radiation, there are two efficiencies to consider that are independent of each other. The first would be the so-called wall-plug efficiency (WPE) [37]. It describes how well a radiation source converts the supplied electrical energy into radiation. The higher the value, the lower the power loss that has to be dissipated in the form of heat. The second efficiency is the microbiocidal efficiency, which depends, among other things, on the emitted peak wavelength and the width of the emission peak (FWHM) in the spectrum. It is also dependent on the microorganism itself. It describes how strongly a specific microorganism can be inactivated at a defined irradiation dose. It is also referred to as the effective spectrum or Wavelength Dependent Inactivation Efficiency.

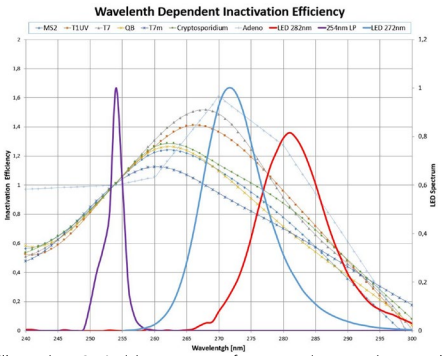
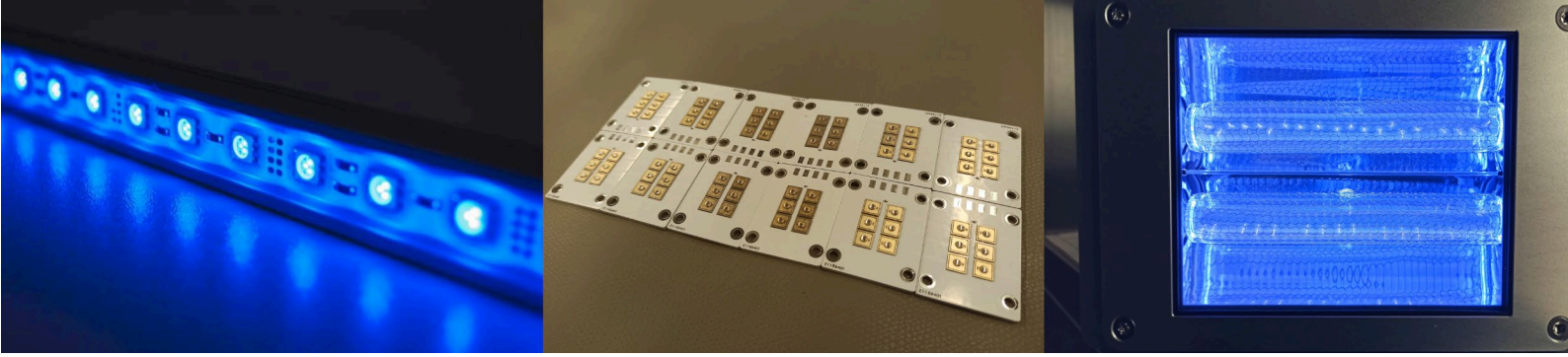


Illustration 2 Activity spectra of some microorganisms and emission spectra of three UVC radiation sources

Another factor in disinfection using optical radiation is the so-called "dose response curve". It describes the progression of the inactivation of microorganisms over time via the applied radiation dose. It is usually characterized by a very steep part, in which very rapid inactivation occurs at the beginning of the irradiation, but which then transitions into a much flatter part, in which only slight further inactivation occurs despite a further increase in the irradiation dose.

The application scenario

The three aforementioned wavelength ranges will be compared in the following sections in the application scenario "Interior disinfection of ambulances and emergency vehicles" with regard to their suitability and efficiency for surface disinfection in small rooms. This scenario was deliberately chosen because a higher irradiation dose can be achieved in a shorter time compared to larger rooms such as waiting rooms or operating theaters. A typical ambulance with internal dimensions of 4 m x 2.5 m x 1.9 m (length x width x height) has a wall area of around 25 m² and a volume of 19 m³. Furthermore, the maximum possible distance from the radiation source to a surface in the room is 5.085 m (room diagonal). In ambulances, disinfection and cleaning are mandatory after every use and the surfaces to be disinfected and their distance from the radiation source are clearly defined and fixed. This makes the procedures comparable. The limits of the procedures are clearly recognizable and can be projected for use in larger rooms.



Ambulances and rescue vehicles are characterized by the fact that the patient changes between individual missions. Once a patient has been transported, suitable measures must be taken to ensure that the vehicle is clean and "germ-free" before the next deployment. This is currently done by wet cleaning followed by wipe disinfection using chemical disinfectants. Depending on the patient, this can be very time-consuming and the vehicle is blocked for subsequent operations. Furthermore, wipe disinfection cannot be validated as it is not possible to check how carefully it is carried out. It would be advantageous if only wet cleaning could be carried out manually and disinfection could be automated during the journey to the next use. Disinfection with optical radiation offers these possibilities. Since an ambulance in Germany has to be at the scene within 13 minutes, we assume a maximum available irradiation time of 10 minutes during the journey in the scenario. Particularly important for disinfection are the patient stretcher with direct patient contact, the work surfaces on which work materials are placed during the operation and the walls, which could be contaminated by blood splashes and other liquids during patient care.

Air disinfection?

Disinfecting the air in the vehicle plays no role in ambulances, as the air is almost completely exchanged when the doors are opened anyway. This air exchange is much more efficient at reducing aerosol pollution than any optical radiation method.

If a patient is transported who emits aerosol-borne pathogens such as SARS-CoV2, for example, none of the currently available radiation sources can achieve sufficient inactivation within the extremely short transmission time of a few seconds of these pathogens. This is due to the fact that the infected patient continuously enriches the air in the vehicle with new contaminated aerosols. Even if good results are achieved in the laboratory [8] assumes that these results are not readily applicable in real-life scenarios. Here, other measures such as the wearing of efficient respiratory protection by medical personnel must be used. Wearing an FFP2 mask by staff and patients is more efficient and, above all, significantly cheaper than optical irradiation. The floor of the vehicle is also of little hygienic relevance, as it is contaminated again the first time the patient enters it. Nevertheless, general cleanliness is also appropriate here, sterility is not necessary and also not achievable.

Disinfection with blue light

It is known from the literature that microorganisms can also be inactivated with blue light at wavelengths between 400 nm and 450 nm, i.e. they are damaged by the blue light [11] [22] [12]. Nowadays, blue light can be produced very cheaply using LEDs. Blue LEDs serve as the basis for the white LEDs used in lighting technology. A fluorescent material is applied to a blue LED, which changes the spectrum so that the LED appears white. These LEDs are now mass-produced by the billions at very low prices, sometimes just a few cents. **Cree XP-E2 LEDs with 450 nm and 550 mW** and **Nichia NCSU275 405 nm 370 mW** were considered as representatives in this wavelength range [5, 27].

The conversion efficiency of electrical energy into radiant energy - the so-called wall-plug efficiency - is very high at over 50% in some cases. Blue LEDs have now achieved optical output powers of several hundred milliwatts, which with the small active emitting area of 1 mm x 1 mm results in a theoretical optical area power of up to 55 W/cm² (@450 nm) and 35 W/m² (@405 nm) (Figure 9). In reality, the achievable value is lower due to the slightly larger package of the LEDs. Large, flat arrays with high radiation density can be produced inexpensively with blue LEDs. This is important in the application scenario under consideration because, as already mentioned, disinfection with optical radiation is only effective where this radiation can strike a surface. Large LED arrays or long LED strips installed in the vehicle generate a very diffuse and homogeneous radiation distribution that reaches many surfaces with a uniform intensity. This also makes it easier to illuminate slightly shaded areas using inexpensive reflectors. Very dark areas with low intensities and therefore a low disinfection effect, as with a spotlight, do not occur.

Wavelength efficiency and dose

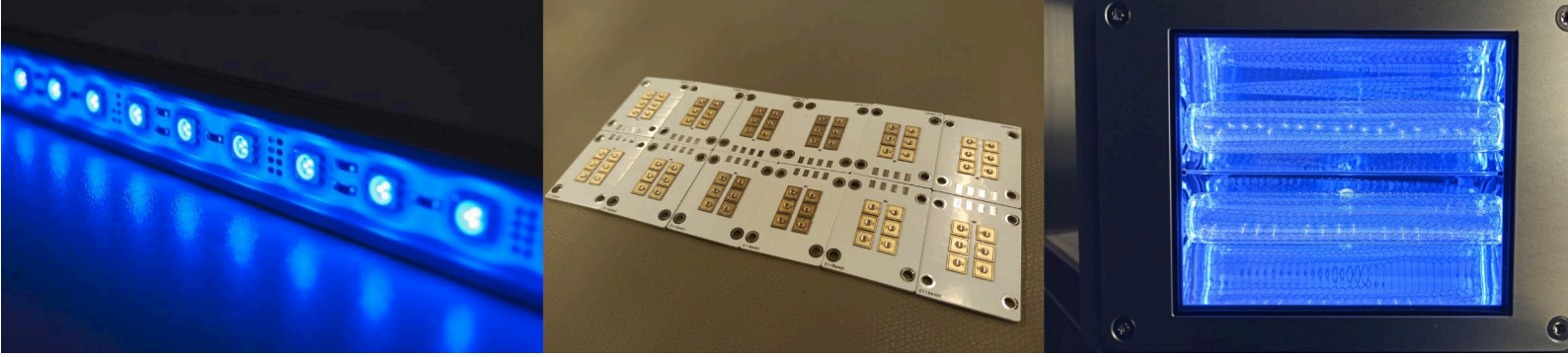
While the WPE of blue LEDs is very high, their microbiocidal effect is very low. For example, in order to inactivate microorganisms of the rather radiation-sensitive bacterium Escherichia coli, a typical faecal germ, by 99.99 %, an irradiation dose of between 700 J/cm² @450 nm and 70 J/cm² @405 nm is required with blue light [13] [25]. The values also vary greatly depending on the study.

The blue light unit trick

Manufacturers of blue light disinfection systems use the unit **J/cm²**. The numerical dose values are similar to those in the UVC and FarUV range, which can easily lead to confusion regarding efficiency. In the latter areas, however, the dose is always specified in **mJ/cm²** or **J/m².**

For a better dimensional comparison with the wavelength ranges to be considered in the following, we choose **mJ/cm²** as the unit at this point. For blue light irradiation, 70 J/cm² (= 70,000 mJ/cm² or 700,000 J/m²) is therefore required as the irradiation dose for the safe 4 log inactivation of Escherichia coli in the best case, according to the above-mentioned sources.

In order to achieve such a high dose within 10 minutes on an area of 1 m², this area would have to be continuously irradiated with an optical power of 1,166 watts. This is roughly equivalent to the average radiant power of the sun per m² in Germany over the entire electromagnetic spectrum (global radiation). In order to disinfect the 25 m² interior walls of an ambulance within the specified time of 10 minutes, 29 kW (25 m² x 1,166 W) of radiant power is required in purely mathematical terms and, with a WPE of the LEDs [27] of 20 %, an impressive 145 kW of electrical power is required. This would cause the vehicle's electrical system



to collapse. It should be noted here that the estimates refer to the more efficient of the two wavelengths (405 nm). At 450 nm [5] the WPE would be 2.5 times higher at 50%, but the required doses would be 10 times higher. The corresponding electrical energies would increase again by a factor of 4.

The emitted wavelengths are in the range in which photoreactivation is also effective (300 nm to 500 nm). This means that with continuous low-intensity irradiation, photoreactivation may have a stronger effect than radiation-induced damage to the microorganism.

Furthermore, with an assumed WPE of 50 %, the remaining 50 % of the electrical energy supplied is converted into heat. This would have to be dissipated, which is hardly technically feasible with the dimensions mentioned. In order to build a microbiologically efficient blue light disinfection system in these dimensions, a total of almost 53,000 LEDs at a unit price of €1.92 would be required if Cree XP-E2 SMD LEDs with an individual output of 550 mW were used [5]. The costs for the LEDs alone would amount to around €102,000.

At the high irradiation intensities required, damage to the human body is to be expected, as blue light penetrates very deeply into the tissue. Although in [4] does not assume any damage, only low intensities were investigated here. Irradiation should only take place in the absence of people and the windows, especially those between the driver's cab and the treatment room in the ambulance, would have to be closed opaque during irradiation. The radiation sources would have to switch off automatically in the presence of people. This is already specified in the guidelines of the manufacturers of these systems [3] and advertise that the systems are switched off by motion detectors when people are in the room. However, the same source also advertises the absolute safety and harmlessness of this procedure, which is in complete contradiction to the aforementioned argument.

Disinfection with UVC LEDs

Various radiation sources are available for generating UVC radiation in the wavelength range between 240 and 280 nm (germicidal UV). In addition to classic mercury vapor lamps, increasingly powerful LEDs are also available here.

The main advantage of mercury lamps is their unbeatably low price. One watt of UV radiation is available for just a few euros, which puts it in the same price range as blue LEDs. Low-pressure mercury lamps emit at wavelengths of 254 nm and 185 nm, whereby the latter wavelength is usually filtered out by doped special glass due to the ozone formation it causes. The output of low-pressure mercury lamps ranges from a few watts to the lower three-digit watt range. The disadvantage is the mercury, which would contaminate the vehicle if the lamp were to break, despite the small quantity of a few milligrams. The risk of glass breakage is a major argument against the use of these lamps in the mobile sector, although this can be technically minimized with suitable measures such as splinter protection and damped suspension. These lamps also have a warm-up phase of several minutes in some cases before they reach their maximum output. They are therefore more suitable for continuous irradiation scenarios. Intermittent operation also significantly reduces the service life. LEDs have also been increasingly available in the UVC sector for some years now. UVC LED technology is still quite new, the optical output and WPE are still quite low at 7-8% compared to mercury lamps and blue LEDs and the price is relatively high. LEDs of the **Bolb S6060** type **with 265 nm and 100 mW** optical power were considered as representatives of these radiation sources [1].

The best UVC LEDs currently achieve optical outputs of 100-130 mW (@265 nm) with a WPE of 7-8 % and prices starting at € 20 per LED for larger quantities (as of 01/2024). One watt of UV radiation therefore costs around €200. With a chip size of 1 mm x 1 mm, optical area outputs of 10-13 W/cm² (@265 nm) are currently theoretically achievable directly at the radiation source. The power of available UVC LEDs also decreases with the emission wavelength. There are currently hardly any UVC LEDs with sufficient output in the range below 250 nm. The price also rises sharply here, which makes the use of LEDs smaller than 250 nm economically unattractive. Similar to blue LEDs, UVC LEDs can be used to produce compact radiation sources with very high surface power that can be connected to form larger LED arrays or LED strips, thus achieving diffuse, homogeneous illumination of a room. The aforementioned problem of strong shading does not occur here either.

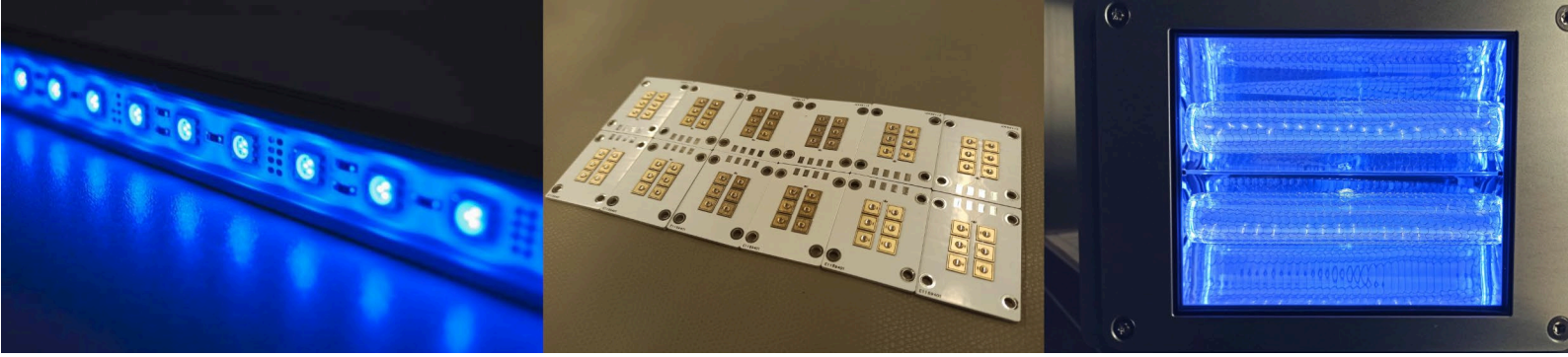
Illustration 3 2.1 Watt UVC-LED module 265 nm (Fraunhofer IOSB-AST)

Illustration 414.4 W 272 nm UVC LED module (water-cooled)

Illustration 5600 mW UVC-LED module in the Binz RESCUBE 3 (Fraunhofer IOSB-AST / Binz automotive)

Wavelength efficiency and dose

In contrast to blue LEDs, the microbiological effectiveness of UVC LEDs is much greater. This is due to the already mentioned very efficient damage to DNA and proteins in



this wavelength range. The example pathogen Escherichia coli already used with blue LEDs only requires an irradiation dose of around 7 to 9 mJ/cm² @265 nm for 99.99 % inactivation [28]. This dose is about a factor of 10^3 lower than with blue LEDs @405 nm and 10^4 lower @450 nm. This also results in the need for a significantly lower total optical power. For the 10-minute irradiation of one square meter, 1.1 watts is sufficient, i.e. 27.5 watts for the entire interior of an ambulance. With a WPE of only 7-8%, this requires an electrical power of 350-400 watts. This can easily be supplied from the vehicle's electrical system. The heat of 92-93 % of the supplied electrical energy generated and to be dissipated due to the low WPE is around 320-370 W, which does not cause any technical problems.

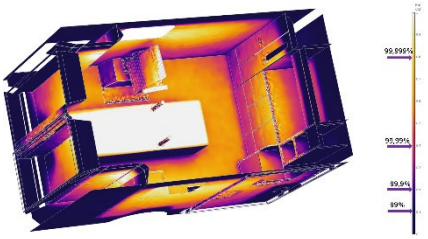


Illustration 6 10-minute inactivation simulation with 24W system in the Binz RESCUBE 3 for Candida auris (Fraunhofer IOSB-AST)

Based on the prices at the beginning of 2024, the UVC LEDs for a 27.5 W system would only cost around €5,000 if a correspondingly high number of units were purchased. However, there would also be costs for control, sensor technology and system integration into the on-board electronics as well as mechanical components such as cover glasses for the radiation sources.

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 been demonstrated for UVC at high irradiation doses. [38] When using a UVC irradiation system, it is therefore important to ensure that special UVC-stable materials are used, for example in vehicle interiors.

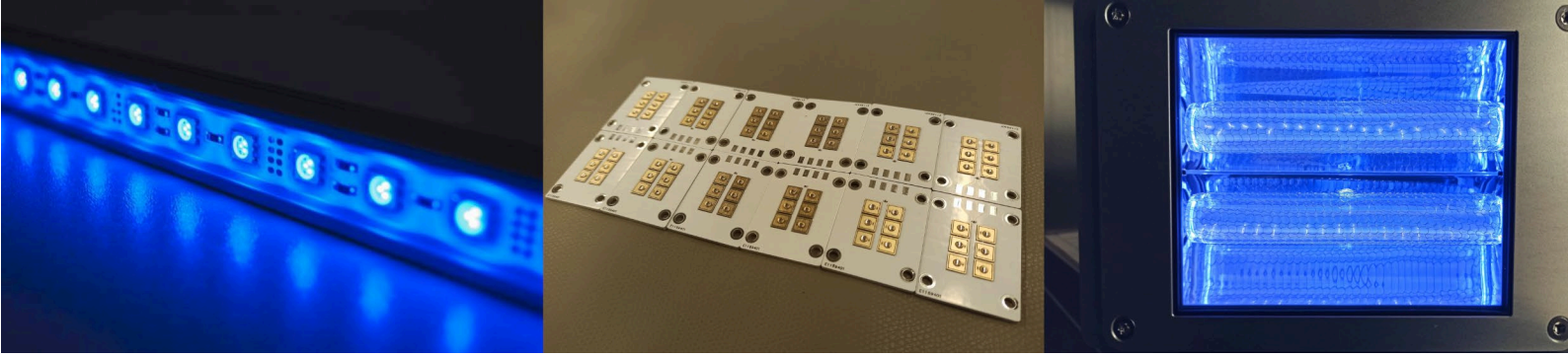
Radiation protection

UVC radiation in the wavelength range under consideration is harmful to human cells, which is why irradiation may only take place in the absence of people. In addition to reddening of the skin (erythema), sunburn and conjunctivitis (inflammation of the conjunctiva of the eye), in extreme cases this could result in skin cancer. It is therefore essential to take measures to ensure that the disinfection system cannot be switched on if there are still people in the radiation field. This can be easily ensured using appropriate sensors in the vehicle interior. The windows of the vehicle do not need to be darkened when using UVC radiation sources, as UVC radiation does not penetrate normal glass or polymer glass such as acrylic glass.

Disinfection with Far-UVC

For some time now, Far-UV radiation sources in the wavelength range between 200 nm and 230 nm have also been available for the disinfection of air and surfaces. Unlike UVC, the term "Far-UV" is not defined internationally. However, it is now used colloquially to refer to the lower part of the UVC range between 200 nm and 235 nm. There are currently no LEDs commercially available in this wavelength range. Although there are the first LED laboratory samples with an emission wavelength of 226 nm [23]these have optical outputs in the single-digit milliwatt range and are therefore not yet suitable for practical disinfection.

The radiation sources of choice in the far-UV range are currently so-called excimer lamps, in which a gas mixture of a halogen and a noble gas, e.g. krypton and chlorine, is excited to glow by means of a high voltage. In the comparison of radiation sources, a **USHIO Care222 module with 222 nm and 100 mW** optical power was considered as this is frequently used in the lamps commonly sold. [34]. The WPE of the KrCl excimer process is only 1 %. A full 99 % of the energy supplied is therefore lost as heat. Manufacturers therefore often only state the electrical output, which is 100 times higher than the optical radiation output of such a radiation source. The emission spectrum of a KrCl excimer lamp has a main emission at 222 nm, but emits to a much lesser extent into the UVB range and could cause skin damage or even skin cancer. This wavelength range is therefore filtered out using special filters. This is referred to as "filtered far-UV". One advantage of this filtered wavelength is the low penetration depth into the skin. Almost all of the radiation is absorbed in the horny layer of the skin and does not penetrate living tissue. Various studies have shown no or only negligible damage to the skin. The optical output of common KrCl excimer lamps offered for room irradiation is around 100 mW (~10W electrical) and is therefore comparable to the output of a single UVC LED at 265 nm [1]. At a price of around € 1,500, one watt of far-UV radiation from a KrCl excimer lamp is therefore available for around € 15,000. Not only is the WPE of an excimer lamp very low, but also its radiant power per unit area. A typical 59 mm x 44 mm module emits at 100 mW with an area power of only 0.0038 W/cm² [34]. At a distance of one meter, conventional systems therefore only achieve radiation intensities of a few µW/cm² due to the distance-dependent reduction in intensity. Significantly longer irradiation times are therefore necessary. Even though studies indicate that damage to the skin and eyes is hardly detectable, a threshold limit value (TLV) of 23 mJ/cm² has been set for the total exposure during an eight-hour working day. Driven by the manufacturers of far-UV radiation sources, the American ACGIH proposed increasing this limit value for 222 nm to 161 mJ/cm² for the eyes and 479 mJ/cm² for skin irradiation [33]. However, these proposed changes by the ACGIH have not yet been incorporated into ISO 15858 (UV-C Devices - Safety information - Permissible human exposure) (as of 06/2024) due to international criticism.



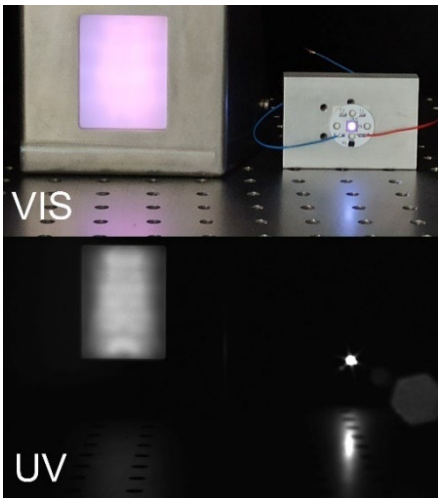


Illustration 7 Comparison of area radiation power: excimer vs. 265 nm LED (visual top, UV camera bottom)

Illustration 8Far-UVC disinfection device for room disinfection (Aliexpress)

Wavelength efficiency and dose

In the far-UV range, the microbiocidal efficiencies are similarly high as in the UVC range around 265 nm. For E. coli is in [2] gives a value of 10.3 mJ/cm² for 4-log inactivation. Although there are some pathogens that are significantly more sensitive in far-UV, there are also pathogens that react somewhat less sensitively to the radiation than at 265 nm. Viruses in particular are more sensitive, as the damage to the protein envelope is more pronounced in the Far-UV range than in bacteria or even molds. Nevertheless, the required dose can be assumed to be approximately the same as for irradiation with UVC LEDs. If you want to use KrCl excimer lamps in an ambulance to inactivate 99.99 % of the example pathogen Escherichia coli within 10 minutes, you can again assume around 20 W total optical radiation power. Due to the WPE of 1 %, this requires 2,000 W of electrical energy. This is significantly more than for UVC LEDs, but still very far from what would be required for blue LEDs. 2,000 W of electrical energy can certainly be generated in an ambulance electrical system.

However, with typical outputs of 100 mW per lamp, 200 lamps would be required for this 20 W optical radiation output. At the above-mentioned cost of €1,500 for one of these lamps, this would result in system costs of €300,000 per vehicle. This is not economically viable.

In their own publications, the manufacturers of far-UV systems postulate disinfection times of several hours to days and only achieve a reduction in germs (~1 log = 90%) but not anywhere near the 4 log levels required for disinfection. Similar to blue LEDs, photoreactivation also plays a role with such long irradiation times. [19] [18] [16] [32]. Only when inactivating viruses can shorter irradiation times be achieved, but even here only a reduction in germs, but not the required disinfection, can be achieved in an adequate time.

Shadowing is another problem. The two aforementioned methods can generate homogeneous irradiation with little shadowing by arranging many LEDs in the room. With Far-UV, only very few radiation sources are usually used, in ambulances often only one. All surfaces that are not directly visible from the radiation source are located in shaded areas in which there is no reduction in the germ load. The reflectivity of materials also decreases significantly in far-UV, which makes it more difficult to illuminate these areas using reflectors.

As the transmission of materials also decreases with decreasing wavelength, the vehicle windows are absolutely opaque and therefore unproblematic when using Far-UV, just as with UVC LEDs.

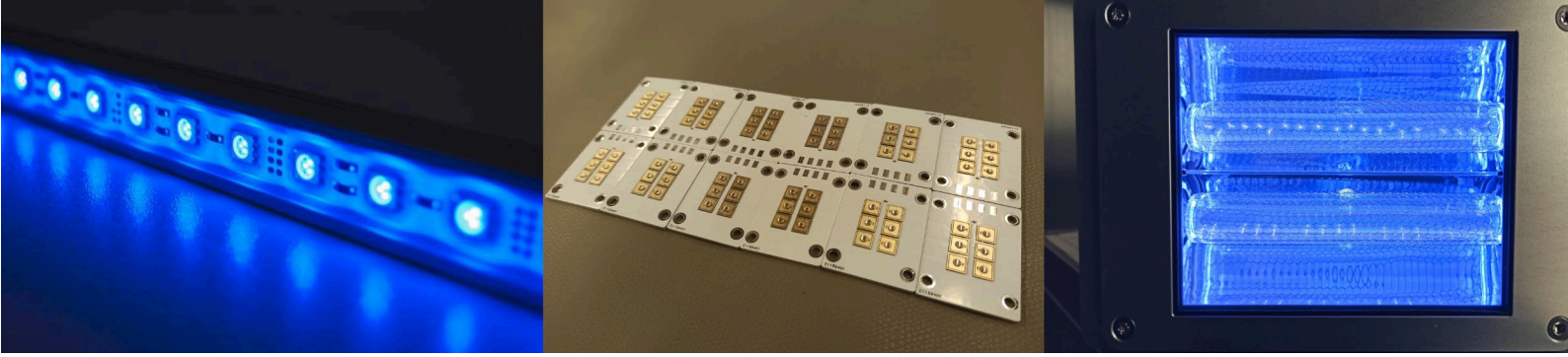
Ozone?

Ozone is a strong and toxic oxidizing agent that can irritate the respiratory tract and eyes of humans and animals and promote respiratory diseases. It is produced by UV radiation with wavelengths below 242 nm. The energy value of the photons has then reached a value that splits the oxygen molecules (O_2) into oxygen atoms (O). When the oxygen atoms react with an oxygen molecule, ozone (O_3) is formed. Ozone is therefore always produced by far-UV sources. The lower the wavelength and the higher the power of the radiation source, the greater the amount of ozone produced. Most ozone is produced at close range, particularly in the lamp housing itself. This can be inactivated using a filter. However, ozone is also produced in certain quantities in the room itself as the power decreases with distance from the radiation source.

Due to the low optical output of the far-UV sources on offer, this ozone formation in the room is relatively low and therefore tolerable, in addition to the low disinfection effect. Nevertheless, it is already detectable with a single lamp. If several lamps or lamp systems with a higher output are used, the permissible limit value is quickly exceeded in small rooms. Conversely, this means that any attempt to shorten the disinfection time by increasing the irradiation power is associated with greater ozone formation and a potentially faster exceedance of the limit value and health risk.

The ozone produced in the room could be removed from the room air by ventilating the room. This would also remove aerosols potentially contaminated with viruses, which would ultimately lead to a reduction in the viral load much more efficiently and, above all, much more cost-effectively than far-UV irradiation itself.

Although studies indicate that far-UVC appears to be harmless to the skin, the Radiation Protection Commission in Germany considers the current data situation to be insufficient to completely rule out health risks to the population from the use of far-UVC radiation in view of the novelty of its use and the potentially harmful photobiological effects of far-UVC



radiation, which have not yet been clarified beyond doubt [31].

The controlled use of far-UV radiation in the medical field, e.g. for prophylactic skin disinfection, is justifiable from a radiation protection point of view, as this is a controlled, temporary exposure of humans, which is carried out after prior indication and consideration of the benefits and risks in accordance with the provisions of the Medical Devices Act.

Diagrams and tables

The data in the tables refer to the following exemplary radiation sources from the corresponding wavelength ranges

- Cree XP-E2 **450nm** 550mW [5]
- Nichia NCSU275 **405nm** 370mW [27]
- Bolb S6060-DR250-W265-P100, **265nm,** 100mW [1]
- Care222® Filtered Far UV-C Excimer Lamp Module 222nm [34]

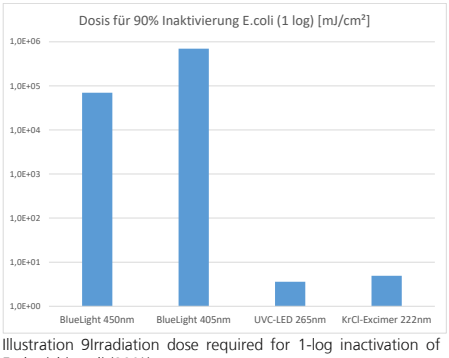


Illustration 9Irradiation dose required for 1-log inactivation of Escherichia coli (90%)

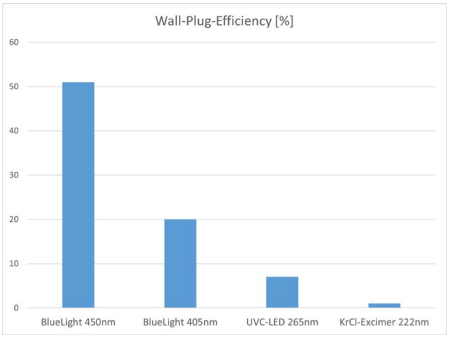


Illustration 10Typical wall plug efficiency (as of 2024)

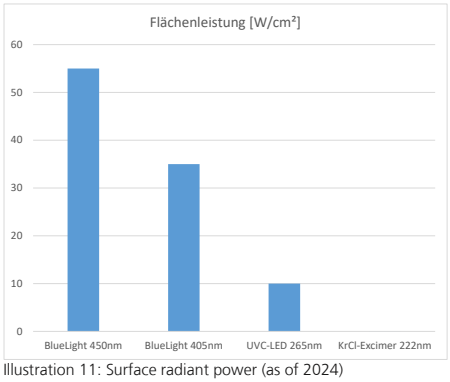


Illustration 11: Surface radiant power (as of 2024)

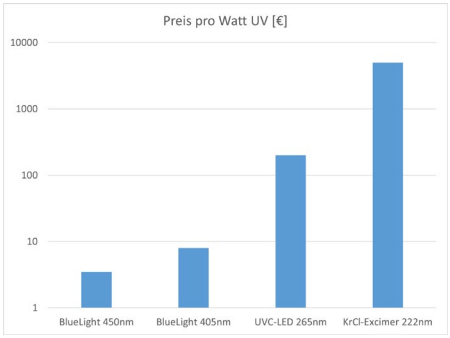


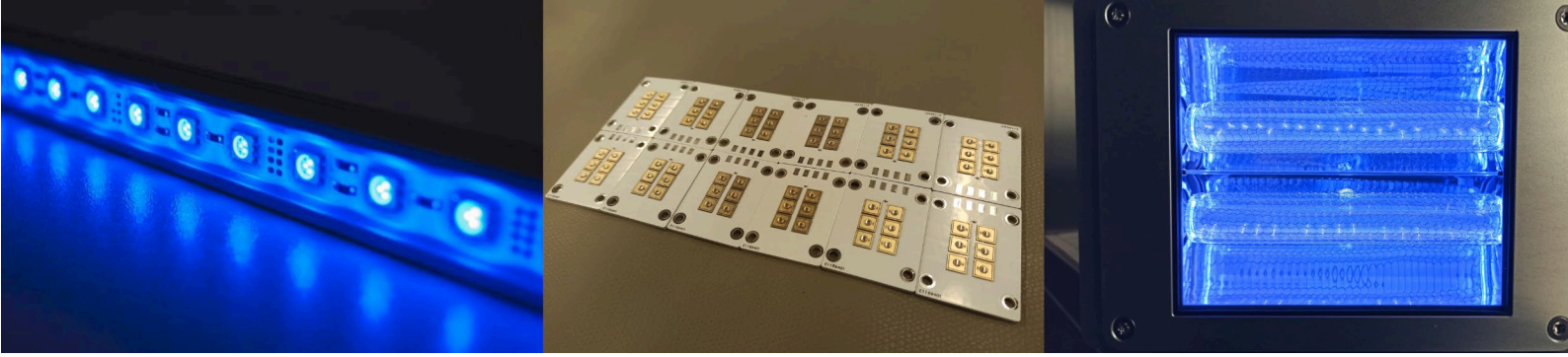
Illustration 12Price per watt of generated optical UV radiation output (as of 2024)

Bakterium	Dauer der Persistenz (Spanne)
Acinetobacter spp.	3 Tage bis 5 Monate
Bordetella pertussis	3 bis 5 Tage
Campylobacter jejuni	bis 6 Tage
Clostridium difficile (spores)	5 Monate
Chlamydia pneumoniae, C. trachomatis	<= 30 Stunden
Chlamydia psittaci	15 Tage
Corynebacterium diphtheriae	7 Tage bis 6 Monate
Corynebacterium pseudotuberculosis	1 bis 8 Tage
Escherichia coli	1.5 Stunden bis 16 Monate
Enterococcus spp. incl. VRE und VSE	5 Tage bis 4 Monate
Haemophilus influenzae	12 Tage
Helicobacter pylori	<= 90 minutes
Klebsiella spp.	2 Stunden bis 30 Monate
Listeria spp.	1 Tag bis Monate
Mycobacterium bovis	> 2 Monate
Mycobacterium tuberculosis	1 Tag bis 4 Monate
Neisseria gonorrhoeae	1 bis 3 Tage
Proteus vulgaris	1 bis 2 Tage
Pseudomonas aeruginosa	6 Stunden bis 16 Monate
Salmonella typhi	6 Stunden bis 4 Wochen
Salmonella typhimurium	10 Tage bis 4.2 Jahre
Salmonella spp.	1 Tag
Serratia marcescens	3 Tage bis 2 Monate
Shigella spp.	2 Tage bis 5 Monate
Staphylococcus aureus, incl. MRSA	7 Tage bis 7 Monate
Streptococcus pneumoniae	1 bis 20 Tage
Streptococcus pyogenes	3 Tage bis 6.5 Monate
Vibrio cholerae	1 bis 7 Tage

Table 1: Persistence times of clinically relevant bacteria on surfaces [21]

Virus	Dauer der Persistenz (Spanne)
Adenovirus	7 Tage bis 3 Monate
Astrovirus	7 bis 90 Tage
Coronavirus	3 Stunden
SARS associated virus	72 bis 96 Stunden
Coxsackie virus	> 2 Wochen
Cytomegalovirus	8 Stunden
Echovirus	7 Tage
HAV	2 Stunden bis 60 Tage
HBV	> 1 Woche
HIV	> 7 Tage
Herpes simplex virus, type 1 und 2	4.5 Stunden bis 8 Wochen
Influenza virus	1 bis 2 Tage
Norovirus and feline calici virus (FCV)	8 Stunden bis 7 Tage
Papillomavirus	16 Stunden bis 7 Tage
Papovavirus	8 Tage
Parvovirus	> 1 Jahr
Poliovirus type 1	4 Stunden bis 8 Tage
Poliovirus type 2	1 Tag bis 8 Wochen
Pseudorabies virus	mehr als 7 Tage
Respiratory syncytial virus	bis 6 Stunden
Rhinovirus	2 Stunden bis 7 Tage
Rotavirus	6 bis 60 Tage
Vacciniavirus	3 Wochen bis 20 Wochen

Table 2Persistence times of clinically relevant viruses on surfaces [21]



Conclusions

Microbiocidal effects can be proven beyond doubt in the laboratory for all wavelength ranges mentioned. However, the decisive factor for practical use is the effectiveness and efficiency of the processes in order to achieve disinfection of at least 4 log levels or 99.99 % within a short time. Long disinfection times of several hours are no guarantee that a chain of infection can be effectively interrupted. Long disinfection times do not achieve any or only a minimal reduction in the pathogen load, especially if rooms such as waiting rooms, ambulances etc. are heavily frequented. Optical disinfection methods will only become established if they have advantages over classic wipe disinfection in terms of disinfection time, inactivation rate, ease of use and validation.

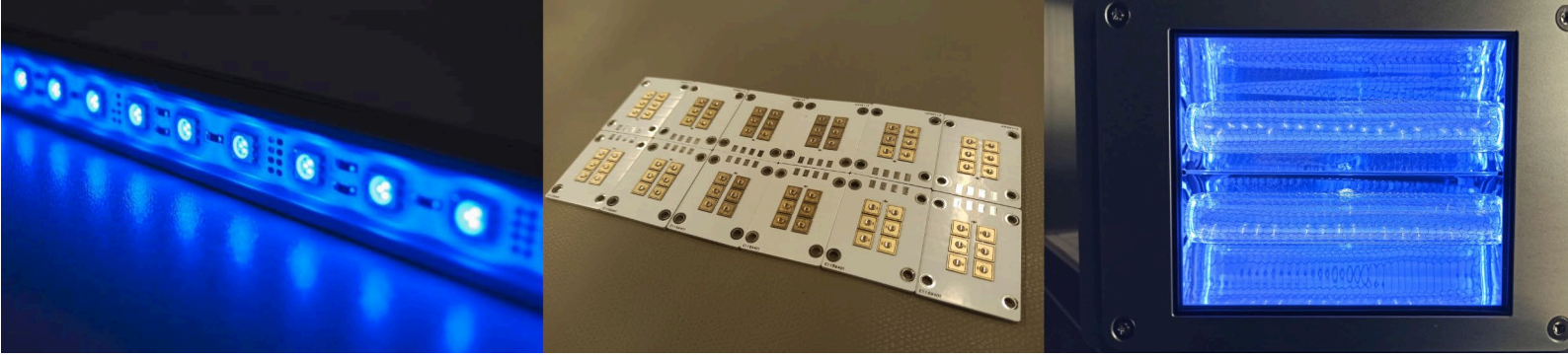
Even though a disinfection effect with very high irradiation doses has been demonstrated with **blue light** in the laboratory, this wavelength range fails due to the low microbiocidal efficiency of the necessary radiation power and the associated enormous energy requirement. The manufacturers use units in their data sheets that make the numerical dose values appear small and therefore highly effective. However, the radiation sources are the cheapest in a comparison of all three methods considered. However, a blue light system is very expensive in relation to the energy requirement and the high number of LEDs for effective disinfection. In addition, the activation of photolyase and thus the process of photoreactivation is in the same wavelength range, which means that many microorganisms are given the tools to repair their DNA damage during irradiation. This leads to a further reduction in efficiency and calls its usefulness into question.

Far-UV irradiation is clearly superior to building light irradiation in terms of its microbiocidal effect in its wavelength range and is on average approximately the same as UVC at 265 nm. However, the optical power of the available excimer radiation sources is so low that even in the small space of an ambulance only insufficient inactivation of microorganisms can be achieved within the short time required to interrupt the chain of infection. Inactivation of very UV-sensitive viruses such as the SARS-Cov2 virus is certainly possible with several radiation sources. The long disinfection time with single sources, the very high price, the very large volume in relation to the output power and the high energy requirement caused by the low WPE make the economic use of this wavelength range with excimer emitters appear questionable. Irradiation times of several hours are not acceptable and feasible from the point of view of vehicle readiness. Although the irradiation of larger rooms with current Far-UV sources should show a certain verifiable reduction in the germ load, whether this leads to the interruption of the chain of infection has not been scientifically proven. Due to the long irradiation times, the effect of photoreactivation in the presence of daylight is not negligible here either. The formation of ozone is always present with far-UV sources.

Nevertheless, this wavelength range has great potential, as current studies suggest that irradiation in the presence of people is possible. The concerns of the Radiation Protection Commission regarding these studies must be taken into account here. Due to the low radiation output, medical applications in the vicinity of the radiation source such as wound irradiation or preoperative skin disinfection are quite conceivable and also tolerable from a radiation protection point of view. For efficient and economical irradiation of entire rooms or more distant surfaces, much more powerful and less expensive radiation sources will be required in the far-UV range in the future.

The disinfection of surfaces in the scenario shown using **UVC LEDs** currently appears to be the most efficient type of radiation-based surface disinfection, although it may only be used in the absence of people or in their presence with appropriate protective measures due to the photobiological risks. Both in terms of the microbiocidal efficiency of the wavelength and in terms of the energy required and the achievable radiation output, UVC LED irradiation is currently and presumably in the future the most efficient and comparatively most cost-effective variant of all three methods considered. The prices for UVC LEDs are currently still comparatively high due to the low quantities on the market, but have already fallen significantly in the past and will continue to fall in the future with further market penetration of UVC LED-based applications. The development potential of UVC LED technology is far from exhausted and the first manufacturers have already indicated increases in WPE of up to 20% and a halving of the price by the end of 2026 in their roadmaps.

Although the currently cheapest UVC sources, low-pressure mercury lamps, could theoretically also be used in this wavelength range, they are only suitable for pulsed operation to a very limited extent. In addition, they are likely to be phased out in the coming years due to the UN Minamata Convention [14] and the resulting bans on mercury-containing radiation sources in many countries [7]. [7] are likely to disappear from the market. There is currently still an exemption for the use of these lamps in the EU until 2027. It is questionable to what extent development activities for devices based on these lamps will still be worthwhile for future systems.



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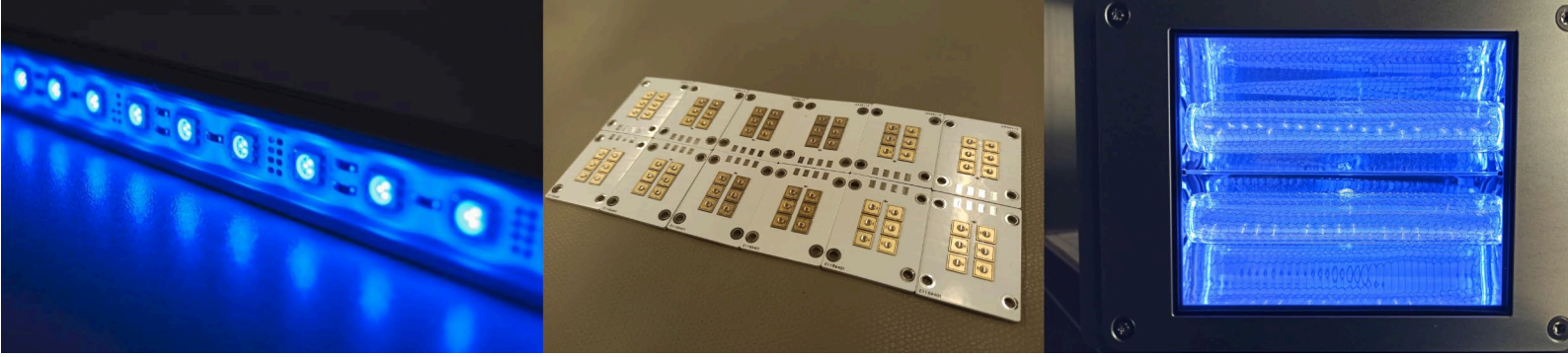

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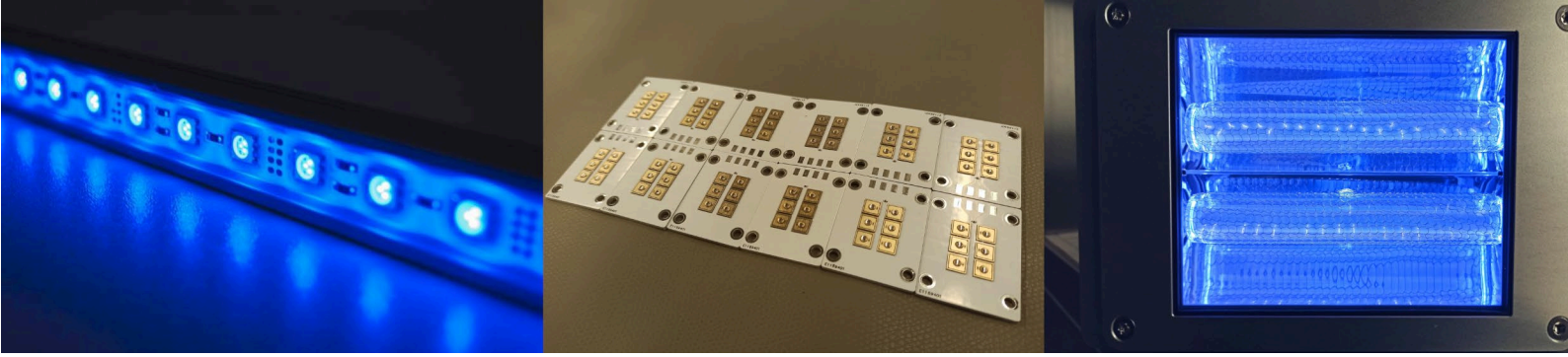

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