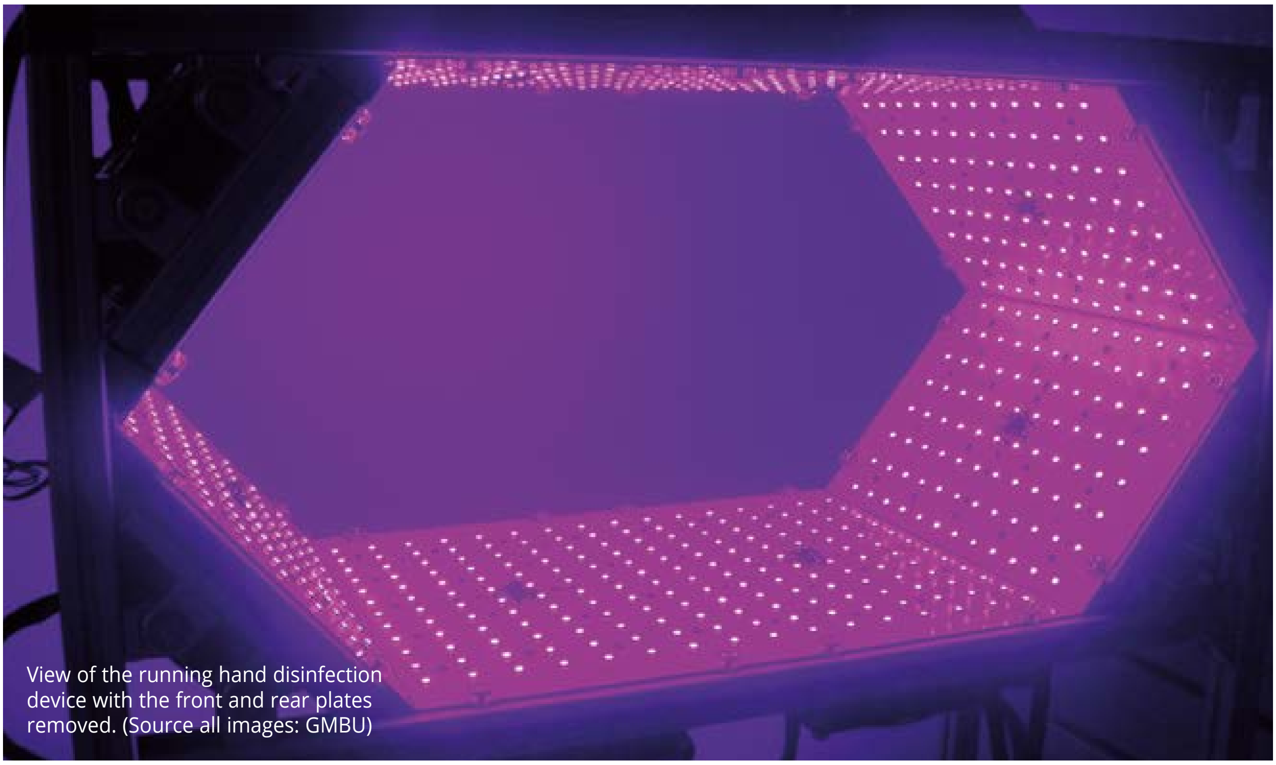
Blue light-emitting diodes for disinfection

Is the process able to improve hygiene in clinics and public buildings?

Bernd Seme, Kerstin Günther, Norbert Winkler, and Walter Wipprich



View of the running hand disinfection device with the front and rear plates removed. (Source all images: GMBU)

Disinfection processes are currently of particular interest due to growing concerns over illnesses caused by human pathogenic germs. Blue light-emitting diodes (LEDs) can reduce the microbial load on surfaces, in liquids and in air. The high wall-plug efficiency of the diodes, their additive-free antimicrobial effect and the good tolerability of the light enable affordable and safe disinfection systems.

LEDs create light by electroluminescence in a semiconductor material. In the first three decades since their market entry in 1962, LEDs emitted only red, orange, yellow, and green light. Typical applications were light indicators and optical signal transmitters. This changed in 1993 with the realization of efficient blue light emitting diodes based on GaN- semiconductor material systems. These new blue LEDs paved the way for white LEDs, which revolutionized the general lighting sector because of their superior energy-efficiency. However, the potential of the inexpensive, compact, durable, and efficient blue LEDs is much more extensive, goes beyond lighting applications and has not yet been exhausted. Processes such as disinfection, photocatalytic cleaning, plant growth and wound healing can be triggered with the help of blue light LED systems. Disinfection processes are of particular interest due to growing concerns over illnesses caused by microorganisms and the persistent problem of healthcare acquired infections. Additionally, because of the rise of antibiotic resistant bacteria, the investigation of novel non-antibiotic approaches for the prevention of infectious diseases has become highly topical.

Even though the use of blue light as a method to reduce bacteria has been the subject of academic interest for more than ten years, the mechanisms of the disinfection process are still not completely clear. It is proposed that endogenous porphyrins, which are present in bacterial cell walls, absorb light and transfer the energy, leading to the production of highly cytotoxic reactive oxygen species (ROS) such as peroxides, superoxide ions, hydroxyl radicals or singlet oxygen. The porphyrin absorption is particularly strong within the Soret band, ranging from about 400 to 420 nm. It reaches a maximum at around 405 nm. Consequently, violet-blue light with a wavelength of 405 nm is the most antimicrobial [1]. LEDs with an

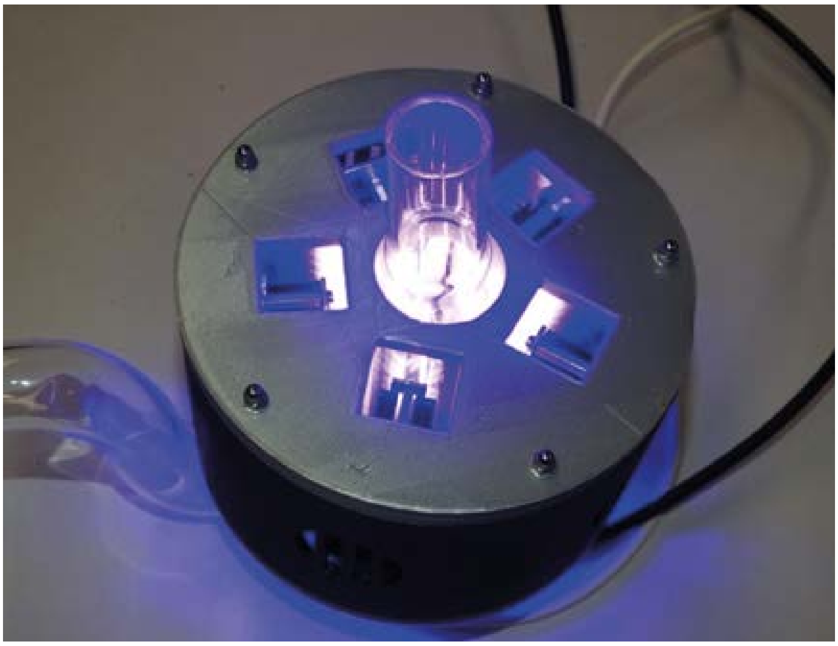


Fig. 1 LED siphon consisting of five LED modules arranged radially around the inlet side. Glass tube diameter: 32 mm.

emission maximum in this range and a narrow spectral width of about 10 nm represent an attractive light source for disinfection applications. In the following, the advantages and disadvantages of blue light in comparison to conventional disinfection methods are discussed. Afterwards we present newly developed LED system concepts for the disinfection of frequently touched surfaces in public buildings, the disinfection of siphons in sanitary facilities and the killing of germs on human hands.

Conventional disinfection methods and their drawbacks

Since Ignaz Semmelweis's pioneering studies during the mid-1800s in Vienna, it is known that hospital-acquired diseases are transmitted via the hands of healthcare workers and doctors. Today the WHO recommends the use of alcohol-based liniments for 20 to 30 seconds as the preferred means for routine hand antisepsis. Alcohol-based hand rubs are effective and have not shown any evidence of inducing bacterial resistance. Although alcohols are more skin-friendly than soaps and detergents, they can still cause dryness and skin irritation. Additionally, alcohol leads to a burning sensation on pre-damaged skin. It is also toxic and flammable. In the event of insufficient ventilation, the formation of ignitable vapor is possible.

The most commonly applied method to disinfect surfaces in hospitals and sanitary facilities involves routine manual cleaning techniques using chemical disinfectants such as phenols or aldehydes. These techniques are far from perfect: in a study, more than 1,000 frequently touched surfaces in three hospitals were checked after routine cleaning and only 47 % of these surfaces had really been cleaned [2]. Moreover, components of the cleaning process may become contaminated themselves during the cleaning procedure. For example, cleaning buckets and fluids are contaminated rapidly and may then transfer pathogens from one surface to another [3]. Additionally, the persistent application of disinfectants on the microorganisms leads to the development of resistance [3] and, finally, the environment and especially the wastewater is contaminated with toxic chemical agents.

Thermal disinfection of liquids such as water is called pasteurization after Louis Pasteur. Pasteurization can take place at temperatures well below boiling point, whereby the pasteurization time decreases with increasing temperature. A typical pasteurization process for water treatment is 10 minutes at 75 °C. Thermal disinfection can kill all pathogens of concern. However, the main disadvantage of pasteurization is its cost.

In addition to chemical disinfectants and pasteurization, UVC irradiation is an established technology for water and medical device decontamination. Low-pressure mercury discharge lamps, which primarily emit at 254 nm wavelength, are commonly used in UVC disinfection. UVC radiation inactivates microbes by damaging their deoxyribonucleic acid (DNA). Unfortunately, serious eye and skin injuries can result if UVC lamps are used improperly or if skin is irradiated accidentally and some materials may show degradation after prolonged exposure to UV light. UV-LEDs are currently seen as a new technology that can replace traditional mercury lamps for disinfection. However, even though UV-LEDs have become more and more powerful in the past decade, LEDs in the UVC range still have low energy efficiencies of 10 % or less.

Performance, advantages and limitations of blue light disinfection

Disinfection processes using blue LEDs are currently attracting increasing attention. This is due to the high wall-plug efficiency of the LEDs in the range of 50 %, the good tolerability of the light and its antimicrobial effect without the addition of exogenous photosensitizers. Under aerobic conditions, all bacteria investigated so far can be inactivated

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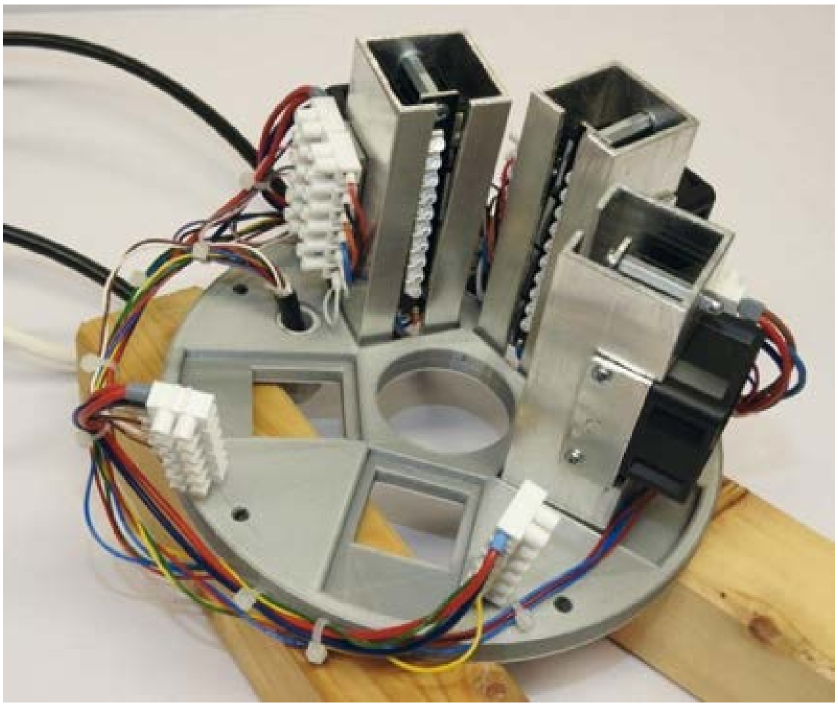

Fig. 2 Arrangement of the siphon's LED modules with ten LEDs connected in series.

by exposure to 405 nm radiation. The antimicrobial efficacy is determined by calculating the difference in $\log_{10}$ colony forming units (CFU) before and after disinfection. Gram-positive and Gram-negative vegetative bacteria require similar doses of violet-blue light for a 1-$\log_{10}$ inactivation, with mean doses of 126 J cm^{-2} and 105 J cm^{-2} respectively [4]. The required doses depend heavily on the experimental setup, the wavelength and the bacterial strain. With a dose of 500 J cm^{-2} at 405 nm, almost all types of bacteria except spores are reduced by three to four $\log_{10}$ levels [5]. Similar to vegetative bacteria, yeasts require average doses of 131 J cm^{-2} for a 1-$\log_{10}$ reduction [4]. In addition, blue light is effective at inactivating both planktonic cells and biofilms of important nosocomial pathogens [6] whereby the development of resistance is very unlikely to occur [7].

Of course, blue light disinfection is not a perfect technique either. Compared to UVC radiation, blue light is far less harmful to humans and materials but it can pass through the cornea and lens to the retina and may cause diseases such as dry eye, cataracts and macular degeneration. It even stimulates the brain, inhibits melatonin secretion and enhances hormone production, which affects sleep quality. Blue LEDs therefore require a precise analysis of their emissions and a classification according to the risk groups defined in the international standard IEC 62471 in order to ensure safe operation. Single blue high power LEDs without diffusors typically belong to risk group one or two and do not represent a photobiological danger as long as you do not stare into the light. Eye-protectors are necessary when high-energy blue LEDs are used and looking into the source cannot be totally ruled out. Another disadvantage of blue light technology is that viruses cannot be deactivated with it because they do not contain endogenous porphyrin. Exogenous photosensitizers are needed to enable the virucidal action of the light.

LED hygiene siphons

Siphons of washbasins in hospitals contain 10^6 – 10^{10} CFU of bacteria per milliliter [8]. Nutrients in the sealing water and temperatures between 20 and 40 °C provide ideal conditions for the multiplication of the bacteria. Even worse, during drainage of water, siphons emit microbes into the ambient air in the form of aerosols and are relevant sources of pathogens and infections. By using blue LEDs, a significant reduction in the bacterial load of the siphon can be achieved with low operating costs. **Fig. 1** shows the demonstration device that has been developed. It consists of five LED modules arranged radially around a glass siphon at the inlet side, **Fig. 2**. The blue light disinfects the sewage water as well as the air above the water level and the siphon's walls by applying irradiances in the range of 200 mW/cm^2. Tests using pseudomonas aeruginosa and burkholderia cepacia bacteria showed that the blue light reduces the number of these active pathogenic hospital germs in the inlet side wastewater by more than four $\log_{10}$ levels within one hour. Moreover, the running costs of the system are only 0.4 euros per day. Compared with a conventional hygiene siphon based on thermal disinfection, the operation of the LED device is about three times cheaper. This will help to make hygienic syphons interesting for areas in which they have not previously been used for cost reasons. Blue LEDs can help to improve hygiene in sanitary facilities, and a market launch of the LED siphon is in preparation.

Antimicrobial handrails

Handrails in clinics, medical facilities, public buildings, day care centers, nursing homes or public transport are frequently touched surfaces that require special attention from a hygienic point of view. Regular disinfection of handrails usually only takes place in medical

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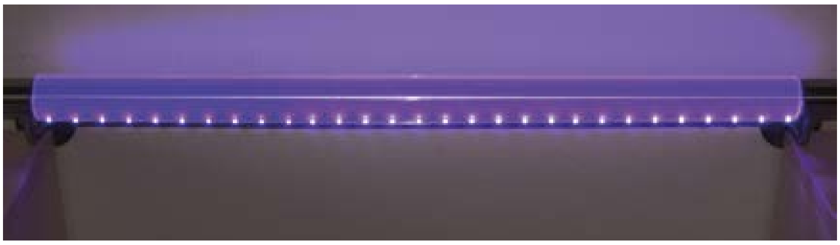

Fig. 3 Antimicrobial LED handrail consisting of a stainless steel support with a light-conducting acrylic glass cover. Length: 1 m, diameter 40 mm.

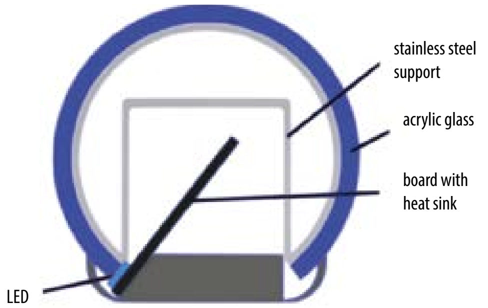

Fig. 4 Schematic cross-sectional drawing of the antimicrobial LED handrail.

facilities at places with a risk of infection, such as surgical departments, operating rooms, units for intensive therapy as well as isolation and functional areas for patients infected with pathogens. In all other cases, regular disinfection of frequently touched surfaces is not carried out at all and they are only cleaned. A first rethink took place during the coronavirus pandemic in 2020 and the handles on shopping trolleys were regularly disinfected with chemical agents. However, the disadvantages of chemical disinfection remain.

Antimicrobial handrails using blue light are continuously disinfected all day long without the need for cleaning staff. This method prevents human errors, such as the use of the wrong disinfectants or the skipping of disinfection intervals. The self-disinfecting handrails make use of the small size of the LEDs to create a lighting concept called LED edge lighting. In this technology, the radiation is fed into an acrylic glass structure via the edges. Diffusing particles incorporated into the glass cause illumination of the whole structure and light output across the entire surface. Fig. 3 and Fig. 4 illustrate the demonstration device. It consists of a pipe made of acrylic glass with a stainless steel support. Electrical boards and the required heat sinks are located inside the tube. A blue light irradiance of at least 3 mW/cm^2 across the whole surface has been achieved by using thirty LEDs with a total power consumption of 30 W. According to IEC 62471, the setup belongs to risk group zero and does not represent a photobiological danger. Nevertheless, it is sufficient to achieve a 4-$\log_{10}$ reduction of bacteria on its surface within 48 hours. For comparison: chemical disinfectants reduce the bacterial load by four to five $\log_{10}$ levels after contact times of a few minutes to ten hours, depending on the agent. We conclude that blue light disinfection of handrails is slower than chemical disinfection, but it is a competitive solution that can improve the hygienic safety of surfaces in a cost effective manner. Full day operation of the system generates electricity costs of only 0.2 euros per meter length, whereas commercial disinfection services charge about five euros per square meter.

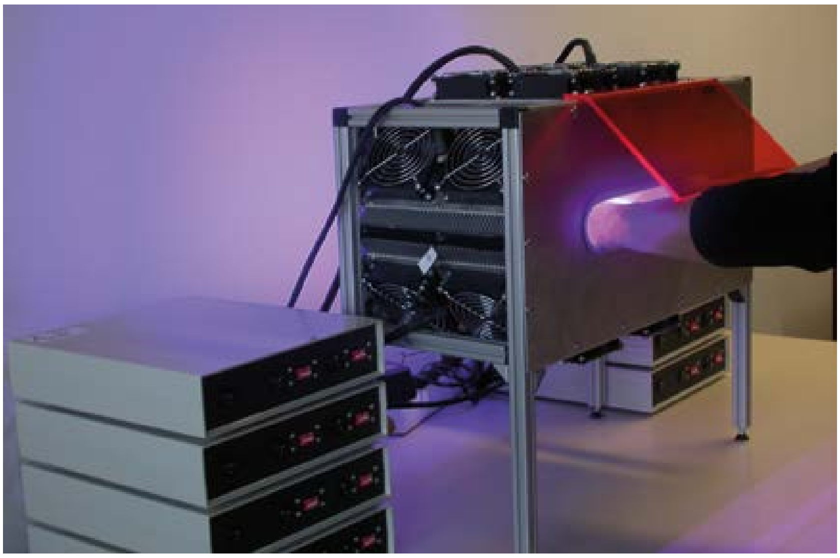

Fig. 5 Hand disinfection device with glare shield (orange) during use.

Optical hand disinfection

We designed a blue light irradiation device, Fig. 5, to examine the potential for blue light to improve hand hygiene. It contains 768 blue LEDs distributed over eight panels, which are arranged to create a volume with a hexagonal cross-section (image p. 91). In this way, hands inserted into the volume can be irradiated, even between the fingers. The front and back of the device are mirrored on the inside, which contributes to the uniform spreading of the radiation. Hands are illuminated with a maximum of 350 mW/cm^2 of blue light centered around 405 nm. Higher irradiance levels lead to the risk of thermal skin damage. The electrical power consumption of the device amounts to 2.4 kW, which gives costs of only about one cent per one-minute disinfection. For comparison: alcoholic liniments cost around ten euros per liter and five cents per application. However, by illuminating model bacteria in suspensions, it could be demonstrated that the system is at best capable of achieving a 0.5-$\log_{10}$ reduction of germs within one minute. Alcoholic rub-in products are much more effective and achieve a 4-$\log_{10}$ reduction of bacteria within sixty seconds. In order to achieve the same 4-$\log_{10}$ reduction of microbes on hands by using blue light, an exposure time of at least twenty minutes would be necessary. We conclude that disinfection of hands with blue light is possible, but it takes too long to be practical and it is not economical compared to alcohol-based hand rubs.

Conclusion

Blue LEDs enable a reduction of the bacterial load on surfaces, in liquids and air without the use of consumables. Compared to UVC radiation, blue light is much more suitable for skin, eyes and materials. Due to the high wall-plug efficiency of the LEDs, blue light disinfection is also affordable. This enables the automatic disinfection of publically accessible surfaces such as handrails and the construction of hygienic LED siphons. Blue light doses of about 500 J cm^{-2} are required for a good disinfection result, that is, the reduction of the CFUs by at least four $\log_{10}$ levels. In practice, the irradiance is typically limited to values less than one W cm^{-2} for thermal, economic or radiation protection reasons. Compared to alcohol-based liniments and UVC disinfection, the blue light disinfection process is therefore slow and is not suitable as the sole process in applications that require fast 4-$\log_{10}$ disinfection within a few minutes.

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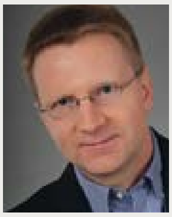
Author

Bernd Seme

graduated in physics in 1996. He then worked for many years in applied research and development with a focus on optics and laser technology. He has been with GMBU in Jena since 2008, where he is responsible for optical measurement technology, spectroscopy and medical applications. Bernd was project manager for the work on the optical disinfection of hands.



Further authors

Kerstin Günther, GMBU e.V.
Norbert Winkler, GMBU e.V.
Walter Wipprich, PURION GmbH

Bernd Seme, Gesellschaft zur Förderung von Medizin-, Bio- und Umwelttechnologien e. V., Felsbachstraße 7, 07745 Jena, Germany; phone: +49 3641 366741, fax: +49 3641 366777; e-mail: seme@gmbu.de, Web: www.gmbu.de