



Photoinactivation of *Staphylococcus carnosus* on Surfaces by Irradiation with Blue and Violet Light †

Florian Sommerfeld *, Patricia Osswald, Pia Weller and Martin Hessling

Department of Medical Engineering and Mechatronics, Ulm University of Applied Sciences, Albert-Einstein-Allee 55, D-89081 Ulm, Germany; patricia.osswald@hotmail.com (P.O.); weller-pia@gmx.de (P.W.); martin.hessling@thu.de (M.H.)

* Correspondence: florian.sommerfeld@thu.de

† Presented at the 2nd International Electronic Conference on Microbiology, 1–15 December 2023;

Available online: <https://ecm2023.sciforum.net>.

Abstract: To control the spread of bacteria and viruses on surfaces in medical environments and everyday life, suitable disinfection methods are required. Visible radiation in the violet or blue spectral range is known to exhibit an antimicrobial impact on microorganisms. However, so far most published studies were performed on liquids. In contrast, the sensitivity of microorganisms to visible radiation on surfaces was only investigated in a few studies. In order to transfer possible conclusions from irradiation in media to irradiation on surfaces and to apply visible light as a possible valid alternative for common disinfection methods, the log reduction doses for surfaces and liquids were compared in this study. The non-pathogenic *Staphylococcus carnosus* was selected as a surrogate for the ESKAPE pathogen *Staphylococcus aureus*, as the experiments were performed in an S1 laboratory. The irradiations were performed with wavelengths of 403 nm (violet) and 453 nm (blue). The observed log reduction doses in liquids (literature with the same strain and setup) and on surfaces (this investigation) were 101.8 J/cm² and 14.0 J/cm² at 403 nm and 374.3 J/cm² and 112.8 J/cm² at 453 nm, respectively. The results suggest that the photosensitivity of *S. carnosus* on surfaces is much higher than in that liquid with a ratio of 7.3 (violet) to 3.3 (blue). On the one hand, this demonstrates that irradiation on surfaces is more efficient than that in liquids, especially in the violet spectral range. On the other hand, depending on the strength of the irradiation source, disinfection with visible irradiation is a useful alternative to conventional disinfection methods.



Citation: Sommerfeld, F.; Osswald, P.; Weller, P.; Hessling, M.

Photoinactivation of *Staphylococcus carnosus* on Surfaces by Irradiation with Blue and Violet Light. *Biol. Life Sci. Forum* **2024**, *31*, 2. <https://doi.org/10.3390/ECM2023-16474>

Academic Editor: Gabriela Jorge Da Silva

Published: 30 November 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: visible irradiation; blue light; violet light; surface; bacteria; *Staphylococcus carnosus*; inactivation; disinfection

1. Introduction

Multidrug-resistant pathogens (MDR pathogens) have emerged with increasing frequency in recent years. This is caused by the numerous and prophylactic administration of antibiotics. MDR pathogens are nonresponsive or only mildly responsive to antibiotics, thus posing a major therapeutic and hygienic problem [1]. One of the most famous MDR pathogens is methicillin-resistant *Staphylococcus aureus* (MRSA). The proportion of MRSA in all identified strains of *S. aureus* on clinical material increased from 1.1% in the 1990s to 20.3% in 2007 [2].

Alcohol-based disinfectants are applied in many areas to prevent the spread of multi-resistant pathogens such as MRSA, but also of non-multi-resistant pathogens. This reduces bacteria and viruses [3], but not all surfaces are suitable for cleaning with disinfectants. As an alternative, disinfection with radiation can be an option that offers several advantages over liquid disinfectants (e.g., less staff and cleaning costs or the cleaning of surfaces where liquid cleaning agents cannot be applied).

Disinfection with visible light (380–780 nm) is generally harmless to humans compared to disinfection with UV radiation and is therefore suitable for the irradiation of premises

frequented by people. The inactivation mechanism is based on endogenous photosensitizers such as flavins and porphyrins, which are excited by light absorption. As a result, reactive oxygen species (ROS), such as singlet oxygen and oxygen peroxides, are produced in an oxygen-containing environment. These highly reactive molecules damage internal cell structures, like cell membranes or cellular lipids and proteins, by oxidative processes and thus inactivate the cell [4–6].

For irradiation, wavelengths of 405 nm (violet) and 450 nm (blue) are selected, as these are most effective in the visible spectral range [7]. The absorption spectra of some photosensitizers match well with the spectra of blue and violet LED emissions, e.g., with peaks at 407 nm (protoporphyrin IX) and 446 nm (riboflavin) [8].

The non-pathogenic relative *Staphylococcus carnosus* was chosen as the test organism for this investigation because it exhibits a visible light photosensitivity similar to that of *S. aureus* [9] and it can be used without infection risk. This and the fact that Staphylococci can be found on almost any surface [10] are reason that *S. carnosus* was selected for this investigation. To draw a comparison and answer the question of which sensitivity of bacteria increases when irradiation is applied to surfaces, the existing data of irradiations in liquids from the literature (published by our group) with the exact same *S. carnosus* strain and the same culturing procedure were employed [11].

2. Material and Methods

2.1. Irradiation Setup

For irradiation with violet light, LEDs from LED-Engin, Inc. (California, Silicon Valley, USA) of the type LZ1-10UB00-00U7 with a peak emission wavelength of 403 nm were applied. To achieve an irradiance of 5.5 mW/cm^2 , the current was set to 1 A. A LED GD CSSRM2.14 from OSRAM Opto Semiconductors Inc. (Munich, Germany) with a peak wavelength of 443 nm was used for blue irradiation. The current was set around 120 mA to achieve an irradiation of 5.5 mW/cm^2 , also.

The irradiation setup includes a glass plate with dimensions of $380 \text{ mm} \times 325 \text{ mm} \times 50 \text{ mm}$, an LED array (three rows: three, one, three), a hollow pyramid covered with a high-reflective inner surface to achieve a homogeneous distribution of radiation [7], a fan to cool the glass plate from below, and a fan to cool the LEDs (four). The glass plate with the bacteria was positioned with the elevation of PMMA 6.5 cm above a black background, which prevented light reflections, so that air circulation kept the plate cooled during the experiments (Figure 1).

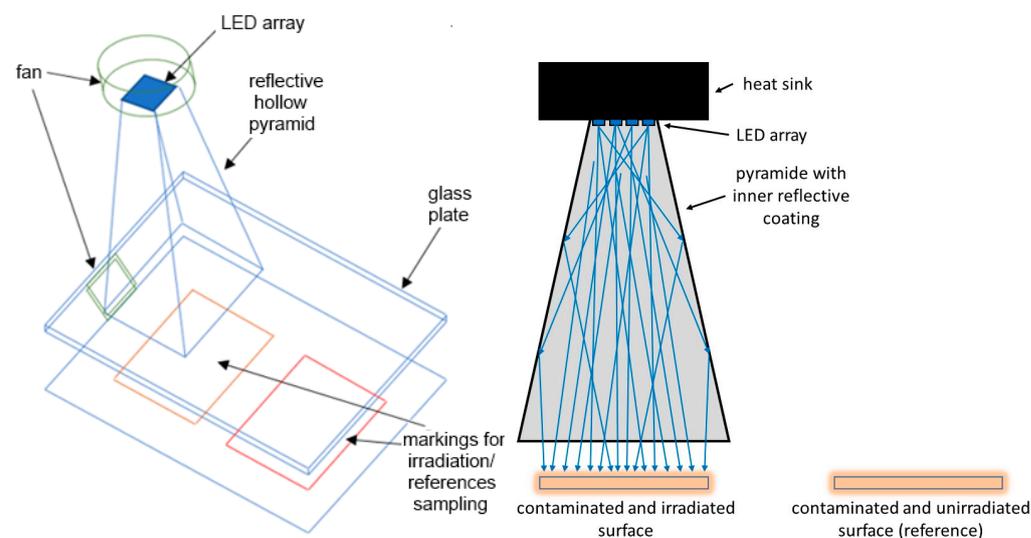


Figure 1. Schematic surface irradiation setup (left: 3D schema; right: cross section).

2.2. Microbiological Procedure

A colony of *S. carnosus* DSM 20501 (DSMZ, Deutsche Sammlung von Mikroorganismen und Zellkulturen, Braunschweig, Germany) was cultivated in M92 medium [12] at 37 °C until an OD of 0.33 was reached, which was equivalent to $1\text{--}5 \times 10^8$ colony forming units (CFU)/mL. Afterwards, 300 μL of the culture was diluted with 11.7 mL of phosphate-buffered saline (PBS) to a final concentration of approx. 10^5 CFU/mL.

A glass plate (380 mm \times 325 mm \times 50 mm) was employed as the test surface. Prior to contamination, it was sprayed with 70% ethanol and then irradiated with UVC (254 nm) for a few seconds. In order to distribute the bacteria quite homogeneously, an industrial paper towel (Glaeser, Ulm, Germany) was placed on the glass plate and 12 mL of the bacterial solution was evenly dispersed with a Pasteur pipette. After 2 h, the paper towel was dried, detached from the plate, and removed.

For sampling, TSA contact plates (VWR-Chemicals, Leuven, Belgium) were used and the glass plate was divided into an irradiated area and a non-irradiated area. Due to the intended irradiances, times of 1.5 h for 403 nm and 10 h for 453 nm were applied for the experiments. In order to reduce potential temperature effects during the experiments, the temperature of the irradiated glass plate was kept between 20 °C and 25 °C, controlled with an infrared thermometer Raynger MX4 (Raytek®, Berlin, Germany). At each sampling interval (every 15 min at 403 nm, every 60 min from 2 to 4 h, and a sample at 10 h at 453 nm), a sample was taken at the irradiated area and a reference sample was taken from the non-irradiated area. For 403 nm, six runs were performed, and nine were performed for 453 nm. After sampling, the bacteria on the contact plates were cultivated at 37 °C in an incubator for at least 24 h before counting the colonies.

3. Results

An exponential reduction of *S. carnosus* was observed with both wavelengths, though they differed significantly. Due to the defined irradiation times, the irradiation doses up to 29.7 J/cm² were applied at 403 nm and those up to 198 J/cm² were applied at 453 nm. The average irradiation doses for the reduction of one log level were 14.0 J/cm² at 403 nm and 112.8 J/cm² at 453 nm (Figures 2 and 3).

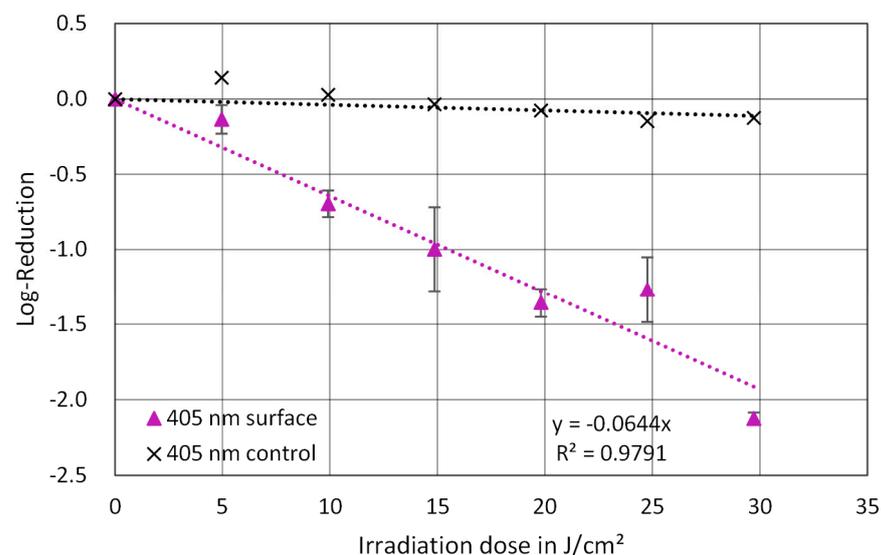


Figure 2. Irradiation of *S. carnosus* on surfaces with 403 nm (triangle) and control (cross). Each data point is the average of at least six independent runs, and for each run, two technical replicates were analyzed. The error bars indicate the standard deviation of the single results.

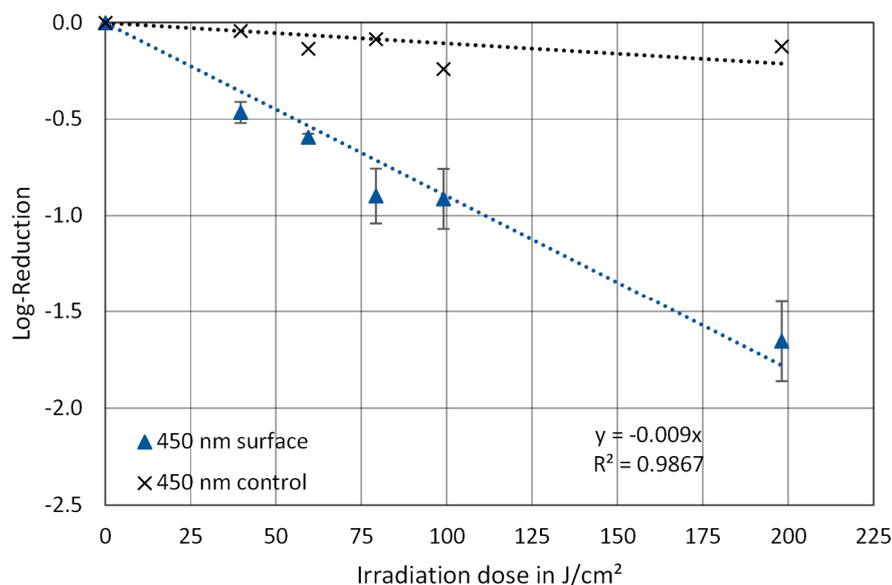


Figure 3. Irradiation of *S. carnosus* on surfaces with 453 nm (triangle) and control (cross). Each data point is the average of at least six independent runs, and for each run, two technical replicates were analyzed. The error bars indicate the standard deviation of the single results.

4. Discussion

The surface results reveal an exponential reduction of *S. carnosus* with both wavelengths (violet and blue). Compared to the log reduction doses of the previously mentioned work with *S. carnosus* in (liquid) PBS [11], a factor of 7.3 (101.8 J/cm²/14.0 J/cm²) for violet and a factor of 3.3 (374.3 J/cm²/112.8 J/cm²) for blue were obtained, which indicate that *S. carnosus* is much more sensitive to visible irradiation on dry surfaces than in liquids.

The reason for this increased sensitivity might be the fact that, during the irradiation on surfaces, the bacteria were exposed to forced drought. Dehydration leads to conformational changes in proteins that can be detected by Fourier transform infrared spectroscopy [13]. In addition, it changes the nature of DNA, partially transforming it from B-DNA to A-DNA, which is more susceptible to blue light than B-DNA [14,15]. Dehydration also leads to oxidative stress [16], which produces partially reduced or activated forms of oxygen, i.e., ROS [17,18], resulting in the dysfunction of organisms and damage to cell membranes. Since no reduction is detectable on the non-irradiated samples, the effect of the dryness is not sufficient to inactivate the bacteria. If violet or blue radiation is added, the effect of this could be synergistically enhanced by the dryness, which would explain the difference between the dry surface and suspension. Nevertheless, this possible synergy seems to differ between the wavelengths.

5. Conclusions

Based on the results, violet light seems to be useful for practical applications, such as disinfection lighting in hospitals or general workplaces. However, violet light alone cannot replace a standard light source due to the fact that it does not achieve the required color temperature, color rendering index, and illuminance [19,20].

Therefore, several possibilities would be conceivable for the realistic application of violet irradiation that also has a sufficient reduction in bacteria:

- Violet LEDs are applied together with white LEDs to achieve a sufficient color rendering index and the required illumination, which has already been attempted in other investigations [21]. This would ensure a continuous irradiation and a sufficient reduction of pathogens.
- Violet LEDs are installed in room lighting, but are only switched on temporarily, when neither working persons or, in the case of hospitals, patients are present in the affected

area. This means that the irradiance can be adjusted as required within the limits of the technical possibilities.

Author Contributions: Conceptualization, F.S., P.O., P.W. and M.H.; methodology, F.S., P.O., P.W. and M.H.; software, F.S., P.O. and P.W.; validation, F.S., P.O., P.W. and M.H.; formal analysis, F.S., P.O. and P.W.; investigation, F.S., P.O. and P.W.; resources, M.H.; data curation, F.S., P.O. and P.W.; writing—original draft preparation, F.S., P.O. and P.W.; writing—review and editing, F.S., P.O., P.W. and M.H.; visualization, F.S., P.O. and P.W.; supervision, M.H.; project administration, M.H.; funding acquisition, M.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are available upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Geffers, C.; Zuschneid, I.; Sohr, D.; Rüden, H.; Gastmeier, P. Erreger nosokomialer Infektionen auf Intensivstationen: Daten des Krankenhaus-Infektions-Surveillance-Systems (KISS) aus 274 Intensivstationen. *AINNS* **2004**, *39*, 15–19. [[CrossRef](#)] [[PubMed](#)]
2. Ruscher, C. Empfehlungen zur Prävention und Kontrolle von Methicillin-resistenten Staphylococcus aureus-Stämmen (MRSA) in medizinischen und pflegerischen Einrichtungen. *Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz* **2014**, *57*, 695–732. [[CrossRef](#)]
3. Christiansen, B.; Dettenkofer, M.; Becker, E.M.; Eikmann, T.; Exner, M.; Heeg, P.; Kramer, A.; Ruf, B.; Schwebke, I. Anforderungen an die Hygiene bei der Reinigung und Desinfektion von Flächen. Empfehlung der Kommission für Krankenhaushygiene und Infektionsprävention beim Robert Koch-Institut (RKI). *Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz* **2004**, *47*, 51–61. [[CrossRef](#)]
4. Plavskii, V.Y.; Mikulich, A.V.; Tretyakova, A.I.; Leusenka, I.A.; Plavskaya, L.G.; Kazyuchits, O.A.; Dobysh, I.I.; Krasnenkova, T.P. Porphyrins and flavins as endogenous acceptors of optical radiation of blue spectral region determining photoinactivation of microbial cells. *J. Photochem. Photobiol. B* **2018**, *183*, 172–183. [[CrossRef](#)] [[PubMed](#)]
5. Lui, G.Y.; Roser, D.; Corkish, R.; Ashbolt, N.J.; Stuetz, R. Point-of-use water disinfection using ultraviolet and visible light-emitting diodes. *Sci. Total Environ.* **2016**, *553*, 626–635. [[CrossRef](#)] [[PubMed](#)]
6. Cunningham, M.L.; Krinsky, N.I.; Giovanazzi, S.M.; Peak, M.J. Superoxide anion is generated from cellular metabolites by solar radiation and its components. *J. Free Radic. Biol. Med.* **1985**, *1*, 381–385. [[CrossRef](#)] [[PubMed](#)]
7. Hessling, M.; Spellerberg, B.; Hönes, K. Photoinactivation of bacteria by endogenous photosensitizers and exposure to visible light of different wavelengths—A review on existing data. *FEMS Microbiol. Lett.* **2017**, *364*, fnw270. [[CrossRef](#)] [[PubMed](#)]
8. Hessling, M.; Wenzel, U.; Meurle, T.; Spellerberg, B.; Hönes, K. Photoinactivation results of Enterococcus moraviensis with blue and violet light suggest the involvement of an unconsidered photosensitizer. *Biochem. Biophys. Res. Commun.* **2020**, *533*, 813–817. [[CrossRef](#)] [[PubMed](#)]
9. Hönes, K.; Bauer, R.; Meurle, T.; Spellerberg, B.; Hessling, M. Inactivation Effect of Violet and Blue Light on ESKAPE Pathogens and Closely Related Non-pathogenic Bacterial Species—A Promising Tool Against Antibiotic-Sensitive and Antibiotic-Resistant Microorganisms. *Front. Microbiol.* **2020**, *11*, 612367. [[CrossRef](#)]
10. Hessling, M.; Haag, R.; Sicks, B. Review of microbial touchscreen contamination for the determination of reasonable ultraviolet disinfection doses. *GMS Hyg. Infect. Control* **2021**, *16*, Doc30. [[CrossRef](#)] [[PubMed](#)]
11. Hönes, K.; Bauer, R.; Spellerberg, B.; Hessling, M. Microbial Photoinactivation by Visible Light Results in Limited Loss of Membrane Integrity. *Antibiotics* **2021**, *10*, 341. [[CrossRef](#)]
12. Deutsche Sammlung von Mikroorganismen und Zellkulturen. M92: Trypticase Soy Yeast Extract Medium. Available online: https://www.dsmz.de/microorganisms/medium/pdf/DSMZ_Medium92.pdf (accessed on 21 September 2023).
13. Prestrelski, S.J.; Tedeschi, N.; Arakawa, T.; Carpenter, J.F. Dehydration-induced conformational transitions in proteins and their inhibition by stabilizers. *Biophys. J.* **1993**, *65*, 661–671. [[CrossRef](#)] [[PubMed](#)]
14. Wood, B.R. The importance of hydration and DNA conformation in interpreting infrared spectra of cells and tissues. *Chem. Soc. Rev.* **2016**, *45*, 1980–1998. [[CrossRef](#)] [[PubMed](#)]
15. Bumah, V.V.; Aboulazadeh, E.; Masson-Meyers, D.S.; Eells, J.T.; Enwemeka, C.S.; Hirschmugl, C.J. Spectrally resolved infrared microscopy and chemometric tools to reveal the interaction between blue light (470 nm) and methicillin-resistant Staphylococcus aureus. *J. Photochem. Photobiol. B* **2017**, *167*, 150–157. [[CrossRef](#)] [[PubMed](#)]
16. França, M.B.; Panek, A.D.; Eleutherio, E.C.A. Oxidative stress and its effects during dehydration. *Comp. Biochem. Physiol. A Mol. Integr. Physiol.* **2007**, *146*, 621–631. [[CrossRef](#)] [[PubMed](#)]

17. Leprince, O.; Hendry, G.A.F.; McKersie, B.D. The mechanisms of desiccation tolerance in developing seeds. *Seed Sci. Res.* **1993**, *3*, 231–246. [[CrossRef](#)]
18. Leprince, O.; Atherton, N.M.; Deltour, R.; Hendry, G. The Involvement of Respiration in Free Radical Processes during Loss of Desiccation Tolerance in Germinating Zea mays L. (An Electron Paramagnetic Resonance Study). *Plant Physiol.* **1994**, *104*, 1333–1339. [[CrossRef](#)] [[PubMed](#)]
19. DIN EN 12464-1:2011-08; Licht und Beleuchtung- Beleuchtung von Arbeitsstätten—Teil 1: Arbeitsstätten in Innenräumen. Deutsche Fassung EN 12464-1:2011; Beuth Verlag GmbH: Berlin, Germany, 2011.
20. Bundesanstalt für Arbeitsschutz und Arbeitsmedizin. Technische Regeln für Arbeitsstätten: Beleuchtung. Available online: https://www.baua.de/DE/Angebote/Rechtstexte-und-Technische-Regeln/Regelwerk/ASR/pdf/ASR-A3-4.pdf?__blob=publicationFile (accessed on 21 February 2022).
21. Bühler, J.; Sommerfeld, F.; Meurle, T.; Hönes, K.; Hessling, M. Disinfection Properties of Conventional White LED Illumination and Their Potential Increase by Violet LEDs for Applications in Medical and Domestic Environments. *Adv. Sci. Technol. Res. J.* **2021**, *15*, 169–175. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.