physical sciences forum

MDPI

Proceeding Paper

Comparison of Different Far-UVC Sources with Regards to Intensity Stability, Estimated Antimicrobial Efficiency and Potential Human Hazard in Comparison to a Conventional UVC Lamp †

Ben Sicks [1], Florian Maiss [1], Christian Lingenfelder [2], Cornelia Wiegand [3] and Martin Hessling [1,*]

[1] Institute of Medical Engineering and Mechatronics, Ulm University of Applied Sciences, Albert-Einstein-Allee 55, D-89081 Ulm, Germany; ben.sicks@thu.de (B.S.); maisfl02@thu.de (F.M.)
[2] Zimmer MedizinSysteme GmbH, Junkersstraße 9, D-89231 Neu-Ulm, Germany; c.lingenfelder@gmx.de
[3] Department of Dermatology, University Hospital Jena, Am Klinikum 1, D-07747 Jena, Germany; c.wiegand@med.uni-jena.de
* Correspondence: martin.hessling@thu.de
† Presented at 1st International Online Conference on Photonics, 14–16 October 2024; Available online: https://sciforum.net/event/IOCP2024.

Abstract: The recently much noticed Far-UVC spectral range offers the possibility of inactivating pathogens without necessarily posing a major danger to humans. Unfortunately, there are various Far-UVC sources that differ significantly in their longer wavelength UVC emission and, subsequently, in their risk potential. Therefore, a simple assessment method for Far-UVC sources is presented here. In addition, the temporal intensity stability of Far-UVC sources was examined in order to reduce possible errors in irradiation measurements. For this purpose, four Far-UVC sources and a conventional Hg UVC lamp were each spectrally measured for about 100 h and mathematically evaluated for their antimicrobial effect and hazard potential using available standard data. The two filtered KrCl lamps were found to be most stable after a warm-up time of 30 min. With regard to the antimicrobial effect, the radiation efficiencies of all examined (Far-) UVC sources were more or less similar. However, the calculated differences in the potential human hazard to eyes and skin were more than one order of magnitude. The two filtered KrCl lamps were the safest, followed by an unfiltered KrCl lamp, a Far-UVC LED and, finally, the Hg lamp. When experimenting with these Far-UVC radiation sources, the irradiance should be checked more than once. If UVC radiation is to be or could be applied in the presence of humans, filtered KrCl lamps are a much better choice than any other available Far-UVC sources.

Keywords: far UVC; UVC; long-term stability; risk assessment; threshold limit values; antimicrobial impact

Citation: Sicks, B.; Maiss, F.; Lingenfelder, C.; Wiegand, C.; Hessling, M. Comparison of Different Far-UVC Sources with Regards to Intensity Stability, Estimated Antimicrobial Efficiency and Potential Human Hazard in Comparison to a Conventional UVC Lamp. *Phys. Sci. Forum* **2024**, *10*, 1. https://doi.org/10.3390/psf2024010001

Academic Editor: Ambra Giannetti

Published: 19 November 2024

1. Introduction

Even before the coronavirus pandemic, it was desired to be able to inactivate pathogens in the presence of humans to prevent the spread of infections without harming people, e.g., in crowded rooms or public transport. However, this was previously not feasible.

There have been and still are effective antimicrobial measures, such as the germicidal 254 nm UVC radiation from mercury vapor lamps that has been applied for 100 years and exhibits a strong antimicrobial effect due to its DNA-destroying mechanism. Unfortunately, it is not discriminatory and can also damage human DNA and cells.

Since the coronavirus pandemic, the UVC spectral range from 200 to 230 nm has attracted particular attention, though there were already studies on the properties of this part of the UVC region before the pandemic [1–3]. This short-wavelength radiation, often called Far-UVC radiation, appears to exhibit the desired properties of a strong antimicrobial

effect without having a major impact on humans. The reason for this is that radiation below 240 nm is not only strongly absorbed by DNA but also by proteins, with the result that the proteins of dead cells in the stratum corneum on the top of human skin, for example, protect vital cells in deeper skin layers.

Despite these observed positive characteristics, the application potential of Far-UVC radiation was initially not widely recognized, even by experts. It was only the coronavirus pandemic that led to an increase in Far-UVC studies and new findings [4–10], which, for example, initiated a reassessment of the effects of Far-UVC irradiation on human eyes and skin. For this reason, the American Conference of Governmental Industrial Hygienists (ACGIH) [11] adopted new, higher daily permissible Far-UVC exposure doses, defined as threshold limit values (TLVs).

Nevertheless, some important aspects of a potential future increase in the application of Far-UVC have not yet been investigated or are still not fully understood, such as the possible photobiological consequences of long-term exposure to Far-UVC radiation. Several important Far-UVC research topics have been suggested by Görlitz et al. [12]. When carrying out such Far-UVC experiments—as with many other UV irradiation experiments—a constant irradiance is often assumed and the desired irradiation dose can then be achieved over time.

Whether the irradiance levels are really constant when the lamps are switched on, or whether it is necessary to wait for an unknown warm-up period, is an open question and is investigated here for the first time for four different Far-UVC radiation sources. These are three 222 nm KrCl lamps from different manufacturers, two of which are equipped with filters for the reduction in harmful long-wavelength UVC components above 240 nm to reduce human health risks. In addition, a 236 nm Far-UVC LED is also examined. For comparison, a conventional 254 nm mercury vapor lamp is included in this study. The relative irradiance levels are determined over a period of about 100 h after switching on the respective radiation source.

Since the various Far-UVC sources differ spectrally, the biological effects on microorganisms as well as on human skin and eyes are not identical. At the moment, expensive studies on animal or human test subjects or tissues would be needed to carry out qualitative and quantitative assessments of the irradiation risk potential. Suitable in vitro models that allow for the transfer of the results into daily life are urgently required to facilitate investigations of antimicrobial efficacy and health risk potentials simultaneously. Until then, a clear and simple mathematical evaluation of the respective Far-UVC source based on the emission spectrum of the lamp is proposed here, and the above-mentioned radiation sources are evaluated and compared with each other with regard to both the antimicrobial effect and the potential risk to humans. The reason for this is that experimental studies on microorganisms are very time-consuming, and studies on human eyes and skin are also ethically difficult, so such investigations cannot be carried out for every new Far-UVC radiation source on the market. To the best of our knowledge, such an approach to carrying out these assessments on the basis of available standardized data has not been presented previously.

2. Materials and Methods

The properties of these five (Far-) UVC sources were investigated:

1. A 222 nm KrCl lamp (20 W, filtered), type “UV222” of UVMedico (Aarhus, Denmark), with a KrCl 222 nm module of Ushio (Cypress, CA, USA);
2. A 222 nm KrCl lamp (20 W, filtered), type “DF28B” of Conlustro (Sheridan, WY, USA);
3. A 222 nm KrCl lamp (5 W, unfiltered), type “DF15B-B1” of France-UVC (Lévignac de Guyenne, France), in combination with a provided electrical converter and a lab power supply at a constant current of 1 A;
4. A 236 nm Far-UVC LED (0.3 W, unfiltered), type “SF1 flat lens” of Silanna UV (Pinkenba, Australia), in combination with a lab power supply at a constant current of 40 mA;

5. A 254 nm Hg lamp (6 W, unfiltered), type "3UV36" of Analytik Jena (Jena, Germany).

The spectrally resolved measurements of the lamp intensities were carried out at close range using a CAS 140D from Instruments Systems (Munich, Germany). This was a calibrated combination of an integrating sphere and a spectrometer, as depicted in Figure 1. For better comparability of the lamps, all spectra were standardized so that the total irradiance in the UV spectral range of 200–400 nm was 1 mW/cm^2. For the determination of the long-term stability of the UVC sources, these measurements were further carried out over a period of about 100 h at a room temperature of approx. 21 °C.

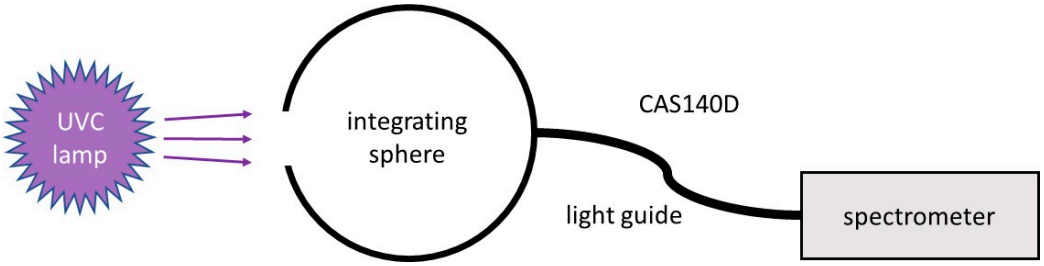

Figure 1. The schematic setup for the determination of the spectrally resolved (Far-) UVC lamp irradiances.

Published data were used to estimate the antimicrobial effects of the radiation from the various lamps and the potential risk to humans. The antimicrobial effect was determined based on the antimicrobial efficiency of UV radiation against *B. subtilis* spores—available in 1 nm steps from the international standard DIN 5031-10 [13]. To assess the potential hazard to humans, the latest ACGIH-TLVs or the so-called relative spectral effectiveness for the irradiation of the eye and skin were applied [11]. Both relative curves can be found in Figure 2.

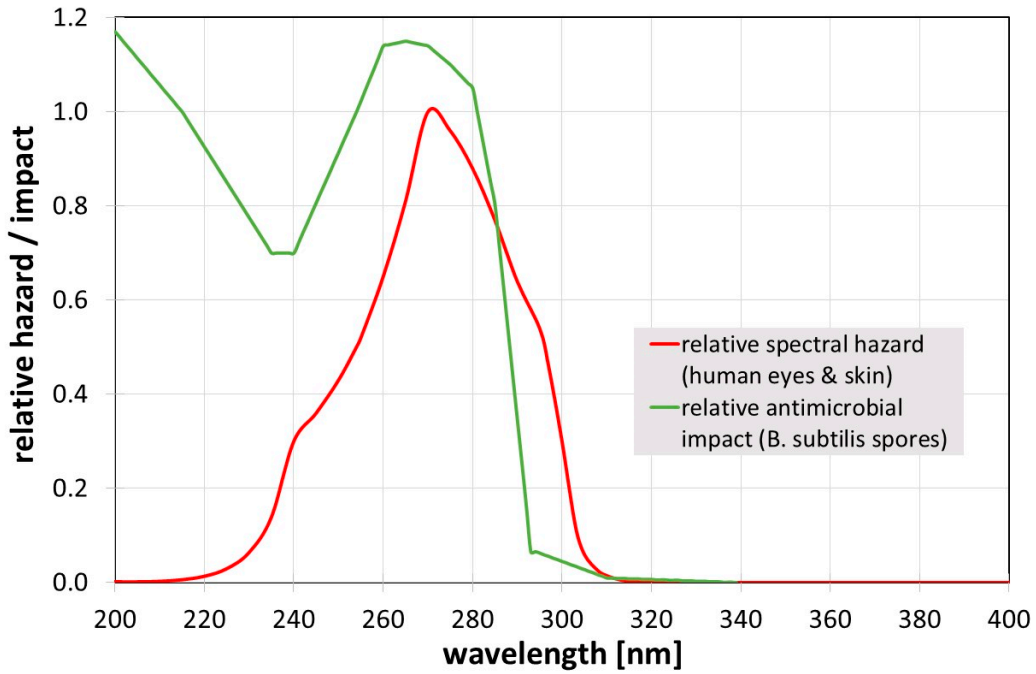

Figure 2. Spectrally resolved relative antimicrobial impact and potential hazards to human eyes and skin for UV radiation in range 200–400 nm according to DIN 5031-10 and ACGIH-TLVs [11,13].

The relative antimicrobial efficacy $X_{antimic}$ of a Far-UVC source can therefore be calculated, as described below, from the measured and standardized spectral irradiance $E(\lambda)$ and the spectral efficiencies $A(\lambda)$ according to DIN 5031-10 on the basis of Formula (1):

$$X_{antimic} = \sum_{200\ nm}^{339\ nm} E(\lambda) \times A(\lambda) \times \Delta\lambda \quad (1)$$

Comparably, the hazard to human eyes and skin X_{hazard} can be calculated on the basis of the relative spectral effectiveness $S(\lambda)$ from the ACGIH data and the measured normalized spectral irradiances $E(\lambda)$ for each Far-UVC source according to Formula (2):

$$X_{hazard} = \sum_{200\ nm}^{400\ nm} E(\lambda) \times S(\lambda) \times \Delta\lambda \quad (2)$$

3. Results

The time course of the relative irradiance of the various (Far-) UVC sources is provided in Figure 3. The two filtered KrCl lamps reached a very stable intensity level within approx. 30 min. For all three other sources, the radiation intensity did not appear to have completely stabilized even after 100 h.

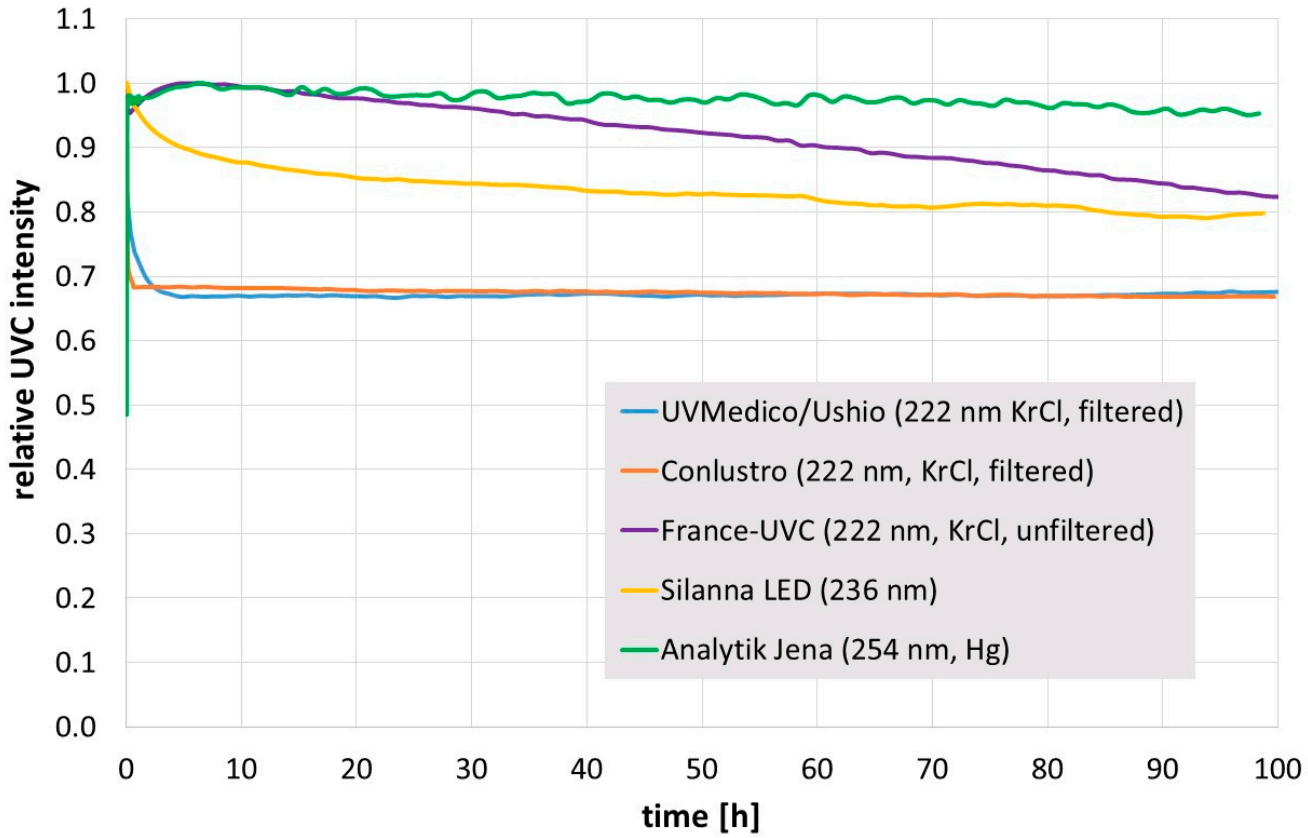

Figure 3. The time-dependent intensity variation in the various (Far-) UVC sources over a period of about 100 h.

The normalized spectral irradiances are plotted in Figure 4. The spectra of the three KrCl lamps are very close to each other around the 222 nm emission peak, with only the unfiltered KrCl source still having relevant spectral components above 240 nm, which account for just under 10% of the total irradiance and also include a weak emission peak at just under 260 nm. The Far-UVC LED has its maximum emission at 236 nm and its spectral half-width is around 10 nm. About 27% of the emission of the Far-UVC LED is

above 240 nm and therefore in a spectral range that poses a higher risk to humans. For comparison, the spectrum of the conventional Hg lamp is also provided in Figure 4.

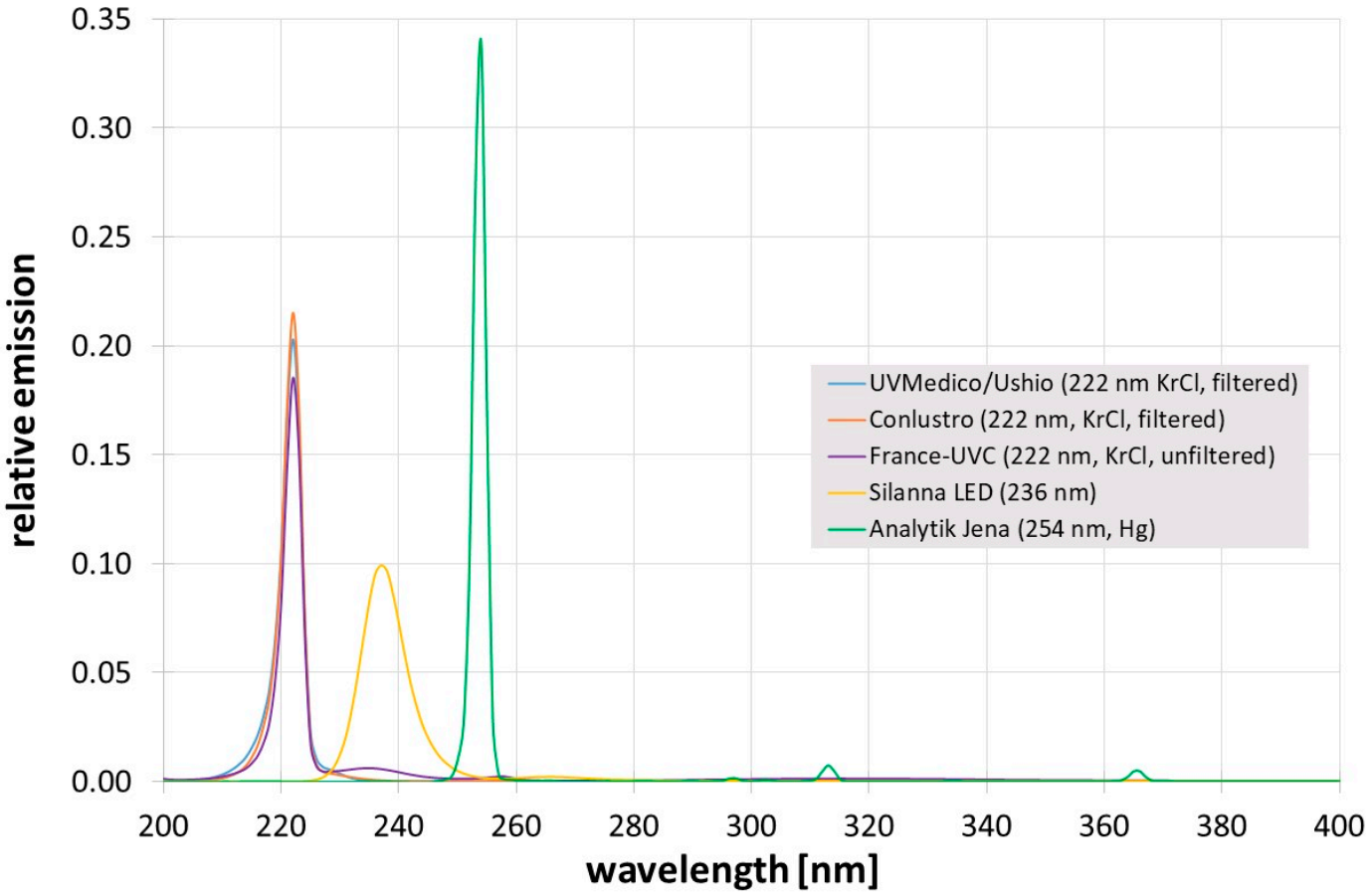

Figure 4. The spectral irradiances of the different (Far-) UVC sources, normalized to a UV irradiation of 1 mW/cm^2.

The calculated (relative) values for the expected antimicrobial effect and the hazard to human eyes and skin can be found in Table 1. In terms of the antimicrobial effect, the effectiveness of the radiation from all UVC sources is of approximately the same order of magnitude. With regard to the human hazard, however, the impact of the conventional Hg lamp is more than one order magnitude higher than for the filtered KrCl lamps. According to this calculation, a 25-times-higher KrCl radiation dose could be applied as with the Hg lamp and would result in the same health risk to humans in both cases.

Table 1. The calculated relative antimicrobial effect according to the *B. subtilis* spore data from DIN 5031-10 and the hazard assessment for human eyes and skin based on ACGIH spectral effectiveness. Both calculations were performed with the normalized relative spectral irradiances, as illustrated in Figure 4. The values for antimicrobial efficacy and human exposure in brackets are scaled to the effect of the Hg lamp and the filtered KrCl lamp from UVMedico/Ushio, respectively.

	UVMedico/Ushio (222 nm KrCl, Filtered)	**Conlustro (222 nm KrCl, Filtered)**	**France-UVC (222 nm, KrCl, Unfiltered)**	**Silanna LED (236 nm)**	**Analytik Jena (254 nm Hg)**
antimicrobial impact (normalized to Analytik Jena lamp)	0.907 (0.96)	0.880 (0.93)	0.826 (0.87)	0.737 (0.78)	0.946 (1.0)
eye and skin hazard (normalized to filtered UVMedico/Ushio lamp)	0.019 (1.0)	0.022 (1.17)	0.055 (2.9)	0.247 (13)	0.475 (25)

The other two Far-UVC sources are obviously worse than the filtered KrCl lamps, whereby the Far-UVC LED with its longer-wavelength UVC components poses a much greater risk to humans compared to the unfiltered KrCl lamp.

4. Discussion

The intensity stability investigations revealed that only the two filtered Far-UVC lamps were stable after a warm-up time of 30 min. This was not the case with any of the other lamps even after about 100 h. In the case of the Far-UVC LED, this may be due to its short lifespan of only a few hundred hours. For the other two lamps, which should have lifetimes of several thousand hours, the reason is unknown. Nevertheless, this demonstrates that it may not be sufficient for irradiation experiments to measure the irradiance once and then assume it to be constant in order to determine irradiation doses as the product of irradiation time and irradiance.

The antimicrobial efficacy was calculated based on data for *B. subtilis* spores. If data from other microorganisms had been used, the values would probably have been slightly different, but it is unlikely that anything would have changed in general, as the antimicrobial effectiveness of all UVC sources is roughly in the same order of magnitude. In any case, this also fits in quite well with our own previously published results and those of other research groups [14–19].

As far as the assessment of the risk to eyes and skin from UVC radiation is concerned, this of course depends on the quality of the ACGIH TLVs or spectral effectiveness. O'Mahoney et al. have suggested that a correction of these data may be necessary [20]. Therefore, if the ACGIH values actually undergo another revision in the future, the computational assessment will also change, but no major differences are expected, and so the current assessments already provide a good impression of the relative safety of different far-UVC sources. The statement that filtered KrCl lamps are less harmful to humans than unfiltered KrCl lamps or even Hg lamps is not surprising and has already been established by various authors [6,20–24]. However, so far, time-consuming experiments on animal or human test subjects or tissues have only yielded a qualitative but no quantitative assessment of the irradiation. For that, we need suitable models to allow for the investigation of antimicrobial efficacy and health risk potentials simultaneously. Such models will also provide appropriate biological data for mathematical approaches. Now, the proposed straightforward and intuitive calculation approach, using current standard data, allows for an approximate assessment based solely on the lamp spectrum. In accordance, Far-UVC LEDs, which have been less frequently investigated to date, can now also be evaluated more rapidly. It could be shown that the hazard potential of their radiation is currently significantly higher than that of filtered and unfiltered KrCl lamps, but the development history of LEDs to date gives reason to the hope that Far-UVC LEDs will develop further. This also suggests that the peak wavelength can be expected to decrease and the undesired longer-wavelength emissions should reduce, which would result in a lower risk potential of future Far-UVC LEDs.

This straightforward determination of the expected biological effects of (Far-) UVC radiation on microorganisms and humans is no real substitute for biological experiments. However, it provides a quick and meaningful estimate, the quality of which is mainly limited by the data provided for the spectral sensitivity of microorganisms and human skin and eyes.

Author Contributions: Conceptualization, B.S., C.W. and M.H.; methodology, B.S., F.M., C.W. and M.H.; software, B.S., F.M. and M.H.; validation, B.S., C.W. and M.H.; formal analysis B.S. and M.H.; investigation, B.S., F.M. and M.H.; resources, C.L. and M.H.; data curation, B.S., C.W. and M.H.; writing—original draft preparation, B.S. and M.H.; writing—review and editing, B.S., F.M., C.L., C.W. and M.H.; visualization, B.S. and M.H.; supervision, C.L. and M.H.; project administration, M.H.; funding acquisition, C.L. and 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 on reasonable request.

Acknowledgments: We are grateful for the instrumental support from J. Moisel and for the lamp loan from Conlustro.

Conflicts of Interest: Christian Lingenfelder was employed by Zimmer MedizinSysteme GmbH. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Sosnin, E.A.; Stoffels, E.; Erofeev, M.V.; Kieft, I.E.; Kunts, S.E. The Effects of UV Irradiation and Gas Plasma Treatment on Living Mammalian Cells and Bacteria: A Comparative Approach. *IEEE Trans. Plasma Sci.* **2004**, *32*, 1544–1550. [CrossRef]
2. Buonanno, M.; Randers-Pehrson, G.; Bigelow, A.W.; Trivedi, S.; Lowy, F.D.; Spotnitz, H.M.; Hammer, S.M.; Brenner, D.J. 207-nm UV light-A promising tool for safe low-cost reduction of surgical site infections. I: In vitro studies. *PLoS ONE* **2013**, *8*, e76968. [CrossRef] [PubMed]
3. Buonanno, M.; Stanislauskas, M.; Ponnaiya, B.; Bigelow, A.W.; Randers-Pehrson, G.; Xu, Y.; Shuryak, I.; Smilenov, L.; Owens, D.M.; Brenner, D.J. 207-nm UV Light A Promising Tool for Safe Low-Cost Reduction of Surgical Site Infections. II: In-Vivo Safety Studies. *PLoS ONE* **2016**, *11*, e0138418. [CrossRef] [PubMed]
4. Eadie, E.; Barnard, I.M.R.; Ibbotson, S.H.; Wood, K. Extreme Exposure to Filtered Far-UVC: A Case Study. *Photochem. Photobiol.* **2021**, *97*, 527–531. [CrossRef] [PubMed]
5. Sliney, D.H.; Stuck, B.E. A Need to Revise Human Exposure Limits for Ultraviolet UV-C Radiation. *Photochem. Photobiol.* **2021**, *97*, 485–492. [CrossRef]
6. Buonanno, M.; Welch, D.; Brenner, D.J. Exposure of Human Skin Models to KrCl Excimer Lamps: The Impact of Optical Filtering. *Photochem. Photobiol.* **2021**, *97*, 517–523. [CrossRef]
7. Welch, D.; De Muro, M.A.; Buonanno, M.; Brenner, D.J. Wavelength-dependent DNA Photodamage in a 3-D human Skin Model over the Far-UVC and Germicidal UVC Wavelength Ranges from 215 to 255 nm. *Photochem. Photobiol.* **2022**, *98*, 1167–1171. [CrossRef]
8. Welch, D.; Kleiman, N.J.; Arden, P.C.; Kuryla, C.L.; Buonanno, M.; Ponnaiya, B.; Wu, X.; Brenner, D.J. No Evidence of Induced Skin Cancer or Other Skin Abnormalities after Long-Term (66 week) Chronic Exposure to 222-nm Far-UVC Radiation. *Photochem. Photobiol.* **2022**, *99*, 168–175. [CrossRef]
9. Zwicker, P.; Schleusener, J.; Lohan, S.B.; Busch, L.; Sicher, C.; Einfeldt, S.; Kneissl, M.; Kühl, A.A.; Keck, C.M.; Witzel, C.; et al. Application of 233 nm far-UVC LEDs for eradication of MRSA and MSSA and risk assessment on skin models. *Sci. Rep.* **2022**, *12*, 2587. [CrossRef]
10. Hickerson, R.P.; Conneely, M.J.; Tsutsumi, S.K.H.; Wood, K.; Jackson, D.N.; Ibbotson, S.H.; Eadie, E. Minimal, superficial DNA damage in human skin from filtered far-ultraviolet C. *Br. J. Dermatol.* **2021**, *184*, 1197–1199. [CrossRef]
11. American Conference of Governmental Industrial Hygienists (ACGIH). *Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs): Based on the Documentation of the Threshold Limit Values for Chemical Substances and Physical Agents*; ACGIH Publications: Cincinnati, OH, USA, 2022.
12. Görlitz, M.; Justen, L.; Rochette, P.J.; Buonanno, M.; Welch, D.; Kleiman, N.J.; Eadie, E.; Kaidzu, S.; Bradshaw, W.J.; Javorsky, E.; et al. Assessing the safety of new germicidal far-UVC technologies. *Photochem. Photobiol.* **2023**, *100*, 501–520. [CrossRef] [PubMed]
13. *DIN 5031-10: 2018-03*; Strahlungsphysik im optischen Bereich und Lichttechnik_-Teil_10: Photobiologisch wirksame Strahlung, Größen, Kurzzeichen und Wirkungsspektren. Beuth Verlag GmbH: Berlin, Germany.
14. Malayeri, A.H.; Mohseni, M.; Cairns, B.; Bolton, J.R. Fluence (UV Dose) Required to Achieve Incremental Log Inactivation of Bacteria, Protozoa, Viruses and Algae. *IUVA News* **2016**, *2016*, 1–41.
15. Hessling, M.; Haag, R.; Sieber, N.; Vatter, P. The impact of far-UVC radiation (200–230 nm) on pathogens, cells, skin, and eyes-a collection and analysis of a hundred years of data. *GMS Hyg. Infect. Control* **2021**, *16*, Doc07. [CrossRef] [PubMed]
16. Gierke, A.-M.; Hessling, M. Investigation on Potential ESKAPE Surrogates for 222 and 254 nm Irradiation Experiments. *Front. Microbiol.* **2022**, *13*, 942708. [CrossRef] [PubMed]
17. Lu, Y.H.; Wang, R.X.; Liu, H.L.; Lai, A.C.K. Evaluating the Performance of UV Disinfection across the 222-365 nm Spectrum against Aerosolized Bacteria and Viruses. *Environ. Sci. Technol.* **2024**, *58*, 6868–6877. [CrossRef]
18. Sun, W.; Jing, Z.; Zhao, Z.; Yin, R.; Santoro, D.; Mao, T.; Lu, Z. Dose-Response Behavior of Pathogens and Surrogate Microorganisms across the Ultraviolet-C Spectrum: Inactivation Efficiencies, Action Spectra, and Mechanisms. *Environ. Sci. Technol.* **2023**, *57*, 10891–10900. [CrossRef]

19. Clauss, M.; Springorum, A.C.; Hartung, J. *Ultraviolet Disinfection with 222 nm Wavelength–New Options to Inactivate UV-Resistant Pathogens: XIV International Congress of the International Society for Animal Hygiene*; International Society for Animal Hygiene: Vechta, Germany, 2009.
20. O'mahoney, P.; Wood, K.; Ibbotson, S.H.; Eadie, E. Potential harm to the skin from unfiltered krypton chloride 'far-ultraviolet-C' lamps, even below an occupational exposure limit. *J. Radiol. Prot.* **2022**, *42*, 043501. [CrossRef]
21. Ivanova, I.; Svilenska, T.; Kurz, B.; Grobecker, S.; Maisch, T.; Berneburg, M.; Kamenisch, Y. Improved Spectral Purity of 222-nm Irradiation Eliminates Detectable Cyclobutylpyrimidine Dimers Formation in Skin Reconstructs even at High and Repetitive Disinfecting Doses. *Photochem. Photobiol.* **2022**, *98*, 1149–1156. [CrossRef]
22. Narita, K.; Asano, K.; Yamane, K.; Ohashi, H.; Igarashi, T.; Nakane, A. Effect of ultraviolet C emitted from KrCl excimer lamp with or without bandpass filter to mouse epidermis. *PLoS ONE* **2022**, *17*, e0267957. [CrossRef]
23. Tavares, R.S.N.; Adamoski, D.; Girasole, A.; Lima, E.N.; Da Justo-Junior, A.D.; Domingues, R.; Silveira, A.C.C.; Marques, R.E.; De Carvalho, M.; Ambrosio, A.L.B.; et al. Different biological effects of exposure to far-UVC (222 nm) and near-UVC (254 nm) irradiation. *J. Photochem. Photobiol. B Biol.* **2023**, *243*, 112713. [CrossRef]
24. Kaidzu, S.; Sugihara, K.; Sasaki, M.; Nishiaki, A.; Ohashi, H.; Igarashi, T.; Tanito, M. Re-Evaluation of Rat Corneal Damage by Short-Wavelength UV Revealed Extremely Less Hazardous Property of Far-UV-C. *Photochem. Photobiol.* **2021**, *97*, 505–516. [CrossRef] [PubMed]