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UVC excilamps as sources of virucidal and bactericidal radiation

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Aim

This review was stimulated by the coronavirus-19 epidemic in 2020.

The purpose of this brief review is to show the prospects for inactivation of various microorganisms using a relatively young class of radiation sources – excilamps. The word “excilamp" is a generic name for a class of devices that emit spontaneous ultraviolet and/or vacuum ultraviolet radiation of excimer and exciplex molecules.

A. M. Boichenko, V. F. Tarasenko, E. A. Fomin, and S. I. Yakovlenko, “Broadband emission continua in rare gases and in mixtures of rare gases with halides”, Quant. Electron., vol. 23, no. 1, pp. 3–25, Jan 1993.
B. Eliasson, and U. Kogelschatz, “UV excimer radiation from dielectric-barrier discharges,” Appl. Phys. B., vol. B46, pp. 299–303, Aug 1988.

In our review we give the general information about the effect of UV radiation on microorganisms, description of excilamps used for inactivation of microorganisms and a brief summary of the most important data on the bactericidal and virucidal effects of UV radiation excilamps on microorganisms that cause hospital-acquired infections, as well as microorganisms (viruses and bacteria) transmitted by airborne droplets.

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Inactivating effect of ultraviolet radiation on bacterial cells

Since the ability of ultraviolet radiation to inactivate (suppress) bacteria was discovered by A. Downes and T.P. Blunt in 1877, this optical factor has been widely used for disinfection of water, air and surfaces. The UV action on various biological objects is characterized by a significant variability in the effects and exposure intensity. However, until now, the use of UV is based on the knowledge gained in the last century. For the most effective use of UV, it is necessary to know what effect different UV wavelengths have on different biological objects. Such research should be interdisciplinary and based on the methodology of natural sciences.

In 1928, F. L. Gates acting with UV radiation on bacteria showed that the greatest inactivating effect is provided by the wavelengths corresponding to the optical spectrum of absorption of nucleic acids, i.e. mainly UV radiation ($200 < \lambda < 290$ nm). The sensitivity of bacteria to the spectral composition of UV radiation has been called the lethal spectrum of radiation, or simply the action spectrum. Clarifying measurements revealed that the absorption spectra of UV radiation by Escherichia coli bacterial culture and the absorption spectrum of DNA do not match (Fig.1).

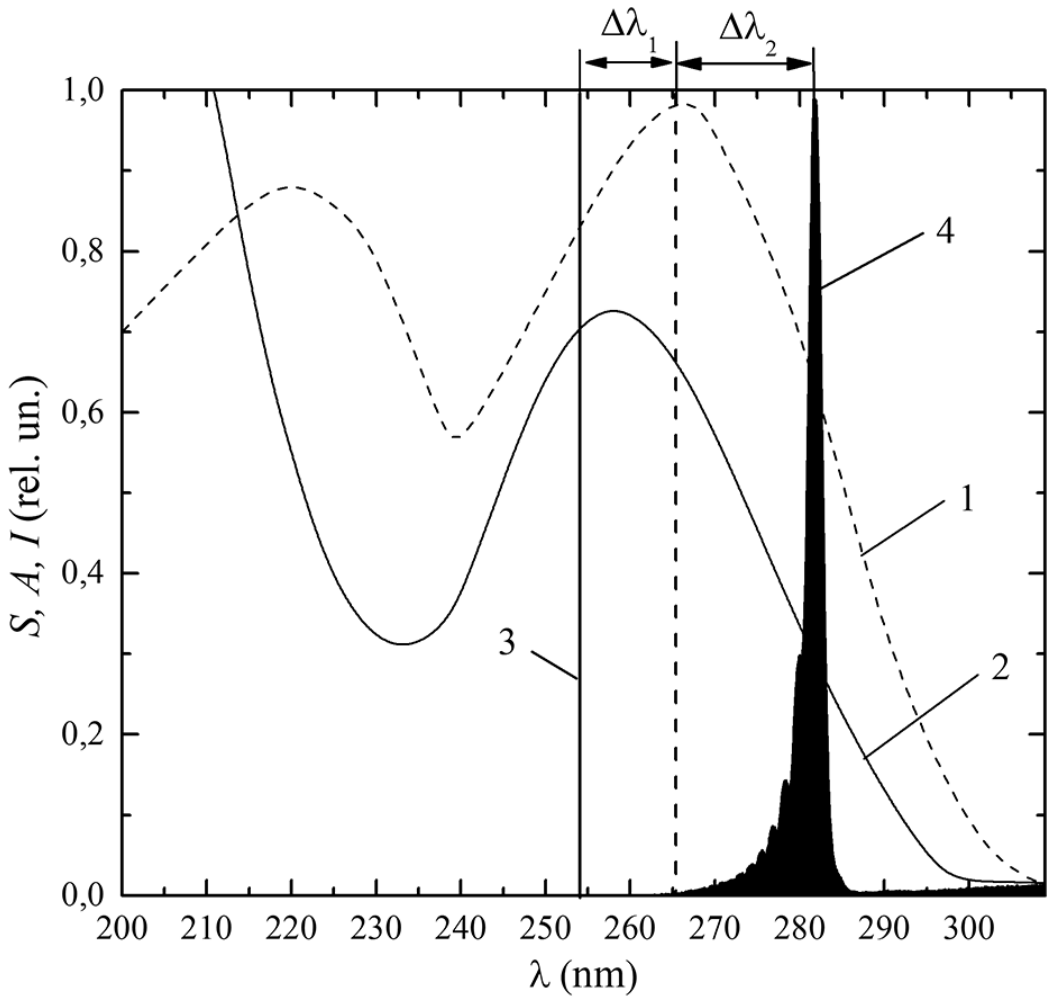

Fig. 1. Important spectral characteristics: 1 – action spectrum of UV radiation on E. Coli, 2 – spectrum of DNA absorption, 3 – intensive atomic line of low pressure mercury lamp (LPML) at λ = 253.7 nm; 4 – XeBr-excilamp radiation spectrum.

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UVC excilamps for inactivation of microorganisms

The BD_P (barrier discharge, portable) series are portable devices containing a coaxial barrier discharge excilamp placed in a casing and equipped with air-cooling and a reflector (Fig. 2, at the top). Such radiation sources have relatively small dimensions of 240 x 80 x 80 mm, an output window of 60 x 90 mm and a weight of 0.7-0.8 kg. In different years, our microbiological studies have used excilamps of this series on XeBr* (282 nm), KrCl* (222 nm), KrBr* (206 nm) and Cl2* (257.8 nm) molecules, providing radiant exitance up to 30, 20, 10 and 2 mW/cm2, respectively. By scaling the model in the direction of increasing the size, increasing the speed of air pumping through the device housing and closing the radiating surface, we obtained a powerful UVC air recirculator, which was tested in 2011. For indoor air irradiation (in the absence of people), it is more effective to use BD_E (barrier discharge, external) series. These are devices in which the excilamp is placed outside the power supply (Fig. 2, below). For improved antimicrobial air treatment, it may additionally contain an air injection unit located at the end of the lamp.

E.A. Sosnin, V.F. Tarasenko, S.A. Avdeev, D.V. Shitts, V.S. Skakun, Patent RU No. 62224, Priority 1.9.2007, publ. 5.27.2007, Bulletin of Inventions. No. 15.

Fig. 2. Design of two excilamp series developed at IHCE SB RAS: BD_P (above), BD_E (below).

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Inactivating effect of XeBr excilamp radiation on bacteria

Figure 1(4) shows the emission spectrum of an exciplex lamp on XeBr* molecules (BD_P model). In this case, at least 95% of the excilamp's radiant flux in the UV range is concentrated in the B→X band of the working molecule with a maximum at 282 nm and a half-width Δλ0.5 ~ 1.8 nm. In 2006, we noticed that the maximum intensity of The B→X band of the XeBr* molecule lies about the same distance from the maximum of the spectrum of action as the LPML resonance line, i.e. Δλ1 ≈ Δλ2. In addition, the excilamp spectrum has a short-wave "tail" in the wavelength range of 260-282 nm, which covers half of the first peak of DNA absorption and the spectrum of action. Therefore, we assumed that both radiation sources (XeBr-excilamp and LPML) should have the same inactivating efficacy. A subsequent test on the Escherichia coli bacterial culture (ATCC 25922) confirmed this hypothesis: both radiation sources provide a comparable bactericidal effect at the same exposure dose.

S.M. Avdeev, E.A. Sosnin, K.Yu. Velichevskaya, L.V. Lavrent'eva,, Proc. SPIE, vol. 6938, 693813, Feb 2008.

Subsequent studies of the comparative inactivating effect of LPML and XeBr-excilamp were performed on strains of pathogens of nosocomial infections, namely on cultures of *E. coli* (501), *Klebsiella pneumonia* (ATCC 2482), *S. aureus* (209P), as well as clinical isolates of *Proteus vulgaris*, *Pseudomonas aeruginosa* and *Candida albicans*. It has been shown that XeBr-excilamp radiation has a more pronounced bactericidal effect on gram-negative microorganisms (*E. coli*, *K. pneumonia*, *P. aeruginosa*) than LPML. Cultures of *S. aureus* and *C. albicans* demonstrated the same sensitivity to radiation from both radiation sources.

O.S. Zhdanova, E.A. Sosnin, E.P. Krasnoszhenov, V.F. Tarasenko, S.M. Avdeev, A.V. Gritsuta, Hospital infections agents sensitivity to XeBr excilamp irradiation, J. Infection Pathology, vol. 17, no. 3, pp. 62–64, 2010 (in Russian).

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Fig. 2. Design of two excilamp series developed at IHCE SB RAS: BD_P (above), BD_E (below).

Inactivating effect of KrBr excilamp radiation on bacteria

Another source of UVC radiation is a barrier discharge excilamp on a Kr-Br2 gas mixture, which is simply called as KrBr-excilamp. It emits two strong bands: B→X band of excited complex KrBr* (207 nm) and D'→A' band of excited dimer Br2* (291 nm) (Fig. 3). By varying the ratio of Kr and Br2 gases in the mixture, as well as the value of the total pressure, it is possible to obtain a radiation spectrum that would be as close as possible to the absorption spectrum of DNA (Fig. 1(2)). In 2004, a study of the bactericidal effect of such excilamp on Escherichia coli, *Staphylococcus aureus* and *Penicillium expansum* strains was conducted, including a comparison with action of XeBr-excilamp. The results showed a much more effective bactericidal effect of KrBr-excilamp radiation compared to XeBr-excilamp.

E.A. Sosnin, S.M. Avdeev, E.A. Kyznetsova, L.V. Lavrent'eva, A bactericidal barrier-discharge KrBr-excilamp // Instruments and experimental techniques, vol. 48, no. 5, pp. 663–666, Sep 2005.

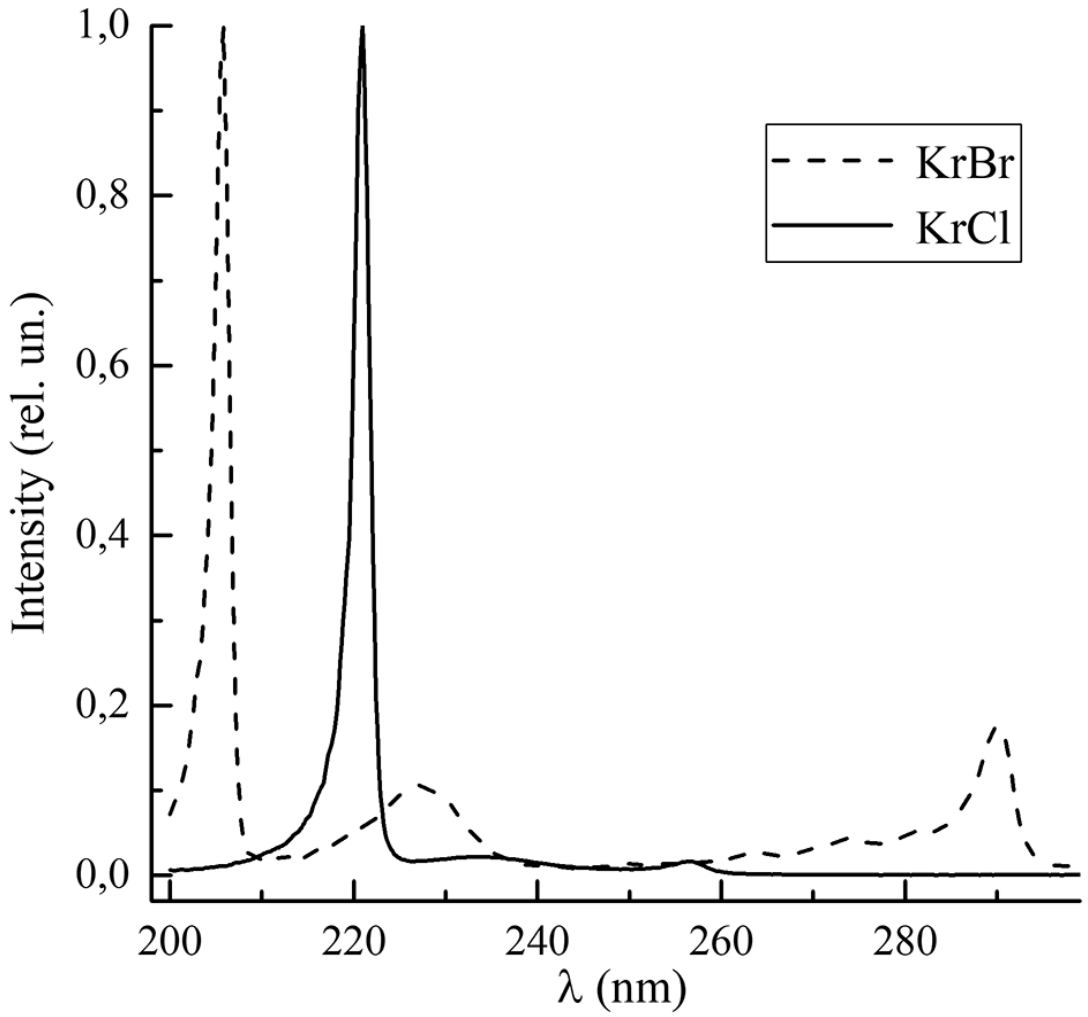

Fig. 3. Emission spectra of KrCl- and KrBr-excilamps.

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Inactivating effect of XeBr excilamp radiation on living cells

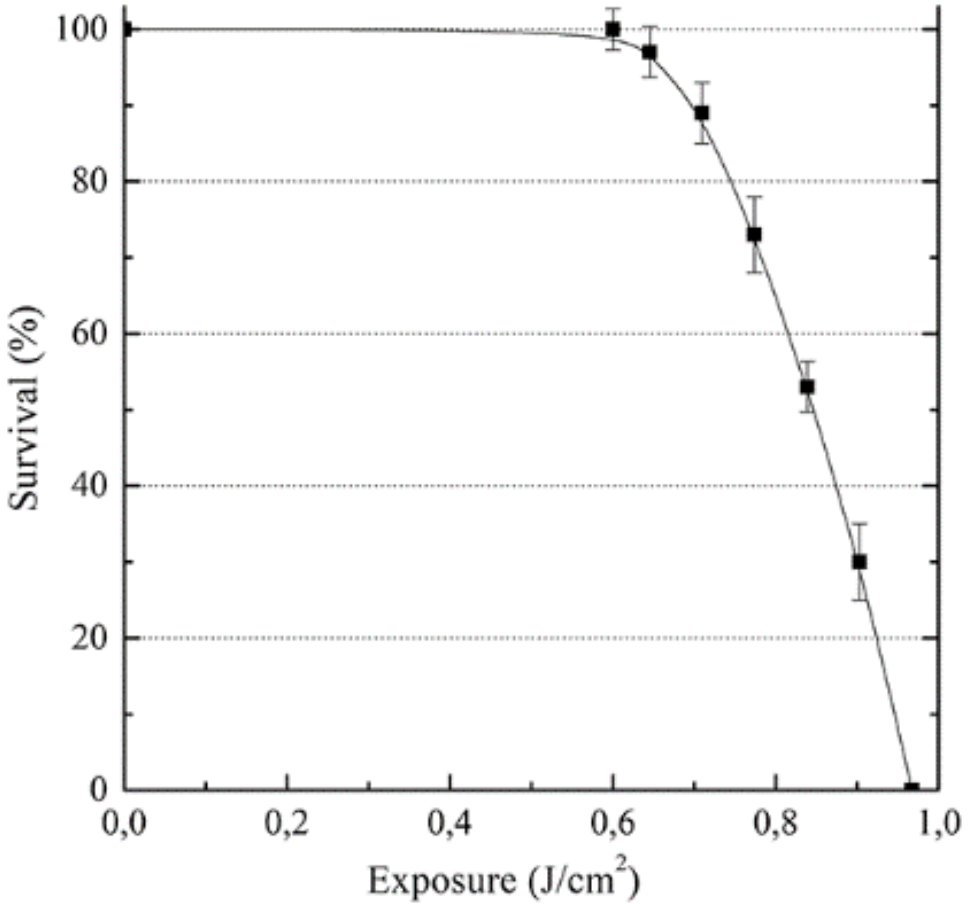

Fig. 4. Survival curve of CHO-K1 after XeBr excilamp radiation treatment.

In 2005 we studied the reaction of the *Chinese Hamster Ovary* (CHO-K1) live ovarian cell culture to the effects of XeBr-excilamp UV radiation. We found that the inactivating effect of UV radiation on a living cell is significantly different from antimicrobial action. The living cell's DNA is virtually undamaged by direct light. Damage occurs due to an indirect chain of transformations: 1) photon + substrate → radicals, 2) radicals + cell components (including DNA) → oxidation and inactivation of cell components. Inactivation is also complicated by the fact that the cell produces antioxidants and is able to regulate the rate of their formation in its internal environment. Highly likely, at high UV radiation doses, the cell responds by increasing the formation of glutathione, until all its internal energy sources for this protective reaction are exhausted. Consequently, the dependence of the degree of inactivation of CHO-K1 living cells on the surface radiation dose has a threshold effect (fig. 4).

From a practical point of view, this means that UV radiation can become a method of selective bacterial sterilization of wounds without inactivating living cells of the body.

M.V. Erofeev, I.E. Kieft, E.A. Sosnin, E. Stoffels, UV excimer lamp irradiation of fibroblasts: the influence on antioxidant homeostasis // IEEE Transactions on Plasma Science, vol. 34, no. 4, pp. 1359–1364, 2006.

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Inactivating effect of XeBr excilamp radiation on bacteriophage

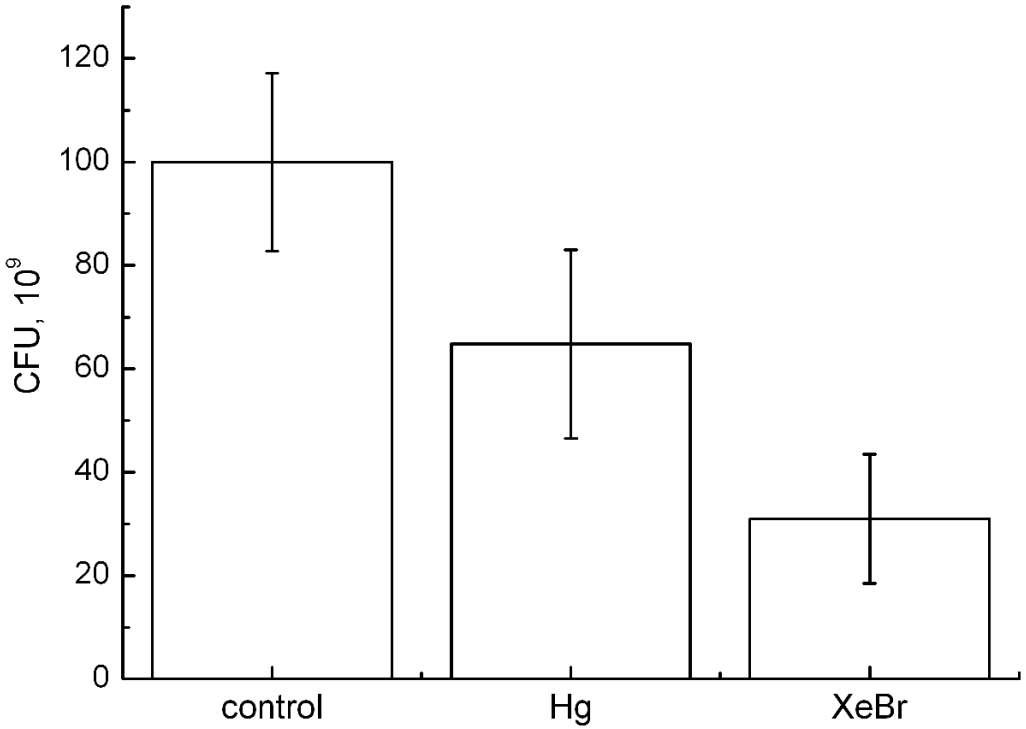

Fig. 5. Sensitivity of MS2 bacteriophage to UV radiation of XeBr excilamp and LP Hg-lamp at the same UV doses (45 J/m2) compared with control.

In 2011 we used the MS2 bacteriophage (VKPM PH-1505 strain) parturiating on *E. coli* culture K 12 F+ (VKPM B-3254 strain) to compare the virucidal effect of UV radiation from LPML and XeBr-excilamp. It was shown that UV radiation from both sources effectively inactivate the MS2 bacteriophage, but its sensitivity to the action of XeBr-excilamp UV radiation was higher (fig. 5). From an optical point of view, this can be explained by the fact that its radiation spectrum (Fig. 1(3)) includes the wavelengths at which proteins are actively absorbed, in particular amino acids with a rigid structure (tryptophan, tyrosine and phenylalanine) and nucleic acids. Therefore, we assumed that the resulting effect is due to damage to the proteins that form the phage envelope as well as damage to the RNA of the bacteriophage.

O.S. Zhdanova, E.P. Krasnoszhenov, E.A. Sosnin, S.M. et al., The effect of narrow-band UV radiation from an exciplex lamp on the functionalization of the MS2 bacteriophage // Bulletin of Siberian science, no. 1(2), pp. 328–332, 2012.

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UV action specta for viruses

The use of bacteriophages for safe testing of radiation sources instead of original viral organisms is a common practice.

G. Ronto, S. Gaspar, A. Berces // J. Photochem. Photobiol. B-Biol., vol. 12, no. 3, pp. 285–294, 1992.

The precise characteristics of UV radiation action spectra for a number of bacteriophages, as well as for the pathogen of a parasitic disease related to eukaryotes *C. parvum* are presented on Figure 6.

We can see, that the best inactivation of viruses (in comparison with LPML) will be provided by sources of UV radiation, the spectrum of which is concentrated in the wavelength range of $200 < \lambda < 240$ nm. Such sources are excilamps on the KrBr* and KrCl* molecules, whose radiation spectra are shown in Fig. 3. It can be seen that both lamps have an intense B→X band with a maximum at 207 and 222 nm, and a half-width of 2.18 and 2.04 nm, respectively.

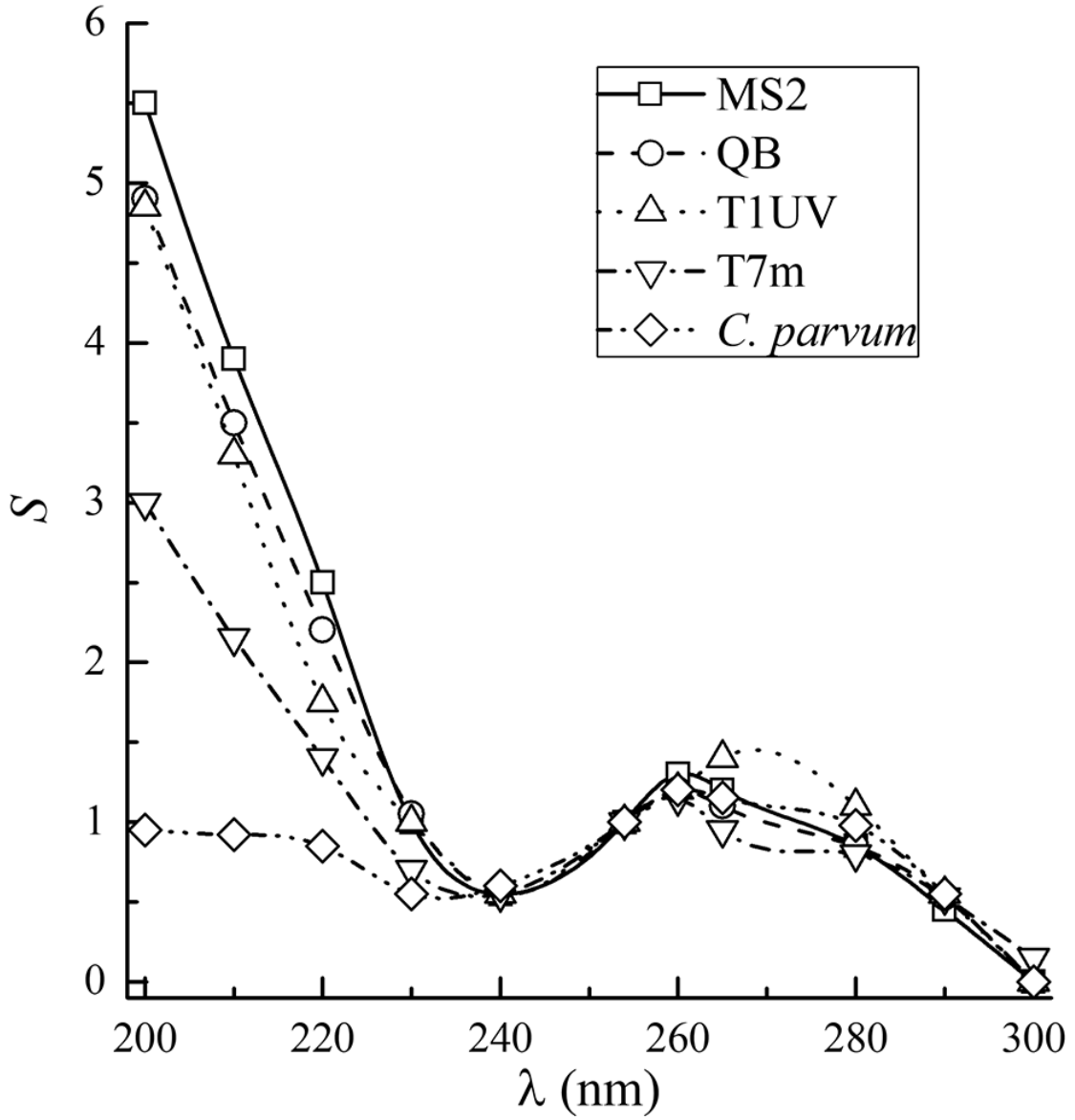

Fig. 6. Action spectra for MS2, QB, T1UV, T7m and *C. parvum* (recovered from data [S.E. Beck, H.B. Wright, T.M. Hargy, et al. // Water Res., vol. 70, pp. 27–37, 2015.]). The points for 200 and 300 nm are obtained by extrapolation.

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Inactivating effect of KrBr excilamp radiation on H1N1 virus

As we mentioned above, such light sources can be used for selective treatment of human skin, since living cells of the human body are less sensitive to UV radiation than viruses and bacteria. This thesis was verified in 2015 at the Center for Radiological Research (Columbia University Irving Medical Center, New York, USA) using the KrCl- and KrBr-excilamps (BD_P model) that we developed.

It was shown that relatively low doses of the short-wave UVC radiation ($200 < \lambda < 228$ nm) effectively inactivated bacteria and viruses without damaging mammalian skin cells (Fig. 7). In addition, recent studies have shown that ultraviolet KrCl-excilamp (BD_P model) at doses of 2 mJ/cm2 inactivates more than 95% of the H1N1 influenza virus in the form of an aerosol and concluded that this excilamp is a promising, safe and inexpensive tool for controlling the spread of infectious diseases transmitted by airborne droplets.

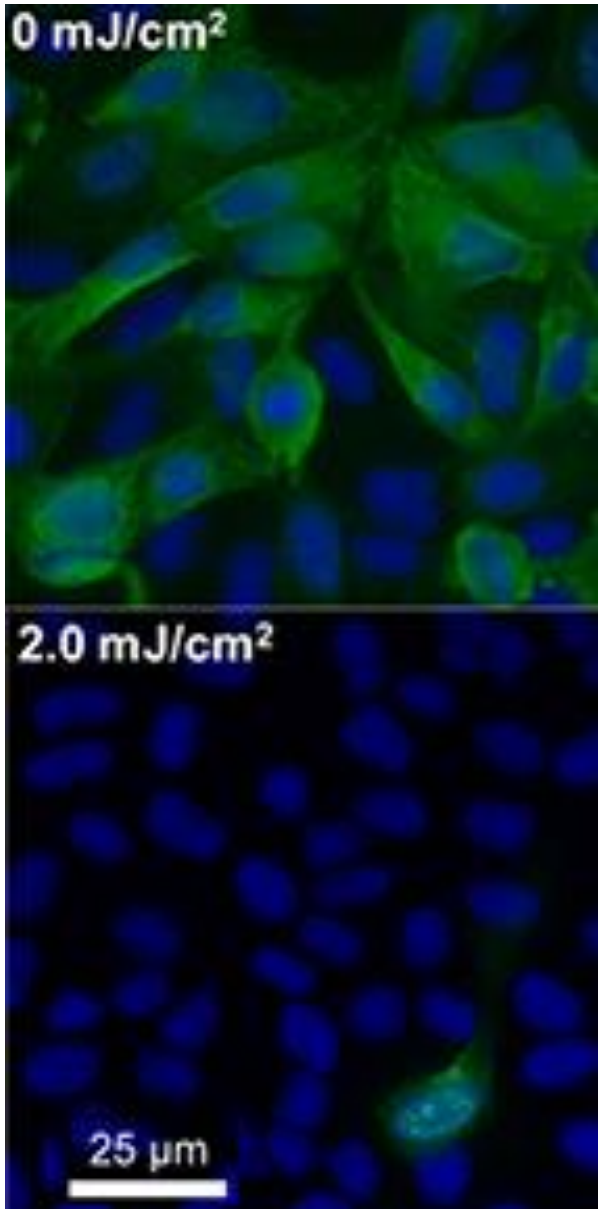

Fig. 7. Antiviral efficacy of different low doses of KrCl radiation. Typical fluorescent images of MDCK epithelial cells infected with H1N1 virus. The viruses were exposed in aerosolized form in the irradiation chamber to doses of 0, 0.8, 1.3 or 2.0 mJ/cm2 of 222-nm far-UVC light. Infected cells fluoresce green [D. Welch, M. Buonanno, V. Grilj, et al. // Sci. Rep., vol. 8, 2752, 2018.**].**

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Inactivating effect of KrBr excilamp radiation on coronaviruses

In 2020, during the COVID-19 outbreak, this scientific group proved that KrCl-excilamp radiation (BD_P model) is effective against two human coronaviruses (HCoV-229E and HCoV-OC43). The authors conclude that in public locations at the currently recommended exposure limit (3 mJ/cm2/hour) would result in 99.9% viral inactivation in ~ 25 minutes. They also noticed that as all human coronaviruses have similar genomic size it is reason to expect that KrCl-excilamps will be comparable inactivation efficiency against other human coronaviruses, for example SARS-CoV-2. Thus, short-wave excilamps give us a new opportunity to prevent the spread of viruses before they enter the human body.

Buonanno, M., Welch, D., Shuryak, I. et al. Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. Sci Rep 10, 10285 (2020).

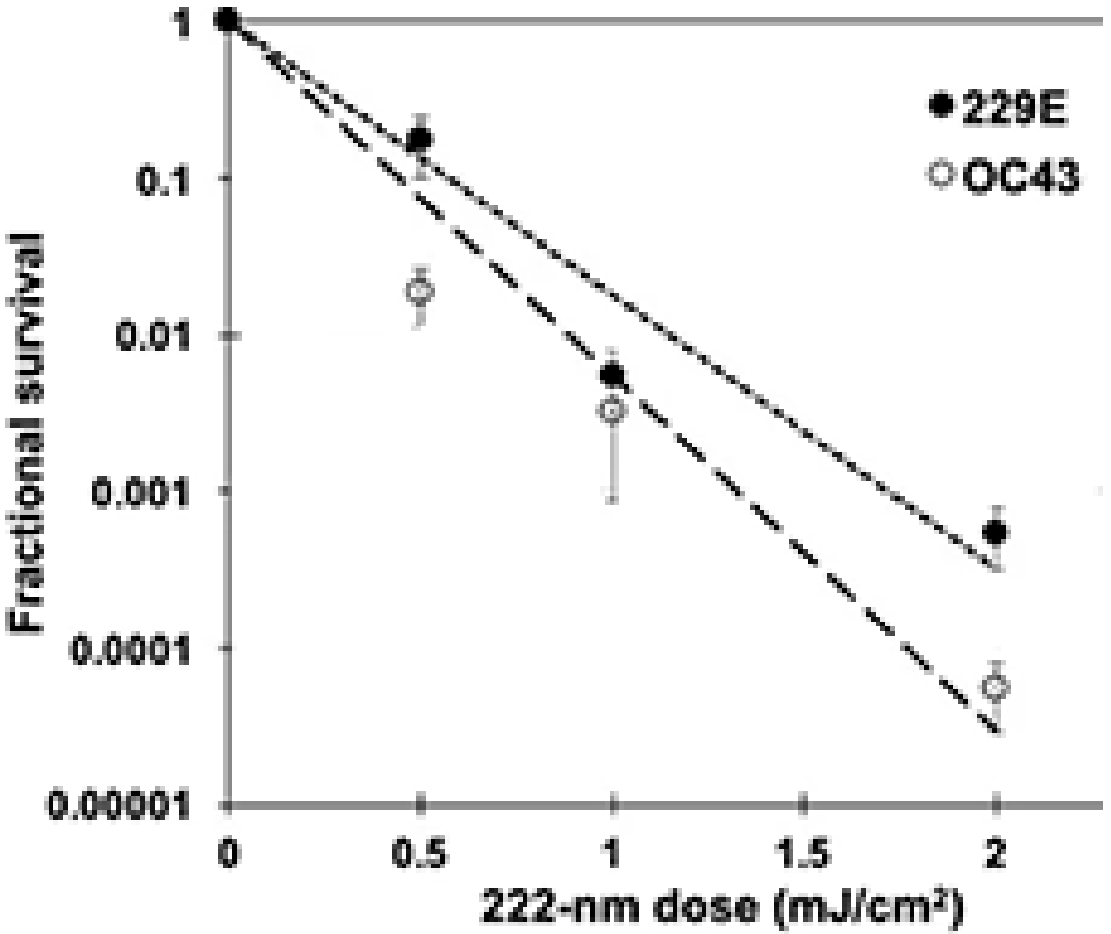

Fig. 8. Coronavirus survival as function of the dose of far-UVC light. [Buonanno, M., Welch, D., Shuryak, I. et al. Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. Sci Rep 10, 10285 (2020). **].**

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Conclusion

So, the known and new scientific data on the optical and biological parameters of microorganisms allow us to conclude what radiation sources can become an alternative to the classic low pressure mercury lamps. To date the bactericidal effect of KrCl-, KrBr- and XeBr-excilamps has been proven. In addition, the available data suggest that KrCl- and KrBr-excilamps are promising for obtaining a virucidal effect that is more strong than that of low pressure mercury lamps.

All this is a scientific basis for setting up new **advanced inactivation technologies**.

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