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Specific Features of Application of Pulsed Xenon UV Irradiators

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Abstract—The analysis of technologies for ultraviolet (UV) disinfection of air and premises showed a transition to UV lamps with a high mean power (1–2 kW). The effectiveness of disinfection with a pulsed xenon source is fully determined by the classical disinfection effect and the UV dose.

Keywords: UV radiation, disinfection, air, pulsed xenon lamps

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Application of UV radiation for disinfection has shown its high efficiency for a century [1–4], so that the method is constantly being improved and the conditions under which certain UV doses are needed for different microorganisms are also being studied. The use of classical chemical disinfectants leads to high risks related to the human factor, additional chemical load on people, and a long time of surface drying [5, 6]. The physical method of disinfection using UV radiation employs irreversible changes in the biological structures of bacterial cells and virions. For a long time, disinfection of air and surfaces was performed with the aid of low-power UV lamps and recirculators that provide a recommended UV dose of 6.6 mJ/cm^2 for radiation with a wavelength of 254 nm, which is necessary for inactivation of *Staphylococcus aureus* by 99.9% [7]. However, practical applications have shown that higher UV doses are needed for disinfection of the premises of medical organizations and public places. Industrialized countries show a tendency toward an increase in the standard UV doses for air and surface disinfection. Such a situation is similar to the evolution of the method of UV disinfection of drinking water [2], when a standard UV dose of 8 mJ/cm^2 was adopted and, then increased to 16, 25, and even 40 mJ/cm^2 for several types of surface waters due to discovery of new pathogens and an increase in the degree of disinfection. At present, the disinfection of drinking water at high UV doses causes no doubts. The world leading institutions and authorized certification centers (ONORM, DWGW, USEPA, etc.) have strictly defined the requirements and conditions for the use, certification, and validation of equipment for various technological tasks of water disinfection.

Disinfection of air and surfaces, especially, in medical organizations, must be performed with allowance for the existence of pathogenic microorganisms that are much more resistant to UV radiation in comparison with *Staphylococcus aureus*. Pathogens that are resistant to drugs and chemical disinfectants (superbugs), for example, the MRSA strain of *Staphylococcus aureus*, resistant to methicillin, and the VRE strain of *Enterococcus*, resistant to vancomycin, are also an urgent problem. In the United States, 1.7 million patients become ill with healthcare-associated infections (HCAIs) each year, of which 98 000 die (one of 17) [8]. In Europe, HCAIs affect approximately 7% of patients, i.e., about 4 million people [9]. Financial losses are estimated at 7 billion euros for Europe [9] and about $28.4 billion for the US (https://www.cdc.gov/policy/polaris/healthtopics/hai/index.html).

The emergence of new pathogens often necessitates an increase in UV dose. For example, the International Ultraviolet Association IUVA recommends a UV dose of 20 mJ/cm^2 (https://iuva.org/iuva-covid-19-faq) for the 99.9% inactivation of the SARS-CoV-2 coronavirus that caused the COVID-19 pandemic. In Russia, a UV dose of 25 mJ/cm^2 is recommended [10] for this purpose. At the same time, it is necessary to understand and take into account that HCAIs are still among the main problems, since patients who are ill or have had coronavirus are more susceptible to such infections.

For fungal spores, UV doses are an order of magnitude or more higher than the UV doses for inactivation of most microbes [1, 2, 7], so that a standard dose of 6.6 mJ/cm^2 needed for the disinfection by three orders of magnitude for *Staphylococcus aureus* is insufficient for inactivation of fungal spores even by one order.

Evidently, an increase in the power of the UV lamps is needed for an increase in the UV dose. Another important factor for practice that forces the use of high-power UV equipment is related to a decrease in the duration of the disinfection process (preferably, to 5–10 min), which is needed for a decrease in the time the room is not used for intended purpose.

At present, world leading manufacturers develop and offer open UV devices on mercury and amalgam lamps with a radiation wavelength of 254 nm and a power of up to 1–3 kW (with indication of the UV irradiation at a certain distance (usually, 1 m)). The irradiation time for most rooms is 3–10 minutes. The devices with such a mean electric power are able to reduce most pathogens by 5–6 orders of magnitude, which is necessary for special medical premises. Such complicated devices are usually equipped with remote activation and control systems and even a laptop computer.

One of the options for the development of high-power UV devices is the use of a large number of low-power low-pressure mercury lamps (up to 32 lamps in one device). Tru-D SmartUVC (USA), Steris (USA), Darlek UV Clean (UK), Finsen Tech (UK), UVD Robots (Denmark), UVC Solutions (Slovenia) are examples of such devices. Such an approach provides a sufficiently high irradiance but reduces the efficiency of the UV lamps, since the UV radiation is partially absorbed by the structural elements of the device and the bulbs of other lamps. Routine maintenance becomes difficult due to the large number of lamps.

It is much more efficient to use few (up to four) high-power UV lamps, in particular, amalgam lamps with a power of 300–900 W at a radiation wavelength of 254 nm and a high (30–35%) efficiency of conversion of electrical energy into bactericidal UV radiation and a working time of 8–16 kh. For example, a SVETOLIT-600 UV device (https://www.lit-uv.ru/) has an electric power of 2 kW and employs four Surfacide Helios amalgam lamps (https://www.surfacide.com/).

We may expect an increase in the power, working time, and the number of on-off cycles for the UV lamps in irradiators, since short-term operation is not typical of most industrial high-power lamps.

It should be re-emphasized that the UV doses globally increase due to an increase in the mean power of UV sources rather than an increase in exposure time. In this regard, it is expedient to reconsider the method of disinfection using cw UV radiation of pulsed xenon lamps. Manufacturers of such equipment in Russia (https://melitta-uv.ru/) compare the high pulse power with the mean power of a mercury UV lamp and indicate an unrealistically high disinfection efficiency promising that the pulsed method will be effective up to distances of 20–30 m. In this case, parameters pulse power, mean power, and UV radiation flux are misinterpreted.

A. Wekhof, who discovered the disinfection effect of pulsed UV radiation [11, 12], clearly indicated two different effects that provide disinfection by high-power pulsed UV radiation: (i) the classical effect of the UV-C irradiation in a wavelength interval of 200–300 nm depending on the UV dose and (ii) cell damage due to overheating caused by the absorption of the UV-A, UV-B, and UV-C radiation.

He also found out that the second effect (overheating leading to cell damage) is efficient only at high irradiances (above 5 kW/cm^2). Knowing the radiative characteristics of a UV lamp, one can easily calculate the irradiance at a certain distance. For pulsed UV lamps used in industrial UV irradiators, the effective distance for the overheating is limited to a few tens of centimeters, and only the classic UV-C effect works at distances of greater than 50 cm. The results of [13, 14] also show that the thermal damage is observed only at short distances (10–20 cm).

In subsequent works, A. Wekhof pointed out that the pulsed disinfection is an order of magnitude more expensive in comparison with rapid disinfection using mercury UV lamps with respect to basic equipment and operation [15].

For disinfection of rooms, the distances to the irradiated surfaces are often greater than 2 m, so that a pulsed xenon irradiator will implement the classical effect, in which the disinfection efficiency depends only on the UV dose. Comparative testing of the Xenex devices with pulsed xenon lamps and Tru-D devices with mercury lamps was carried out in the USA [16]. The disinfection efficiency at a distance of 1.2 m for the pulsed device with the xenon lamps was lower and was determined by the UV dose rather than the pulse power.

The website of the manufacturer of pulsed irradiators with xenon lamps (Melitta company) (https://melitta-uv.ru/) informs that, for the Alfa-06 device with an electric power of 1.5 kW and a power supply of the lamp of 1 kW, the time of surface disinfection at a distance of 2 m is 5–7 minutes (in particular, an exposure time of 4.5 minutes is required for a degree of disinfection of 99.99% for the SARS-CoV-2 virus). According to https://melitta-uv.ru/media/articles/evaluation-of-pulsed-xenon-ultraviolet-irradiation-of-continuous-spectrum-for-efficacy-against-multi/, the lamp with a power supply of 1 kW provides a UV radiation flux of 42 W and an irradiance of 1 W/m^2 at a distance of 2 m. Thus, the lamp has a very low efficiency of the conversion of electric energy into UV radiation (only 4.2%). For pulsed xenon lamps, most manufacturers indicate a higher flux of UV radiation of no less than 15% and a bactericidal UV dose (taking into account the spectral efficiency of exposure) of approximately 11%. The calculations show that, for a 5-min work of the irradiator in the experiment, the UV dose at a distance of 2 m is greater than 25 mJ/cm^2, which is significantly higher than the UV doses indicated in the R 3.5.1904-04 Russian guideline for the disinfection by 99.9% for *Staphylococcus aureus* (6.6 mJ/m^2) and *Pseudomonas Aeruginosa* (10.5 mJ/m^2). Such a UV dose is also in agreement with the IUVA and Russian MOH recommendations for the SARS-CoV-2. Thus, the indicated disinfection efficiency for the pulsed xenon source is completely determined by the classical disinfection effect (UV dose).

The efficiency of generation of the UV-C radiation by a pulsed xenon lamp is 3–5 times less than that of low-pressure mercury and amalgam lamps with the same mean electric power, and, hence, the UV dose will be less by the same factor. Note that the price of pulsed irradiators is several times higher, and the time of continuous operation until the lamp is replaced is several times less.

An urgent problem for the use of pulsed xenon lamps is the formation of ozone, since the continuous spectrum of radiation extends to the region of wavelengths of less than 200 nm. Modern amalgam and mercury UV lamps cannot generate ozone owing to the use of specific quartz. Therefore, pulsed UV radiation must be used with monitoring of the ozone concentration in the room after disinfection and ozone removal when its concentration exceeds the MPC. The results and conclusions published on the aforementioned Melitta website show that the use of the Alfa-06 or Yanex-2 irradiators for time intervals needed for effective disinfection with respect to clinical strains of bacteria with multidrug resistance and resistance to various groups of chemical disinfectants and various viruses leads to ozone concentrations in the disinfected room that exceed the MPC of the working area. After pulsed UV irradiation, the ozone concentration in the room must be decreased to an allowed level. The classical and only really applicable method is ventilation with either street air (which is not allowed according to modern standards for medical organizations) or air from the supply ventilation. And the question immediately arises: why do we disinfect the air in the room, if it will then be replaced by air of unknown quality? Another important factor is the time that is needed for ventilation of the room, which will be much longer than the time to irradiate the room.

Note the importance of certification of UV irradiators. Leading manufacturers have already begun to indicate UV exposure at a distance of 1 m or several distances from the irradiator. Foreign experts discuss the certification of equipment taking into account specific applications, measurement and certification methods, and creation of certification centers. Such problems are also important for Russia, since the characteristics of most commercially available irradiators in Russia are either not indicated, or the reliability of the data provided is not confirmed.

The concluding remarks are as follows.

(i) A worldwide tendency is a transition to UV irradiators with a high mean power (1–2 kW), which provide a high UV dose and a high degree of disinfection for a wide range of microorganisms at short working times (5–10 min).

(ii) Pulsed UV devices also have a high mean power (1 kW), which makes it possible to provide the required high doses. However, the UV flux from pulsed irradiators is 3–5 times less than that from mercury irradiators with the same mean power, and the price of the former is several times higher. Apparently, this is the main reason for rare use of pulsed UV irradiators for disinfection of premises; to the best of our knowledge, only two companies in the world produce such equipment.

(iii) A UV irradiator must be chosen with allowance for effective UV doses specified in the current regulatory documents (e.g., R 3.5.1904-04 guideline). Note that the UV dose must be chosen for the most stable (resistant) microorganism that can be found in a room rather than rated *Staphylococcus aureus*. One can use a base dose of 25 mJ/cm^2, which is sufficient for disinfection against various HCAIs and the SARS-CoV-2 coronavirus.

CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest.

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