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Original Research Article

Disinfection as a factor reducing microbial threat at workposts in museum and library - a comparison of the effectiveness of photocatalytic ionization, UV irradiation and chemical misting

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A B S T R A C T

More often have been shown that conservators, museum workers, librarians, archivists are workers groups who can be exposed to harmful biological factors at the workposts. The aim of study was to determine the effectiveness of three disinfection methods: continuous - photocatalytic ionization, UV irradiation and periodical - chemical misting with quaternary ammonium salt (QACs) in library and museum storage areas. The experiments included disinfection, quantitative and qualitative microbiological assessment of the air and surfaces prior, during and following disinfection. Disinfection was carried out using FreshAir purifiers, MEDIVENT flow lamps, Mgła-E TURBO electrical sprayer. Air was sampled with MAS-100 Eco Air Sampler, surface using contact plates Envirocheck®. Microorganisms number was determined by culture method. Identification was performed by microscopic method (molds) and biochemical tests (bacteria, yeasts). Photocatalytic ionization and UV irradiation were found to be highly effective in reducing the microbes number. Chemical disinfection was characterized by lower effectiveness, but it was found to be superior in molds elimination, especially those resistant to other methods. The minimum process effectiveness duration of photocatalytic ionization and UV irradiation was 2 or 3 days at continuous mode, while for QACs disinfection, up to 1 day. Disinfection methods efficiently eliminated pathogenic microorganisms from storage areas.

Keywords

Microorganisms; Workposts; disinfection; photocatalytic ionization; UV irradiation; chemical misting.

Introduction

Previous studies have shown that conservators, museum workers, librarians, and archivists constitute a group of workers that may be exposed to noxious biological factors at the workpost (Zielińska - Jankiewicz et al. 2008; Wiszniewska et al. 2009; Karbowska - Berent et al. 2011). High numbers of airborne microbes in such places have been observed in storage areas and conservator's workshops.

In these environments, the sources of microorganisms include technical

materials contaminated by microorganisms, e.g., paper, fabrics, wood, and leather. Many microbes contribute to degradation of historical objects and archival materials. Examples of biodeterioration include weakening or loosening of paper, books overgrown with fungi and foxing, mostly appearing in the form of loss of structure, discoloration on the surface and the presence of filamentous fungi and slimy substances (Mandrioli et al. 2003; Strzelczyk 2004; Sterflinger 2010).

Due to the high susceptibility of the materials in question to microbial growth, in the storage areas of libraries and museums certain precautions should be taken, such as limited lighting, low temperature (16–18°C), and relative humidity in the range of 40–50% (Nyuksha 1979; ISO 11799:2003). However, it is often impossible to comply with these requirements, especially those concerning the microclimate, due to the location of storage areas, which are often situated in cellars, are not properly insulated from the ground, and lack ventilation. The presence of dust contamination in the form of organic material additionally contributes to the growth of microorganisms.

Work with materials contaminated by microorganisms may affect the health of the personnel. Indeed, the occupational diseases of this group of workers include allergies, upper respiratory tract infections, dermatoses, and other disorders linked to the presence of fungi in buildings, such as SBS (Sick Building Syndrome) and mycoses (Flannigan 1989; Wiszniewska et al. 2009; Singh et al. 2010). Therefore, it is essential to both provide personal protection to the staff at the workpost and maintain hygiene of the storage areas. In practice, such areas are not disinfected.

The use of UV irradiation for effective elimination of microorganisms from hospital and laboratory environments is well known (Beggs and Sleigh 2002). The UV flow lamps manufactured these days can be safely used in the presence of personnel because generated UV radiation is completely contained within the device.

Food, cosmetic, pharmaceutical, and biotechnological plants use chemical misting for disinfection. Quaternary ammonium compounds (QACs) are widely employed as they exhibit strong antimicrobial properties, are readily soluble in water, do not destroy the disinfected surfaces, and are highly efficient. The chemical preparations are sprayed in the absence of humans; due to the small size of droplets (5–50 μm), the mist is highly penetrating for the air in disinfected rooms (Carson et al. 2008; Manivannan 2008).

Numerous studies have been devoted to the use of the photocatalytic ionization method for purification of water, filters, and air in office and commercial buildings (Fujishima and Zhang 2006; Pietrzak and Gutarowska 2013). This method is based on producing reactive oxygen species, which inactivate microbial cells (Greist et al. 2002; Dalrymple et al. 2010).

The above-mentioned methods may be used for the sanitation of museum and library storage areas. However, the effectiveness of these methods should be examined at such workposts due to the special conditions and types of microflora.

The objective of this work was to determine the effectiveness of three disinfection methods – two continuous (photocatalytic ionization and UV irradiation) and one periodical method

(chemical misting with QACs) in library and museum storage areas. The experiments included disinfection as well as quantitative and qualitative microbiological assessment of the air and surfaces prior to, during, and following the process of disinfection (depending on the method used).

Materials and Methods

Description of museum and library storage rooms

Experiments were conducted in 1 museum and 1 library room. The museum storage room had a volume of 220 m^3 and mainly stored flags, banners, and historical documents, while the library storage room had a volume of 68 m^3 and stored popular science books and magazines. The rooms were not equipped with a ventilation system, and molds were observed on some stored objects.

Temperature and humidity in the tested rooms were determined using a PWT-401 hygrometer (Elmetron, Poland).

Disinfection

Disinfection was carried out by three methods at about 1 month intervals. All equipment used for disinfection was safety certified by producers.

The first process was conducted using FreshAir purifiers (Vollara, USA) employing the photocatalytic ionization method with a wavelength 254 nm, capacity of 235 m^3/h. The purifiers were used in a 24 h mode. Two purifiers were used in the museum, and one in the library; they were placed in the central part of the rooms. In the museum, two devices afforded 2 air changes per hour, while in the library the one device afforded 3 air changes per hour. Prior to starting the purifiers, reference samples were taken, and subsequently experimental samples were collected after 2, 3, and 7 days of continuous purification.

Subsequent disinfection was conducted using UV flow lamps (Medivent, Poland), with a wavelength 254 nm, capacity of 150 m^3/h each, operating in a 24 h mode. The lamps were placed on stands distributed evenly in the rooms (3 lamps in the museum and 1 in the library). The capacity of the lamps ensured 2 air changes per hour in the museum and in the library. Prior to turning the lamps on, a reference sample was taken (t=0). Experimental samples were collected after 2, 3, and 7 days of continuous purification.

To ascertain whether ozone was emitted to the air during the processes of photocatalytic ionization and UV irradiation, ozone concentration was measured with an S-200 meter (Aeroqual, New Zealand) with a limit of detection of 0.001 ppm.

Chemical misting disinfection was conducted using a Mgła-E TURBO electrical sprayer (Poltech sp. z o.o., Poland) with a capacity of 60 L/h in the library, and an Igeba TF 35 thermal sprayer (DEZ DER, Poland) with a capacity of 30 L/h in the museum. The size of the droplets produced was 0.5–50 µm. The chemical used for disinfection was based on quaternary ammonium salts with the main component being N,N,n,n-didecyl-N,N-dimethylammonium chloride [CAS 7173-51-5]. The preparation had a concentration of 1 g/m^3. The sprayers worked for 20 min. Samples for analysis of microbiological contamination of the air and surfaces in the storage rooms were

collected prior to disinfection (t=0) as well as on day 1, 3, and 5 following it.

Determination of microbiological contamination of the air and surfaces

Microbiological contamination of the air was determined using an MAS-100 Eco Air Sampler (Merck, Germany) with 100 L/min flow rate calibrated by producer. Samples of 50 L and 100 L of air were taken during 30 sec. and 60 sec. Air samples were collected on MEA medium (Malt Extract Agar, Merck, Germany) with chloramphenicol (0.1%) and on DG18 medium (Dichloran 18% Glycerol Agar, Oxoid, UK) for fungi (including hydrophilic and xerophilous strains), and on TSA medium (Tryptic Soy Agar, Merck, Germany) with nystatin (0.2%) for bacteria. Surface samples were collected using Envirocheck® Contact Plates (Merck, Germany) with an area 25 cm^2 with TSA medium containing neutralizers (bacteria) or with Sabouraud medium (fungi) by manually presses against a surface for 10 sec. Air and surface samples were taken in 6 repetitions for each tested day.

The samples were incubated at 30±2°C (bacteria) for 48 h and at 27±2°C (fungi) for 5–7 days, and after disinfection for 14 days to allow for cell regeneration. After incubation, colonies were counted and expressed as CFU/m^3 (air) or CFU/100 cm^2 (surfaces). The final results are the arithmetic means of all repetitions.

Identification of microorganisms

Following microbial isolation, the dominant microorganisms (collectively accounting for more than 70% of all the isolated microorganisms) were identified. The bacteria were identified by examination of macroscopic features (color, texture, size, dyes), Gram staining, catalase testing, oxidase testing (Bactident Oxidase, Merck, Germany), and by the following API tests (bioMérieux, France): 50 CH, STAPH, 20 E, and 20 NE. Mold identification was performed on MEA and Czapek–Dox Agar medium (Difco, USA) based on micro- and macroscopic examinations, and using taxonomic keys (Klich 2002; Frisvad and Samson 2004; Pitt and Hocking 2009; Bensch et al. 2010).

Mathematical calculations

The reduction in the microorganisms number after the disinfection *R* (%) was determined using the preparation:

$$R = \left[\left(N_0 - N_t \right) / N_0 \right] \times 100\% \qquad (1)$$

where:

N_0 - number of microorganisms before the disinfection (CFU/m^3 or CFU/100cm^2);

N_t – number of microorganisms in *n* days after the disinfection (CFU/m^3 or CFU/100cm^2).

Results and Discussion

The studied museum and library rooms were found to have a relative humidity of 53–65%, an air temperature of 15–22°C (Table 1).

The number of microorganisms in the library air prior to the process of disinfection (t=0) was 3.0×10^2–6.9×10^2 CFU/m^3 with the prevalent group being fungi (1.7×10^2–5.0×10^2 CFU/m^3). The number of microbes in the museum air

was much higher as the total microbial count was 5.4×10^2–4.0×10^4 CFU/m^3, with fungi amounting to 2.6×10^2–3.9×10^4 CFU/m^3 (Tables 2–4). Prior to disinfection, the number of microorganisms on the surfaces of the walls, shelves, and tables in the studied storage rooms was 1.1×10^2–4.7×10^2 CFU/m^3, which is typical of this kind of environments, while visual assessment of museum and archival items revealed symptoms of biodeterioration.

Photocatalytic disinfection led to a decline in the number of microorganisms with the maximum reduction in the air on day 7 being 63% for the library and 99% for the museum; the reduction on the surfaces was 55% and 58%, respectively (Table 2). The microorganisms number reduction in the air fluctuated within the disinfection time, while on the surfaces it was on the similar level during the disinfection process (Table 2). Disinfection by UV irradiation with the number of air changes similar as in the case of the photocatalytic method in a 24 h working mode resulted in lower microbial reduction values for the air, but higher for the surfaces (Table 3). After 7 days of disinfection, 21% to 80% of microorganisms present in the air and 78% to 99% of those present on the surfaces were eliminated (in the library and museum, respectively). In the library, the decrease in the microorganisms number in the air was not satisfying, while the surfaces disinfection was very successful, the microbial reduction equaled to 99%. In the museum, the high microorganisms elimination has been observed already on 2nd day of disinfection (a decrease of 79% in the air and 84% on surfaces) (Table 3). Due to the special features of chemical misting with QACs, tests were conducted 1 day after the procedure (in the museum), and then on day 3 and 5 in both studied places (Table 4). In the library, this method did not bring about satisfactory results as the concentration of microorganisms in the air was not diminished, while their reduction on the surfaces was only 46%. In the museum, the decrease in the number of microbes was greater and amounted to 84% in the air and 69% on the surfaces. However, the effects of the process were found to be short-termed: in the library the concentration of airborne fungi was diminished only up to day 1 following disinfection; in the museum, chemical misting affected only bacteria, and its effects gradually decreased over time following the first day after disinfection.

Qualitative analysis revealed the presence of pathogenic species in the museum and library workposts prior to disinfection. The identified pathogens included the molds *Aspergillus fumigatus* and *Stachybotrys chartarum*, which produce harmful mycotoxins, as well as other toxigenic and allergenic species belonging to the genera *Alternaria*, *Cladopsorium*, *Penicillium*, and *Aspergillus* (Tables 5-7). In terms of bacteria, we identified *Vibrio vulnificus*, which belongs to group 2 of hazardous biological agents (based on Directive 2000/54/EC) as well as numerous species in the genera *Bacillus*, *Staphylococcus*, and *Streptomyces* with potentially pathogenic characteristics (Tables 5-7).

Disinfection effectively inactivated most of these pathogenic microorganisms. Photocatalytic ionization eliminated 5/7 bacterial species and 3/8 fungal species from the air; the other airborne species were either affected to a lesser degree (their numbers were reduced by 20–78%) or not affected at all (Table 5). In the case of UV irradiation, 8 fungal species out of the 14 present in the air as well as 7 out of

9 bacterial species were eliminated from the air to the extent of 90–100% (Table 6). Chemical misting with QACs turned out to be more effective against fungi, as 7 out of 10 airborne fungal species and 6 out of 13 airborne bacterial species were eliminated (Table 7).

In the studied library and museum storage rooms we found elevated relative humidity (53–63%), while in the library also the temperature exceeded the recommended limits (ISO 11799:2003). Analysis of airborne dust showed its high concentration in the studied areas.

Increased bacterial contamination and very high fungal contamination were found in the museum, while a high number of fungi was also found in the library. The number of airborne microbes, and especially that of fungi, exceeded the permissible values (4.5×10^2 CFU/m^3) proposed by the Commission of the European Communities presented in the report Indoor Air Quality and Its Impact on Man (1993). This shows that both the workers and the stored items are at risk.

The microorganisms isolated prior to disinfection included the pathogenic fungi *Aspergillus fumigatus* (4.5×10^2 CFU/m^3) and *Stachybotrys chartarum* (1.0×10^2 CFU /m^3), which produce mycotoxins harmful to human health, as well as a smaller concentration of the bacterium *Vibrio vulnificus* (1.4×10^1 CFU/m^3), which belongs to group 2 of hazardous microorganisms based on the Directive 2000/54/EC.

Furthermore, we identified a number of species potentially harmful to human health in the studied areas; these included molds of the genera *Alternaria*, *Cladosporium*, *Penicillium*, and *Aspergillus* as well as bacteria of the genera *Bacillus*, *Staphylococcus*, *Streptomyces*, and others (Dutkiewicz et al. 2007). The presence of some of these species in library, archive, and museum areas has been confirmed in previous studies (Zielińska-Jankiewicz et al. 2008; Karbowska-Berent et al. 2011).

The high numbers of airborne microorganisms as well as the presence of potentially pathogenic species indicate the need to find an appropriate method of eliminating microbiological contaminants from these workposts.

The studied places were disinfected by three methods: photocatalytic ionization, UV irradiation, and chemical misting with QACs. The microbiological analyses carried out during disinfection by UV irradiation and photocatalytic ionization as well as following disinfection by chemical misting showed a reduction in the number of microorganisms in the air and on surfaces both in the library and in the museum.

The photocatalytic ionization method was more effective in reducing the number of microorganisms in the air (63–99% reduction) than on the surfaces (55–58% reduction). A satisfactory reduction in the number of microorganisms was observed after 2 or 3 days of disinfection. In light of the results obtained herein as well as previous model works (Pietrzak and Gutarowska 2013), photocatalytic ionization seems to be a suitable method for sanitization of the air in library and museum storage rooms. Such disinfection must be conducted for several days to achieve high effectiveness.

A considerable reduction in the number of microorganisms was also obtained using

UV irradiation (28–80% for the air and 96–99% for the surfaces). This method was found to be less effective in eliminating airborne microorganisms than photocatalytic ionization at the same air change rate, but it was more effective in the case of purging surfaces. The microorganism's number reduction fluctuated within the disinfection time, which may be caused by working personnel, moving of objects or airing.

The obtained results show that UV irradiation conducted using flow radiators is an effective method of eliminating microbiological contamination; its high effectiveness has been previously confirmed in other environments (Gutarowska and Kancler 2009).

Ozone was not detected (<0.001 ppm) during disinfection by photocatalytic ionization and UV irradiation; however, according to literature reports, other chemical species which may be generated, such as $OH^{\bullet}$, H_2O_2, OH^-, and H^+, may react with various technical materials (Chen et al. 2010). As no research to date has dealt with the influence of reactive oxygen produced during disinfection by photocatalytic ionization on the strength parameters of museum and archival collections, this process should be conducted with caution and applied rather in non-historical storage rooms and surfaces.

The lowest effectiveness was achieved using chemical misting with QACs. The reduction in the number of microorganisms amounted to 0–84% and 46–69% in the air and on the surfaces, respectively. Furthermore, the effects of the process were short-termed, as the decline in the number of airborne microbes was observed up to day 1 following disinfection, while the reduction on the surfaces lasted a little longer (up to day 5), probably due to continued deposition of molecules of the chemical compound.

A comparison of the effectiveness of inactivation of airborne microbial species by disinfection with the three methods showed that bacteria were more sensitive to photocatalytic ionization and UV irradiation than to chemical disinfection with QACs. It was found that approximately 70% of all bacterial species were eliminated with the above-mentioned methods with an effectiveness greater than 90%. On the other hand, molds were best eliminated by chemical misting with QACs (60% of the strains), followed by UV irradiation (57%), and by photocatalytic ionization (37%). Considerable sensitivity of molds to chemical disinfection with QACs has been previously reported in the literature (Fraise et al. 2004; Vijayakumar et al. 2012).

Nevertheless, some strains were found to be resistant to all the tested methods. Fungi exhibited much higher resistance: 7%, 10%, and 37% of strains were not inactivated by UV irradiation, chemical misting with QACs, and photocatalytic ionization, respectively. In the case of bacteria, the corresponding figures for resistant strains are 0%, 7%, and 14%.

It should be noted that the mold species that are harmful to the health of the personnel, that is, *Aspergillus fumigatus* and *Stachybotrys chartarum* have been completely eliminated from the air, while the content of *Vibrio vulnificus* decreased by 30%; the majority of potentially pathogenic microorganisms were removed from the air of the storage rooms.

Table.2 Number of microorganisms in the air and on surfaces at workposts in museum and library before and during the photocatalytic ionization disinfection

Place	Day	Number of microorganisms in the air (cfu/m^3) / Reduction (%) (N=6)			Number of microorganisms on the surfaces (cfu/100cm^2) / Reduction (%) (N=6)		
		Bacteria	**Fungi**	**Total**	**Bacteria**	**Fungi**	**Total**
Library	0	M:2.4×10^2 SD:1.3×10^2	M:3.7×10^2 SD:9.9×10^1	M:6.2×10^2 SD:1.5×10^2	M:9.4×10^1 SD:7.6×10^1	M:1.4×10^2 SD:1.2×10^2	M:2.4×10^2 SD:2.0×10^2
	2	M:2.4×10^2 SD:1.7×10^2 R:0	M:7.7×10^1 SD:5.4×10^1 R:80	M:2.3×10^2 SD:2.5×10^2 R:62	M:4.3×10^1 SD:2.7×10^1 R:54	M:7.0×10^1 SD:6.1×10^1 R:51	M:1.1×10^2 SD:8.6×10^1 R:52
	3	M:4.7×10^1 SD:3.2×10^1 R:81	M:3.1×10^2 SD:1.8×10^2 R:17	M:3.6×10^2 SD:1.9×10^2 R:42	M:2.2×10^1 SD:1.8×10^1 R:76	M:9.1×10^1 SD:7.6×10^1 R:36	M:1.1×10^2 SD:8.7×10^1 R:52
	7	M:6.3×10^1 SD:3.5×10^1 R:74	M:1.7×10^2 SD:3.9×10^1 R:55	M:2.3×10^2 SD:6.7×10^1 R:63	M:5.1×10^1 SD:1.8×10^1 R:46	M:5.5×10^1 SD:3.7×10^1 R:61	M:1.1×10^2 SD:5.1×10^1 R:55
Museum	0	M:6.9×10^2 SD:3.5×10^2	M:3.9×10^4 SD:1.4×10^4	M:4.0×10^4 SD:1.5×10^4	M:7.0×10^1 SD:1.1×10^2	M:4.0×10^2 SD:5.9×10^2	M:4.7×10^2 SD:7.1×10^2
	2	M:8.8×10^1 SD:3.3×10^1 R:87	M:2.4×10^2 SD:2.3×10^2 R:99	M:3.3×10^2 SD:2.1×10^2 R:99	M:3.1×10^1 SD:4.3×10^1 R:56	M:5.0×10^2 SD:6.5×10^2 R: –	M:5.3×10^2 SD:7.0×10^2 R: –
	3	M:5.8×10^1 SD:3.3×10^1 R:92	M:1.5×10^2 SD:1.2×10^2 R:99	M:2.1×10^2 SD:1.1×10^2 R:99	M:2.4×10^1 SD:3.8×10^1 R:66	M:1.7×10^2 SD:1.6×10^2 R:57	M:2.0×10^2 SD:2.0×10^2 R:58
	7	M:2.7×10^2 SD:2.4×10^2 R:61	M:3.9×10^4 SD:1.4×10^4 R:0	M:4.0×10^4 SD:1.4×10^4 R:0	M:4.6×10^1 SD:6.9×10^1 R:34	M:2.6×10^2 SD:3.1×10^2 R:35	M:3.1×10^2 SD:3.8×10^2 R:35

M – mean; SD – standard deviation; N - number of samples for each M and SD; R – reduction; (–) - no reduction

Table.3 Number of microorganisms in the air and on surfaces at workposts in museum and library before and during the UV radiation disinfection

Place	Day	Number of microorganisms in the air (cfu/m^3) / Reduction (%) (N=6)			Number of microorganisms on the surfaces (cfu/100cm^2) / Reduction (%) (N=6)		
		Bacteria	**Fungi**	**Total**	**Bacteria**	**Fungi**	**Total**
Library	0	M:1.3×10^2 SD:7.4×10^1	M:1.7×10^2 SD:6.0×10^1	M:3.0×10^2 SD:5.4×10^1	M:1.8×10^2 SD:5.4×10^1	M:1.2×10^2 SD:5.1×10^1	M:3.0×10^2 SD:4.9×10^0
	2	M:1.6×10^2 SD:8.3×10^1 R: –	M:2.7×10^2 SD:1.1×10^2 R: –	M:4.3×10^2 SD:1.8×10^2 R: –	M:1.5×10^2 SD:5.2×10^1 R:15	M:6.3×10^1 SD:3.6×10^1 R:46	M:2.2×10^2 SD:8.4×10^1 R:28
	3	M:3.3×10^0 SD:8.2×10^0 R:97	M:2.1×10^2 SD:6.5×10^1 R: –	M:2.2×10^2 SD:6.4×10^1 R:28	M:1.2×10^2 SD:3.3×10^1 R:33	M:8.0×10^1 SD:7.8×10^1 R:32	M:2.0×10^2 SD:1.1×10^2 R:33
	7	M:6.7×10^1 SD:6.6×10^1 R:47	M:1.7×10^2 SD:7.1×10^1 R:2	M:2.4×10^2 SD:1.1×10^2 R:21	M:1.4×10^0 SD:62.4×10^0 R:99	M:1.4×10^0 SD:2.4×10^0 R:99	M:2.8×10^0 SD:2.4×10^0 R:99
Museum	0	M:4.9×10^2 SD:2.6×10^2	M:6.3×10^2 SD:2.9×10^2	M:5.4×10^2 SD:2.6×10^2	M:1.5×10^1 SD:1.7×10^1	M:2.0×10^2 SD:3.4×10^2	M:2.2×10^2 SD:3.6×10^2
	2	M:1.1×10^2 SD:7.1×10^1 R:78	M:6.5×10^1 SD:3.3×10^1 R:90	M:1.1×10^2 SD:6.9×10^1 R:79	M:4.2×10^0 SD:4.2×10^0 R:73	M:3.1×10^1 SD:4.6×10^1 R:85	M:3.5×10^1 SD:5.0×10^1 R:84
	3	M:1.9×10^2 SD:1.7×10^2 R:61	M:2.4×10^2 SD:2.2×10^2 R:63	M:2.1×10^2 SD:1.6×10^2 R:61	M:1.4×10^0 SD:2.4×10^0 R:91	M:7.0×10^0 SD:6.4×10^0 R:97	M:8.4×10^0 SD:7.3×10^0 R:96
	7	M:1.1×10^2 SD:6.1×10^1 R:79	M:4.7×10^1 SD:3.7×10^1 R:93	M:1.1×10^2 SD:6.1×10^1 R:80	M:5.6×10^0 SD:6.4×10^0 R:64	M:4.2×10^1 SD:3.3×10^1 R:79	M:4.8×10^1 SD:2.8×10^1 R:78

M – mean; SD – standard deviation; N - number of samples for each M and SD; R – reduction; (–) - no reduction

Table.4 Number of microorganisms in the air and on surfaces at workposts in museum and library before and after the chemical misting disinfection with quaternary ammonium salts

Place	Day	Number of microorganisms in the air (cfu/m^3) / Reduction (%) (N=6)			Number of microorganisms on the surfaces (cfu/100cm^2) / Reduction (%) (N=6)		
		Bacteria	**Fungi**	**Total**	**Bacteria**	**Fungi**	**Total**
Library	0	M:5.0×10^2 SD:3.8×10^2	M:1.9×10^2 SD:6.6×10^1	M:6.9×10^2 SD:5.5×10^2	M:7.4×10^1 SD:6.1×10^1	M:6.4×10^1 SD:6.9×10^1	M:1.4×10^2 SD:9.6×10^1
	3	M:7.0×10^2 SD:2.6×10^2 R:44	M:1.1×10^2 SD:4.2×10^1 R: –	M:8.0×10^2 SD:2.8×10^2 R: –	M:7.2×10^1 SD:5.4×10^1 R:26	M:4.7×10^1 SD:2.4×10^1 R:3	M:1.2×10^2 SD:6.8×10^1 R:14
	5	M:9.7×10^2 SD:3.6×10^2 R: –	M:2.1×10^2 SD:4.7×10^1 R: –	M:1.2×10^3 SD:6.1×10^2 R: –	M:1.9×10^1 SD:1.2×10^1 R:13	M:5.5×10^1 SD:4.4×10^1 R:74	M:7.4×10^1 SD:4.8×10^1 R:46
Museum	0	M:1.1×10^3 SD:1.0×10^2	M:2.6×10^2 SD:7.3×10^1	M:1.3×10^3 SD:2.5×10^2	M:8.7×10^1 SD:9.6×10^1	M:1.8×10^1 SD:2.1×10^1	M:1.1×10^2 SD:1.9×10^2
	1	M: 1.6×10^2 SD:1.1×10^2 R:85	M:5.7×10^1 SD:2.9×10^1 R:78	M:2.2×10^2 SD:1.5×10^2 R:84	M:2.8×10^1 SD:3.2×10^1 R:68	M:2.2×10^1 SD:3.9×10^1 R: –	M:5.1×10^1 SD:7.0×10^1 R:52
	3	M: 1.7×10^2 SD:7.0×10^1 R:84	M:1.1×10^4 SD:8.5×10^3 R: –	M:1.1×10^4 SD:1.1×10^4 R: –	M:3.2×10^1 SD:4.5×10^1 R:63	M:4.1×10^1 SD:6.7×10^1 R: –	M:7.3×10^1 SD:6.3×10^1 R:46
	5	M:1.9×10^2 SD:4.1×10^1 R:82	M:1.1×10^4 SD:9.1×10^3 R: –	M:1.2×10^4 SD:1.1×10^4 R: –	M:2.0×10^1 SD:3.4×10^1 R:77	M:1.3×10^1 SD:1.8×10^1 R:31	M:3.2×10^1 SD:5.2×10^1 R:69

M – mean; SD – standard deviation; N - number of samples for each M and SD; R – reduction; (–) - no reduction

Table.5 Airborne microorganisms present in the studied workposts before and after disinfection by photocatalytic ionization

	Microorganism	Number of microorganisms in the air (cfu/m^3)		Reduction (%)
		Before disinfection	After disinfection	
Molds	*Acremonium*sp.	2.0×10^1	2.0×10^1	-
	Alternaria alternata	3.0×10^1	0	100
	Aspergillus sp.	9.0×10^1	2.0×10^1	78
	Botrytis sp.	2.0×10^1	0	100
	Cladosporium sp.	8.0×10^1	2.4×10^2	-
	*Mucor*sp.	1.0×10^1	0	100
	Penicillium sp.	6.8×10^2	4.8×10^2	29
	Rhodotorula sp.	1.0×10^1	1.0×10^1	-
Bacteria	*Bacillus* sp.	2.7×10^2	0	100
	Bacillus megaterium	2.0×10^2	0	100
	Brevundimonas vesicularis	3.0×10^2	2.4×10^2	20
	Kocuriakristinae	2.0×10^2	0	100
	Sphingomonaspaucimobilis	2.8×10^2	0	100
	Stenotrophomonas maltophilia	9.0×10^1	0	100
	Streptomyces sp.	6.0×10^1	1.9×10^2	-

(–) - no reduction

Our study shows that photocatalytic ionization, UV irradiation, and chemical misting with QACs can all be used for disinfection of library and museum storage rooms.

However, it should be noted that the inactive microorganisms, their parts and microbial substances e.g. mycotoxins, bacterial endotoxin may adversely affect the health of workers. Therefore the aim of disinfection carried out in the work environment is not complete remove microorganisms from the air and surfaces, but to obtain the hygienisation effect of workposts.

However, prior to practical implementation, further research should be conducted concerning the influence of the studied storage room disinfection methods on museum and library objects. It would also be important to preparationte some guidelines for the procedures, such as the frequency of application, taking into account the effects of various factors (e.g., climatic parameters) on disinfection effectiveness.

Increased bacterial contamination and very high fungal contamination was found in the museum, while a high number of fungi was also found at the library workposts. The microorganisms isolated in tested workposts prior to disinfection included the pathogenic fungi and bacteria.

Table.6 Airborne microorganisms present in the studied workposts before and after disinfection by UV irradiation

	Microorganism	Number of microorganisms in the air (cfu/m^3)		Reduction (%)
		Before disinfection	After disinfection	
Molds	*Alternaria alternata*	1.5×10^2	3.0×10^1	80
	Aspergillus fumigatus	4.5×10^2	0	100
	Aspergillus niger	5.0×10^1	0	100
	Aspergillus wentii	3.3×10^2	0	100
	Cladosporium cladosporioides	0	8.0×10^1	-
	Cladosporium herbarum	1.4×10^2	8.0×10^1	43
	*Penicillium*sp.	1.3×10^2	8.0×10^1	38
	Penicillium citrinum	2.1×10^3	2.0×10^1	99
	Penicillium commune	2.4×10^2	2.0×10^1	92
	Penicillium digitatum	0	2.0×10^1	-
	Penicillium expansum	4.0×10^1	0	100
	Penicillium polonicum	3.0×10^1	3.0×10^1	-
	Penicillium waksmanii	5.5×10^2	5.0×10^1	91
	Stachybotryschartarum	1.0×10^2	0	100
Bacteria	*Aeromonasachromogenes*	3.0×10^1	0	100
	Bacillus subtilis	4.5×10^2	3.1×10^2	31
	Bacillusmycoides	5.9×10^2	5.0×10^1	92
	Micrococcus sp.	5.3×10^2	1.0×10^1	98
	Pseudomonasluteola	2.8×10^2	0	100
	Staphylococcus lentus	6.0×10^1	0	100
	Staphylococcussaprophyticus	6.0×10^1	0	100
	Staphylococcusxylosus	5.6×10^2	4.0×10^1	93
	Streptomyces sp.	1.1×10^2	2.0×10^1	82

(–) - no reduction

Table.7 Airborne microorganisms present in the studied workposts before and after disinfection by chemical misting with quaternary ammonium compounds

	Microorganism	Number of microorganisms in the air (cfu/m^3)		Reduction (%)
		Before disinfection	After disinfection	
Molds	*Aspergillus* sp.	7.2×10^1	0	100
	Cladosporium herbarum	1.0×10^2	0	100
	Cladosporium cladosporioides	6.7×10^2	7.0×10^1	90
	Fusarium sp.	1.5×10^1	0	100
	*Mucor*sp.	1.0×10^2	2.0×10^1	80
	Penicillium citrinum	1.5×10^1	3.5×10^1	-
	Penicillium commune	2.0×10^2	0	100
	Penicillium italicum	3.2×10^2	9.8×10^1	70
	Penicillium purpurogenum	2.3×10^1	0	100
	Trichodermakoningii	3.3×10^1	0	100
Bacteria	*Bacilluslentus*	2.2×10^1	1.7×10^1	24
	Bacillus subtilis	3.7×10^1	1.0×10^1	73
	*Brevibacillus*sp.	4.9×10^1	2.7×10^1	46
	Chrysobacteriumindologenes	1.5×10^1	0	100
	Kocuriakristinae	7.2×10^1	0	100
	Kocuriavarians	6.0×10^1	1.0×10^1	83
	Ochrobactrumanthropi	1.6×10^1	1.0×10^1	36
	Staphylococcus capitis	1.6×10^1	1.5×10^1	6
	Staphylococcus cohnii	1.8×10^1	0	100
	Staphylococcus haemolyticus	5.8×10^1	0	100
	Staphylococcus lentus	3.3×10^1	0	100
	Streptomyces sp.	2.5×10^1	0	100
	Vibriovulnificus	2.0×10^1	1.4×10^1	30

(–) - no reduction

Photocatalytic ionization and UV irradiation methods were found to be highly effective in reducing the number of microbes in the work environments. Chemical disinfection with QACs was characterized by lower effectiveness. This method was found to be superior in terms of eliminating molds, especially those resistant to other methods. Longer disinfection times with photocatalytic ionization and UV irradiation increase the effectiveness of the process, while the sanitation effect following QAC disinfection is short-termed. The discussed disinfection methods efficiently eliminate pathogenic or potentially pathogenic microorganisms from storage areas.

Significance of the results

Chemical misting with QACs, UV radiation and photocatalytic ionization can be used for disinfection of the air and surfaces at workposts in libraries and museums, due to their high effectiveness in microorganisms removal and elimination of majority of pathogens. The choice of disinfection method depends on inhabiting microbiota and microclimatic conditions in premises. Chemical misting with QACs and photocatalytic ionization are more efficient against fungi, while UV radiation, against bacteria. High dust contamination of the air, limits the application of UV radiation and photocatalytic ionization disinfection methods. The higher efficiency in the microorganisms removal and longer effect of surface disinfection, compared to the air, has been shown, which implies that to achieve the good results of the air disinfection, the process should be extended over more than three days for UV radiation and photocatalytic ionization; in case of chemical misting – the disinfection process should be performed often and regularly.

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