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Aerosol Disinfection in the System of Preventive and Anti-Epidemic Measures: a Review

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ABSTRACT

Organization and implementation of disinfection measures are among the most effective strategies of non-specific prevention of infectious diseases. *Aerosol disinfection* has now gained widespread use due to its practicality and efficacy.

A literature search was carried out using such keywords as *aerosol disinfection, prevention, anti-epidemic measures*, and *ventilation* in both Russian and English, across the *Scientific Electronic Library, eLIBRARY.RU* search engine, and *Google Scholar*. For English-language publications, searches were conducted in *PubMed*, the *National Center for Biotechnology Information* (NCBI) database, and *Google Patents* (Patents.google.com). The search covered a time period of 84 years (1940–2024). A total of 1,751 articles were identified, of which 55 met the selection criteria.

Analysis of the literature revealed that aerosol disinfection, now widespread in many countries and various fields of activity, has a long-standing history dating back to the late 18th century. Aerosol disinfection technologies have become indispensable in the modern world, although issues related to the bactericidal properties of dispersed systems, optimization of disinfection equipment, and the development of quality standards for effective disinfection remain unresolved.

Aerosol disinfection holds a valuable place within the system of preventive and anti-epidemic measures, having a significant impact on reducing the risk of epidemic outbreaks of infectious diseases with various mechanisms of transmission.

Keywords: aerosol disinfection; prevention; anti-epidemic measures; review.

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Аэрозольная дезинфекция в системе профилактических и противоэпидемических мероприятий: научный обзор

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АННОТАЦИЯ

Организация и проведение дезинфекционных мероприятий являются одними из основных действенных направлений неспецифической профилактики инфекционных заболеваний. В настоящее время широкое распространение получил метод аэрозольной дезинфекции ввиду его практичности и результативности.

Поиск публикаций осуществлялся путём введения поисковых запросов по ключевым словам «аэрозольная дезинфекция», «профилактика», «противоэпидемические мероприятия», «вентиляция», «aerosol disinfection», «prevention», «anti-epidemic measures», «ventilation» на русском и английском языках в научной электронной библиотеке (НЭБ), поисковой системе eLibrary, поисковой системе Google Scholar. На английском языке — в поисковой системе PubMed, базе Национального центра биотехнологической информации США (National Center for Biotechnology Information, NCBI), поисковой системе от Google по патентам (Patents.google.com). Глубина поиска составила 84 года (1940–2024 гг.). В процессе поиска найдена 1751 публикация, из них критериям отбора соответствовали 53 статьи.

Анализ литературных данных показал, что аэрозольная дезинфекция, приобретая широкое распространение во многих странах мира и различных сферах жизнедеятельности, имеет долгую историю, начавшуюся с конца XVIII века. Технологии аэрозольной дезинфекции стали незаменимыми в современном мире, хотя остаются нерешёнными вопросы о бактерицидности дисперсных систем, оптимизации используемого оборудования и разработки стандартов для качественной дезинфекции.

Аэрозольная дезинфекция занимает важное место в системе профилактических и противоэпидемических мероприятий, оказывая значимое влияние на снижение риска возникновения эпидемических вспышек инфекционных заболеваний с различными механизмами передачи.

Ключевые слова: аэрозольная дезинфекция; профилактика; противоэпидемические мероприятия; обзор.

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INTRODUCTION

The 21st century is marked by increasingly aggressive microorganisms. According to the World Health Organization, infectious diseases are attacking on all fronts, justifying increased attention to disease prevention and the growing need for effective disinfection measures. The widespread emergence of resistant strains of microorganisms requires ongoing evaluation of the biocidal activity of disinfectants [1].

Of the many disinfection technologies currently in use, aerosol disinfection with hydrogen peroxide is one of the safest for the environment. Hydrogen peroxide does not significantly damage interior surfaces and breaks down into chemically safe elements [2]. The aerosol disinfection method effectively kills bacteria, viruses, and pathogenic fungi in the air and on surfaces, which is especially important in high-traffic areas such as hospitals, offices, and public transportation. Aerosol disinfection creates microscopic droplets that provide uniform coverage and deeper, more comprehensive treatment. This method effectively controls airborne infections by exposing microorganisms to the fine aerosol of disinfectants.[1], [2]

Bacteria and viruses, primarily airborne, pose a significant threat to public health [3]. Consequently, there is an ongoing need to develop new disinfection methods by implementing an automated and continuous system to enhance the efficiency, reliability, and economic viability of disinfection, thereby reducing the influence of human factors, minimizing the risk of cross-contamination, and ensuring flexibility and adaptability in diverse environments [4, 5].

DATA SEARCH METHODOLOGY

A search of publications was performed using the following keywords: аэрозольная дезинфекция / aerosol disinfection, профилактика/prevention, противоэпидемические мероприятия / anti-epidemic measures, вентиляция/ventilation. The search was performed in both Russian and English using the National Electronic Library, the eLibrary search engine, and the Google Scholar search engine. The search was performed only in English using the PubMed search engine, the National Center for Biotechnology Information, and the Google Patents search engine (Patents.google.com). The search covered a time period of 84 years (1940–2024). A total of 1751 publications were found.

Inclusion criteria for publications: availability of data on disinfection methods in different time periods; availability of data on aerosol-type disinfection and its application across different areas using different disinfectants; availability of the study conclusion; availability of the full text with free access; availability of keywords.

Exclusion criteria for publications: lack of keywords; non-compliance with the research topic; irrelevance due to the year of publication; inaccessibility of the full text.

Consequently, 53 articles were selected and included in the review.

HISTORICAL ASPECT

Since ancient times, physicians have recognized the importance of disinfection, particularly when treating wound surfaces. This was necessary to prevent and reduce the risk of infection, improve healing processes, and destroy pathogens that could lead to inflammation and complications. Hot irons, boiling oil, vinegar, lime, and ointments with balsamic properties were used [6]. Advances in chemistry led to the synthesis of hydrogen peroxide in 1818. Iodine was first used to treat wounds in 1885 [7, 8].

The first research on air disinfection was conducted in the 19th century. In 1863, Joseph Lister—the English surgeon and scientist who invented surgical antisepsis—proposed using carbolic acid to disinfect operating rooms before and during surgery using a sprayer [9]. The concept of an aerosol emerged in 1790 with the introduction of the first pressurized carbonated beverages in France. Pulverizers, also known as atomizers, were invented simultaneously in 1865 by the English inventor Edon and the Russian scientist Shpakovsky. The primary purpose of atomizers was to optimize the atomization of disinfectant solutions.[3]

During outbreaks of infectious diseases, such as pandemics or epidemics, disinfecting the air and surfaces was especially important. In 1878, a serious plague epidemic broke out in Vetlyanka (Russia). However, timely measures prevented the epidemic from spreading beyond the village. To educate the population, Professor Chudnovsky wrote a brochure titled “Protective Measures Against Plague,” where he described methods of combating the disease, including spraying with salicylic acid [10].

British professor Donnan first coined the term “aerosol” at the end of World War I to describe highly dispersed systems, such as the poisonous fumes of chemical warfare agents used for military purposes [11]. The first aerosol can with a valve was patented in 1927 by Norwegian chemical engineer Rotheim and American entomologists Goodhue and Sullivan [12].

ADVANCED TECHNOLOGIES

Since the 1930s, aerosol technology [13, 14] has been developed, allowing for the emergence of more effective air disinfection methods. In 1954, 1957 and 1958, three inventions

[1] Methodological Recommendations 3.5.0315-23 for the Selection and Application of Air Purification and Disinfection in Public Buildings and Premises approved by the Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing on January 30, 2023. Available at: https://base.garant.ru/408056345/?ysclid=m8yf21r3ex639336800 Accessed on: November 15, 2024.

[2] World Health Organization [Internet]. Cleaning and disinfection of environmental surfaces in the context of COVID-19: Infection prevention and control. Available at: https://www.who.int/publications/i/item/cleaning-and-disinfection-of-environmental-surfaces-inthe-context-of-covid-19 Accessed on: November 15, 2024.

[3] Encyclopedic dictionary of Brockhaus and Efron. Oil Heating. Available at: https://dic.academic.ru/dic.nsf/brokgauz_efron/137252/Отопление?ysclid=m8ygd3om7n742531958 Accessed on: November 15, 2024.

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based on the principle of aerosol disinfection and treatment of various premises were patented [15–17].

In 1961, the aerosol method was used for aircraft disinfestation. The ventilation system of the aircraft was used to spread DDVP (O,O-dimethyl-2,2-dichlorovinyl phosphate) vapors throughout the plane. This method resulted in 100% mortality of houseflies [18, 19]. In 2001, a 4% peroxymonosulfate solution was used to disinfect surfaces in veterinary practices [20]. In the same year, the dry aerosol disinfection technique using hydrogen peroxide was introduced for disinfecting surfaces, interior rooms, ambulances, and medical equipment of various types [21]. In 2010, a study was conducted to inactivate methicillin-resistant Staphylococcus aureus and vancomycin-resistant Enterococcus on various environmental surfaces by spraying a disinfectant containing stabilized chlorine dioxide and a quaternary ammonium compound (Cryocide 20) [22]. During the COVID-19 pandemic, aerosol disinfection became critical to preventing the spread of the virus and creating a safe environment with reduced risk of infection [23].

Over time, the range of disinfectants used in aerosol disinfection has grown, as have the safety and environmental friendliness requirements for these products. A new generation of biocidal preparations with a broad spectrum of action was introduced that was more effective and safer [24]. Concurrent with the development of disinfectants, methods of disinfectant atomization have improved. These methods ranged from cans [25], ultrasonic atomizers that create a fine aerosol for uniform disinfectant distribution and deeper penetration into hard-to-reach places [26], and high-speed atomizers that provide more precise and directed atomization [27] to intelligent spray control systems that use sensors to automatically adjust the intensity and direction of the aerosol flow depending on environmental conditions and the type of disinfectant [28].

Automating the process enabled the integration of aerosol disinfectors with ventilation systems. This provided an automated indoor air treatment system that eliminated the need for manual spraying [29]. Sensors and software controlled the concentration of the disinfectant in the air, thereby optimizing the disinfection process and ensuring safety [25, 30]. Similarly, safety improved and the risk of infection decreased with the introduction of a remote control and emergency stop system. With this system, the operator could control the disinfector remotely. The system also automatically stopped the disinfector in case of abnormal situations [31].

As the fight against infectious diseases evolved, the effectiveness and safety of aerosol disinfection for preventing and controlling contagious diseases was increasingly recognized, leading to its adoption in many countries worldwide. Importantly, the disinfection technique, type of disinfectant, and method of application were performed according to the recommendations of specialists and the specifics of the object and disinfection tasks (see Table 1) [32–37]. The main element of the device for producing aerosols was the atomizer, which achieved the highest relative velocity of the liquid and surrounding air. The disinfectant flow rate varied from 10 to 50 mL/m^3, the exposure time varied from 60 to 120 min, and the dispersity varied from 5 to 30 μm. Increasing the dispersity of the aerosol and the concentration of the working solution did not always yield positive results. For air disinfection, the most effective methods were less stringent than those for surface disinfection [38]. When creating the device, the optimal variant was chosen depending on specific requirements, taking into account characteristics such as the dispersibility of the obtained particles, productivity, energy consumption, size, and mass [39].

TECHNOLOGY RATIONING

In general, aerosol disinfection is an effective method; however, it requires special care. All risks and limitations must be considered, and the appropriate disinfectant and method of use must be selected. Only products that are properly registered (and have a certificate of state registration, instructions for use, a label, and a declaration of conformity) are permitted for use in medical organizations. The equipment used for aerosol disinfection must have a certificate or declaration of conformity to the technical regulations of the Customs Union.[4] The correct disinfection mode must be chosen depending on the room's purpose, technology, and precautions. The correct equipment for disinfecting ventilation and air conditioning systems must be used during treatment.[5]

Although recommended regulatory documents on the disinfection of ventilation systems are available, they do not adequately reflect the criteria for assessing the microbial contamination, sanitation, and technical condition of ventilation systems. There are no proven disinfection technologies for ventilation systems that include quality control measures.[6], [7], [8], [9]

[4] TR CU 004/2011, No. 768, On Safety of Low Voltage Equipment, dated August 16, 2011. Available at: https://docs.cntd.ru/document/902299536?ysclid=m8yq9aiup1337994018 Accessed on: November 15, 2024.

[5] Methodological Recommendations 3.5.1.0103-15 for the Application of Aerosol Disinfection in Medical Organizations, dated September 28, 2015. Available at: https://www.garant.ru/products/ipo/prime/doc/71117992/?ysclid=m8yqin35pu809233282 Accessed on: November 15, 2024.

[6] Resolution No. 4 on Approval of Sanitary Rules and Regulations 3.3686-21, Sanitary and Epidemiological Requirements for the Prevention of Infectious Diseases, dated January 28, 2021. Available at: https://docs.cntd.ru/document/573660140 Accessed on: November 15, 2024.

[7] Methodological Recommendations 3.5.0071-13 Organization and Implementation of Disinfection Measures at Various Facilities during Preparation and Holding of Public Events, dated May 24, 2013. Available at: https://www.garant.ru/products/ipo/prime/doc/70310128/?ysclid=m8yqtw7s4b267292844 Accessed on: November 15, 2024.

[8] Methodological Recommendations No. 3.1/2.1.0186-20 on the Prevention of the Spread of a New Coronavirus Infection (COVID-19) During the Resumption of Core Activities of Medical Organizations, dated May 25, 2020. Available at: https://www.garant.ru/products/ipo/prime/doc/74110050/?ysclid=m8yr06gc9x902084325 Accessed on: November 15, 2024.

[9] Resolution No. 44 on the Approval of Sanitary Rules 2.1.3678-20 "Sanitary and Epidemiological Requirements for Premises, Buildings, Structures, Equipment, and Transportation, as well as Business Entities Engaged in Selling Goods, Performing Work, or Providing Services," dated December 24, 2020. Available at: https://docs.cntd.ru/document/573275590?ysclid=m8yr4ol6c5445788973 Accessed on: November 15, 2024.

Table 1. Experience of aerosol disinfection in different spheres of human activity

Experience	Area of application and country	Disinfectants used
Patterson et al., 2005 [32]	Veterinary disinfection was performed to evaluate the effectiveness of a 4% hydrogen peroxide-based disinfectant sprayed on surfaces in a large animal hospital based on the detection of *Staphylococcus aureus* and *Salmonella enterica Typhimurium* (Fort Collins, Colorado). The effectiveness of disinfection was tested by evaluating the reduction of *S. aureus* and *S. enterica Typhimurium. S. aureus* and *S. typhimurium* were placed in various locations throughout the hospital. After spraying the disinfectant, the number of viable bacteria was compared to the number in the control samples to assess the reduction in bacteria. On average, there was 4.03×10^7 colony-forming units (CFU) of S. aureus and 6.17×10^6 CFU of *S. Typhimurium contamination*. Using a directed spray of a 4% peroxymonosulfate solution for environmental disinfection resulted in a reduction of bacterial CFUs by >99.9999%.	4% peroxymonosulfate solution
Amodio et al., 2020 [33]	Disinfection was performed at the University Hospital Zurich: A 950-bed clinical hospital with six intensive care units (Switzerland). A programmable device (HyperDRYMist, 99MB microspray modulator, 99Technologies) generating a dry mist of hydrogen peroxide with < 1 μm particles was used. Disinfection was performed in a 60 m^3 unventilated room with closed but leaky doors and windows. The HPDM microsprayer was installed in one corner of the room, with the study subjects located more than 2 m away. A total of 3 mL/m^3 of disinfectant solution was sprayed, corresponding to 140 parts per million of hydrogen peroxide. Of the 124 samples with detectable colonization, only skin or environmental microbiota were found, and no pathogenic bacteria were identified. Bacterial counts decreased by over 90% in 45% (95% CI: 37–53) of the facilities. In highly contaminated facilities, spraying with HPDM resulted in an average 89% reduction in the number of CFUs.	6.6% hydrogen peroxide solution, 60 mg/L silver cations
Artemov et al., 2021 [34]	Disinfection of sanitary vehicles and transportation box was performed in the garage of the Territorial Center for Disaster Medicine (TCDM; Voronezh Region, Russia). In 2020, when organizing medical care for patients with suspected or confirmed COVID-19 infection, preventive and anti-epidemic measures were conducted, including the final disinfection of sanitary vehicles and transportation boxes in the TCDM garage equipped with a special box. A paramedic wearing personal protective equipment disinfected the interior of the vehicle with a 6% hydrogen peroxide solution using an aerosol disinfection apparatus (Nocospray) followed by an open-type ultraviolet irradiator.	6% hydrogen peroxide solution
Arunwuttipong et al., 2021 [35]	Disinfection was performed in public transport to develop and validate an effective public transport disinfection system (Bangkok, Thailand). Thirteen intercity public buses were used for experimental studies. The experiment employed an aerosol generator with an ultrasonic atomizer. Disinfection was validated using chemical and biological indicators on spore disks. Concentrations of 5% and 7% hydrogen peroxide were used for comparison. During the aerosol phase, both concentrations were effective in achieving a 6-log sporocidal reduction within 30 min. The decontamination cycle was 100 min, based on an average decomposition time of 70 min.	5% and 7% hydrogen peroxide solution
Wood et al., 2021 [36]	Disinfection of the operating room was performed at the UN peacekeeping army's secondary care hospital in Lebanon (China). The bactericidal effects of a conventional sodium dichloroisocyanurate spray, a sodium dichloroisocyanurate aerosol spray, a conventional peracetic acid spray, a peracetic acid aerosol spray, and ultraviolet light were compared in the presence of humans using the natural deposition method. The bactericidal effect of the sodium dichloroisocyanurate/sodium peracetic acid aerosol spray was more effective than the other two spraying methods. Bacterial removal rates were 74.6% and 69%, respectively, a few minutes after disinfection.	Chlorine derivatives, peracetic acid
Estienney et al., 2022 [37]	Ambulances were disinfected during the COVID-19 pandemic in Boulogne-Billancourt, a commune in the western suburbs of Paris (France). The experiment used a Renault SA ambulance equipped with a pediatric intensive care unit. Virus samples were placed on the stretcher inside the vehicle. A hydrogen peroxide nebulizer was used to generate a hydrogen peroxide mist. According to the manufacturer, the nebulizer was placed in a corner of the cabin. The vehicle was parked outside, and the average cabin temperature during the experiment was 25 °C. The nebulizer was sprayed for 5 min, followed by a 1 h exposure to allow for the complete decomposition of hydrogen peroxide. Chemical indicators were used to confirm sufficient exposure to hydrogen peroxide. Swabs were taken from surfaces before and after treatment and tested for the SARS-CoV-2 genome using a real-time polymerase chain reaction. Similar virus experiments were conducted in the waiting room of the Infectious Diseases Department, which had no ventilation. The spraying time was 13 min, and a total volume of 44 m^3 was treated, including the toilet.	6% hydrogen peroxide solution, silver nitrate

For a long time, the practical disinfection of ventilation systems has been problematic, including insufficient normative and methodological support, the development of new disinfectants that meet specific quality and safety requirements, and the introduction of new disinfection technologies, ensuring the effectiveness of disinfecting internal air duct surfaces. The size of the aerosol particles used for disinfection is not uniform. During treatment, the disinfectant is deposited unevenly, increasing consumption. Additionally, the disinfectant may be distributed unevenly, resulting in inadequate exposure of some treated areas [40]. Furthermore, aerosol particles may settle on surfaces, creating uneven coverage and leaving unprotected areas [41].

Some aerosol disinfectants may be toxic to humans, especially in confined spaces. Since disinfectants are flammable, they should be used as safely as possible, especially in areas with open flames [42].

Several disinfectants, including chlorinated lime, formaldehyde, alkaline glutaric aldehyde, quaternary ammonium compounds, and peracetic acid, can damage the coatings of surrounding furnishings and finishes. Disinfectants based on anolyte solutions may leave residues on surfaces [43]. The improper use of aerosol disinfection may pose health hazards, requiring specialized equipment and staff training.[10]

The use of aerosol disinfection as part of a preventive and anti-epidemic system has a centuries-long history. The term "aerosol" first appeared in the late 18th century and was initially used to describe highly dispersed chemical warfare agents at the end of World War I. Notably, Russia was the first to systematize data on the use of disinfection equipment to generate aerosols, and Russian scientists are considered the founders of the science of aerosols. The establishment of the etiology and transmission routes of infectious diseases, the study of the physicochemical properties of aerosols, the identification of numerous highly active chemical compounds, and the development and implementation of aerosol-forming equipment in agriculture, veterinary medicine, and crop production have contributed to the widespread use of aerosol disinfection in the system of preventive measures [44]. Research on using aerosols to disinfect rooms and air in medical organizations started in the 1970s and 1980s [45].

The active application of aerosol disinfection has been observed since the 2000s, when hospital-acquired infections became widespread and "cold" and "hot" fog generators appeared on the disinfection services market [46]. Currently, disinfection activities are unimaginable without aerosol technology. However, existing problems in the practice of aerosol disinfection require further study of the bactericidal efficacy of dispersed systems, optimization of equipment, and development of regulatory documents for the high-quality disinfection of premises and environmental objects. The aerosol system's instability and constant changes require determining the level of disinfection, the dispersibility of a particular disinfectant, and the directionality of its action [47]. Disinfectant aerosols must meet the following requirements: environmental safety, reduced exposure time, preservation of treated surfaces, and easy neutralization [48].

The high epidemiological efficiency of aerosol disinfection has been demonstrated in organized collectives and livestock complexes, as well as in agriculture and the disinfection of military equipment and civilian transportation. Moreover, it has been demonstrated during the construction and commissioning of new facilities, including medical institutions [49–51]. However, disinfecting ventilation systems using aerosol technologies remains an urgent concern [52].

When performing aerosol disinfection, it is important to consider the factors that contribute to achieving the desired disinfection effect. First, the temperature regime (the temperature difference between the air, walls, and inventory) is considered. Next, the dispersity of the aerosol should be taken into account: the higher the dispersity, the more particles will settle on vertical surfaces and ceilings. Additionally, it is important to consider the disinfecting effect of the disinfectant aerosol, which is most effective in the dust phase (application of a "dry" fog with droplets ranging from 2.0 to 10.0 µm in size). The quality of pre-cleaning surfaces and the quantity of spray solution also play significant roles. Finally, the compatibility of the disinfectant aerosol with the materials to be treated must be considered [53].

CONCLUSION

A systematic review was conducted to study various aspects of aerosol disinfection in different spheres. The review summarized and systematized the available data on the method's efficiency, identified its advantages and disadvantages, and substantiated the need for further improvement and expansion of the practical application of aerosol disinfection, while considering the identified features and limitations.

Aerosol disinfection holds a valuable place within the system of preventive and anti-epidemic measures, having a significant impact on reducing the risk of epidemic outbreaks of infectious diseases with various mechanisms of transmission.

ADDITIONAL INFORMATION

Authors' contribution. S.S. Smirnova: coordination of work, management of the process of collecting and analyzing literature, editing the manuscript; A.A. Kameneva, N.N. Zhuikov: collection and systematization of literary sources, analysis and generalization of data, writing the text of the manuscript; I.A. Egorov, Yu. S. Stagilskaya, D.D. Avdyunin: search and analysis of relevant scientific publications, preparation of materials for inclusion in the review, editing the manuscript. Thereby, all authors provided approval of the version to be published and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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[10] Methodological Recommendations 3.5.0315-23 for the Selection and Application of Air Purification and Disinfection in Public Buildings and Premises, dated January 30, 2023. Available at: https://base.garant.ru/408056345/?ysclid=m8yra3whgd589497795 Accessed on: November 15, 2024.

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