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The impact of ventilation systems on the risk of viral transmission (review article)

Darya V. Abramkina, Vishal Verma

Moscow State University of Civil Engineering, Moscow, Russia

ABSTRACT

Understanding the aerosol transmission mechanism of respiratory infectious diseases is crucial for predicting indoor air circulation and optimizing ventilation system design. A literature search was conducted using various keyword combinations in the PubMed database. The selection included studies examining the impact of indoor microclimate parameters and ventilation system performance on the risk of viral transmission. Since 2020, there has been increasing interest in studying how viral infections spread via aerosols within buildings and transportation infrastructure, considering the operational conditions of engineering systems. Currently, substantial evidence supports the dependence of viral aerosol viability on indoor temperature and humidity levels. Maintaining an optimal relative humidity of 40–60% at standard room temperature is essential not only for aerosol stability but also for virus neutralization. However, there is a lack of studies investigating the effects of air mobility and indoor pollution on the stability of viral pathogens. A significant body of literature confirms the influence of ventilation system efficiency on infection risk in buildings. To reduce the spread of respiratory viruses, an air exchange rate of at least 30 m^3/h per person is recommended. Based on the findings, a set of practical recommendations for ventilation system operation amidst increased disease incidence has been developed. Discrepancies between international and Russian regulatory requirements regarding indoor climate parameters and air quality standards have been identified, emphasizing the need for improved measures to mitigate the spread of respiratory infections.

Keywords: ventilation; virus; environmental pollutants; aerosol.

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Влияние систем вентиляции на риск распространения вирусов (обзорная статья)

Д.В. Абрамкина, В. Верма

Московский государственный строительный университет, Москва, Россия

АННОТАЦИЯ

Понимание механизма аэрозольной передачи респираторных инфекционных заболеваний имеет важное значение для прогнозирования воздушного режима помещений при проектировании систем вентиляции. Поиск теоретических исследований производили с помощью различных комбинаций ключевых слов в базе данных PubMed. В выборке были представлены статьи по влиянию параметров внутреннего микроклимата и условий работы вентиляционных систем на риск распространения вирусов. С 2020 г. наблюдается повышенный интерес к изучению механизма распространения вирусных инфекций посредством аэрозольной передачи внутри зданий и объектов транспортной инфраструктуры с учётом условий эксплуатации инженерных систем. В настоящее время существует серьёзная доказательная база зависимости жизнеспособности вирусных аэрозолей от температурно-влажностного режима помещений. Поддержание оптимальной относительной влажности воздуха от 40 до 60% при стандартной комнатной температуре необходимо не только с точки зрения стабильности аэрозольных систем, но и нейтрализации вирусов. Выявлено недостаточное количество исследований по влиянию подвижности и загрязнения внутренней среды на стабильность вирусных патогенов. Представлена значительная выборка статей, подтверждающих влияние эффективности работы вентиляционных систем на инфекционную нагрузку в зданиях. Для снижения риска распространения респираторных вирусов необходимо обеспечивать расход воздуха не менее 30 $м^3$/ч на человека. На основе проведённых теоретических исследований была разработана система практических рекомендаций по режиму работы систем вентиляции в условиях роста заболеваемости. Выявлены отклонения международных и российских нормативно-технических требований по обеспечению комфортных параметров внутреннего микроклимата и качества воздушной среды с точки зрения уменьшения риска распространения респираторных заболеваний.

Ключевые слова: вентиляция; вирус; загрязнители окружающей среды; аэрозоль.

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通风系统对病毒传播风险的影响（综述）

Darya V. Abramkina, Vishal Verma

Moscow State University of Civil Engineering, Moscow, Russia

摘要

了解呼吸道传染病的气溶胶传播机制对于预测室内空气流动模式和优化通风系统设计至关重要。本研究基于 PubMed 数据库，采用多种关键词组合进行文献检索，筛选了研究室内微气候参数和通风系统运行条件对病毒传播风险影响的相关论文。自 2020 年以来，关于建筑物及交通基础设施内病毒气溶胶传播机制的研究逐渐增多，并开始关注工程系统的运行条件对病毒扩散的影响。现有研究证实，病毒气溶胶的存活能力与室内温湿度条件密切相关。维持 40－60% 的相对湿度及标准室温不仅有助于降低气溶胶的稳定性，还可有效降低病毒的活性。然而，关于空气流动特性及室内污染物对病毒病原体稳定性影响的研究仍较为有限。此外，大量文献证实通风系统的效率对建筑物内感染风险有直接影响。为降低呼吸道病毒的传播风险，建议通风量至少达到每人 30 m³/h。基于本综述的研究结果，制定了在呼吸道疾病流行期间优化通风系统运行的实践建议。此外，本研究还分析了国际和俄罗斯在室内气候参数及空气质量要求方面的法规差异，强调了优化通风措施在减少呼吸道疾病传播中的关键作用。

关键词：通风；病毒；环境污染物；气溶胶。

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BACKGROUND

This systematic review presents data on the impact of ventilation systems on viral spread in buildings. Approximately 90% of recorded infectious disease cases are associated with acute respiratory infections [1]. Over the past 20 years, several major outbreaks of respiratory diseases caused by airborne pathogens have been reported [2]. High transmission intensity and prolonged persistence of indoor aerosols lead to a sharp increase in the disease incidence.

A significant number of the Middle East Respiratory Syndrome (MERS-CoV) and coronavirus (COVID-19) cases has demonstrated substantial transmission rates of hospital-acquired infections. It was established that 41% of individuals infected with COVID-19 had hospital-related transmission of this disease [3]. Prevalence of respiratory infections among healthcare professionals ranges from 0.3% to 43.3%. According to the national health report, nosocomial outbreaks in Russian healthcare facilities recorded in 2023 were primarily airborne transmission-related (79.11%). In 2020, during the COVID-19 pandemic, infection rates peaked at 130,803 cases. Upper and lower respiratory tract infections constitute the most prevalent types of nosocomial infections [4–6].

Understanding airborne transmission mechanisms of infectious diseases is critical for predicting indoor air conditions and designing ventilation systems.

METHODS

To assess the impact of ventilation systems on infectious disease transmission risk, possible mechanisms of pathogen spread indoors must be considered alongside viral stability under varying microclimate parameters.

Theoretical studies were searched for in the PubMed database using keywords. The research sample comprised reviews and systematic reviews with openly accessible full-text versions.

The keyword query «virus» AND «aerosol transmission» yielded 510 results within the past 10 years, with 393 articles published in 2020–2021, reflecting heightened research relevance during the COVID-19 pandemic. Analysis of the most relevant sources identified factors influencing viral aerosol transmission indoors: air composition, temperature, relative humidity, air movement, and ventilation system airflow configuration and exchange rate. Subsequent stage involved compiling research samples for individual parameters using queries like: (virus AND aerosol transmission) AND (relative humidity OR RH).

The addition of «ventilation» narrowed results to 89 articles since 2006. Duplicates were excluded, and studies relevant to the topic were manually selected since the term «ventilation» frequently refers to respiratory therapies (mechanical ventilation). Ultimately, 47 studies were included for review.

Notably, the impact of ventilation systems on pathogenic aerosol transmission was scarcely examined before 2020—only two articles from 2006–2020 linked infection rate increases to ventilation efficiency [7, 8]. Since 2020, there has been increasing interest in studying how viral infections spread within buildings and transportation infrastructure, considering the operational conditions of engineering systems.

RESULTS

Airborne Pathways of Viral Pathogen Spread

Key transmission paths for viral diseases indoors include cross-dispersion from infected individuals, pathogen migration from contaminated rooms to corridors and adjacent spaces, transport of contaminated air via ventilation systems, and fomite-mediated viral transmission. Earlier studies questioned aerosol transmission of viral respiratory infections [7]. However, outbreak analyses demonstrate that indoor air dynamics and ventilation performance critically influence pathogen transmission occurring exclusively through airborne infection spread in multifamily residential buildings [8, 9], public dining facilities [10], retail stores [11], fitness centers [12], and public transport [13].

An aerosol constitutes a dispersed system of suspended particles in a gaseous medium. Breathing, speaking, sneezing, and coughing release microscopic fluid droplets carrying viral pathogens. The term «aerosol» refers to particles of all sizes capable of being suspended under prevailing microclimatic conditions. Particle size variability spans 5–6 orders of magnitude. Minimal aerosol sizes are molecular clusters containing ⩾6–10 molecules exhibiting significant stability while adhering irreversibly upon surface impact without rebound. Fine-particle aerosol systems (<50 μm) pose the highest disease transmission risk due to prolonged airborne stability, lower respiratory tract penetrability, and heightened fomite transmission potential. Particles <20 μm easily penetrate the body through the larynx; those <5–6 μm reach alveolar spaces, which is typical for viral diseases like MERS-CoV [14].

The upper limit of aerosol size is defined by particle dynamic behavior and dispersion system particle stability. Emerging theory posits that pathogenic bioaerosols may include particles up to 100 μm [15, 16]. Cough- and sneeze-induced local convective airflows disperse aerosol particles over ⩾2-meter distances [17, 18].

Indoor aerosol particle aerodynamics are determined by the impact of various internal and external factors on the suspended particles, including gravitational and inertial forces, Brownian motion, electrophoretic, and thermal forces. For pathogenic bioaerosols, we should consider not only physical features influencing the system stability but also biological virus inactivation due to environmental impact.

The Impact of Microclimate Parameters on Viral Transmission Risk

Indoor Temperature and Humidity Regime

Establishing correlations between indoor temperature and humidity regime and viral aerosol dynamics constitutes a complex interdisciplinary challenge, requiring determination of physicochemical properties for each specific viral disease.

Respiratory disease transmission risk is higher in cold-climate countries due not only to immune suppression at sub-zero temperatures but also to low air moisture content [19]. Hot and humid regions, particularly during rainy seasons, are less susceptible to aerosol-driven viral outbreaks, though tropical climates increase contact transmission potential [20].

Respiratory virus inactivation due to protein and nucleic acid denaturation occurs at elevated air temperatures (27–70 °C) [21], exceeding permissible indoor parameters. Thus, it is excluded from further consideration.

Indoor relative humidity (RH, φ, %) critically influences bioaerosol system stability by affecting both counts of suspended particles during breathing and coughing and viral aerosol survivability [20]. Higher RH slows exhaled droplet evaporation, increasing large-particle concentrations that gravitationally settle. Ideal conditions would show minimal pathogen sedimentation for isolated droplets in stagnant air [22]. Turbulent flows from human movement, door opening, natural ventilation, and operation of ventilation systems reduce droplet evaporation time while extending dispersal range and sedimentation duration [23]. Lower RH accelerates aerosol particle evaporation forming droplet nuclei that remain suspended for hours, enabling prolonged infectious transmission [24].

Maintaining target RH is essential not only for aerosol system stability control but also for viral neutralization. Researchers identify various viral viability dependencies on air humidity: increased inactivation with rising RH, decreased inactivation with rising RH, and U-shaped viability [21]. Respiratory viruses (influenza, SARS-CoV-2) exhibit U-shaped viability [25–27], enabling determination of optimal indoor RH ranges. Thus, 40%–60% RH at room temperature represents the ideal humidity for reducing airborne respiratory infection spread [28, 29].

Russian regulatory documents (GOST 30494-2011, GOST 12.1.005-88) specify optimal and admissible RH requirements for cold and warm seasons of the year. For residential and public buildings, the optimal RH in winter and summer should be within 30%–45% (admissible ⩽60%) and 30%–60% (admissible ⩽65%), respectively. For industrial buildings, microclimatic parameters depend on the work intensity, with annual optimal RH considered 40%–60% (admissible ⩽75%) The design of ventilation systems must maintain admissible parameters throughout occupied areas within buildings. Achieving the most comfortable optimal criteria requires technical specifications or economic justification. Most buildings fail to maintain RH ranges that reduce the risk of respiratory virus transmission during cold seasons.

Air Mobility in Building Work Areas

Alongside temperature and relative humidity, air movement velocity (mobility) in work areas significantly influences indoor thermal-physical conditions.

Air remains in continuous motion within ventilated spaces. Uneven air distribution creates local stagnation areas with elevated temperatures and pollutant concentrations. Low air mobility forms a stagnant personal microclimate around individuals—quickly saturated with exhaled moisture and exhibiting higher temperatures.

Increased air velocity accelerates pathogenic aerosol dispersion through spaces, heightening contamination risk for individuals distant from the source [30]. On the other hand, greater air mobility enhances evaporation rates and droplet nuclei formation, accelerating aerosol particle sedimentation. The optimal air velocity for minimizing viral transmission risk in work areas remains understudied. The reviewed research sample reveals no recommended mobility range for reducing airborne infection likelihood.

Indoor Air Quality

Poor air quality and elevated dust levels accelerate viral spread [31] and indirectly increase respiratory mortality [32].

Enclosed spaces harbor volatile organic compounds, biological contaminants, vapors, gases, and dust. Infected individuals release aerosol clouds through talking, breathing, and coughing that disperse throughout rooms, depositing on enclosure structures, furniture, and equipment surfaces and binding to airborne pollutants. Fine particulate matter, also known as PM2.5, acts as viral pathogen vectors, penetrating deep into human airways [33]. Airborne organic surfactants stabilize viral aerosols and prolong their viability [34].

All aforementioned factors governing viral aerosol dispersion intensity and stability depend on building engineering system efficacy. This research further outlines primary ventilation-based strategies for reducing indoor infectious loads.

Impact of Ventilation Systems on the Risk of Viral Transmission

After the COVID-19 pandemic, numerous international standardization bodies and engineering associations recognize the need for implementing «proper ventilation» in enclosed spaces to reduce infectious loads [35]. Unfortunately, current scientific research insufficiently addresses specific measures for modifying ventilation system operations during periods of elevated disease incidence. General guidelines include reducing room occupancy, periodic natural ventilation, and increasing air exchange rates [36–38]. However, practical recommendations for establishing special operational regimes for ventilation systems in residential, public, and administrative buildings to mitigate viral transmission risks remain undeveloped.

Mechanical and Natural Ventilation Systems

Supplemental natural ventilation serves as an effective measure to reduce viral load in indoor spaces. In kindergartens, schools, universities, and offices, mandatory ventilation during breaks is recommended. For layouts with windows on opposite facades, natural flow-through (cross) ventilation should be implemented. Studies demonstrate that cross-ventilation significantly decreases viral load: in a 100 m^2 room, virion counts drop from 10,000 to 0 within 15 minutes at a consistent air velocity of 1.5 m/s [39]. Unilateral ventilation is less efficient, but still reduces viral load by half.

During winter, outdoor air typically has low moisture content. When naturally ventilated through open windows or vents, this air enters rooms and warms via heating systems, potentially increasing thermal energy consumption in residential and public buildings by up to 35% annually [40]. Concurrently, relative humidity rapidly declines, reaching 10%–15%. As discussed earlier, low RH causes aerosol particles shrinking to smaller sizes due to evaporation of their aqueous envelopes. Particles smaller than 50 μm become difficult to capture and remove effectively via ventilation systems [41].

When implementing natural ventilation, outdoor air quality must be ensured and prioritized. Periodic ventilation in areas with high suspended particle concentrations may compromise indoor air quality and reduce viral aerosol removal efficacy. Respiratory disease incidence increases with elevated concentrations of airborne suspended particles [42]. Research investigating dust content in museum environments [43] indicates that drum-type humidifiers not only maintain optimal relative humidity (40%–60%) but also substantially reduce fine particulate matter in the air. Dust concentration reductions exceeding 70% were observed for particles sized 2.5–10.0 μm. Drum-type humidifiers operate via natural evaporation, preventing humidity from exceeding 60%. Local devices allow for decreasing airborne respiratory virus viability.

Centralized ventilation and air-conditioning systems increase ariborne infection transmission risks across building heights, particularly in multi-story residential complexes equipped with natural exhaust ventilation systems featuring vertical collection ducts and warm attics. Under adverse weather conditions, «backdraft» effects may occur, allowing contaminated air from ventilation ducts to infiltrate apartments through exhaust grilles [44].

Mechanical ventilation systems effectively deliver clean outdoor air and remove indoor contaminants. However, design, installation, or operational errors can create tragic scenarios where ventilation itself becomes an infection source. Hospital ward inspections [45, 46] revealed PCR-positive samples from ventilation grilles and exhaust units, confirming viral spread through ductwork with accumulation on equipment. Delayed filter replacement and failure to clean and disinfect ducts facilitate pathogen transmission and disease outbreaks indoors. These issues are exacerbated in air-recirculation systems, as standard coarse filters in public buildings cannot efficiently capture particles below 5 μm. Therefore, during increased disease incidence, mandatory inspection and cleaning of ventilation systems and transition to direct-flow air configurations is recommended.

Required Air Exchange Rate

The COVID-19 Expert Group identified three primary factors enabling disease outbreaks in buildings: enclosed spaces with inadequate air exchange, overcrowded rooms with high occupancy, and close contact [47]. Increased air exchange rates reduce infectious loads indoors. The recommended airflow rate per person is at least 30 m^3/h [47]. This value is based on the long-term experience in the field of building hygiene and occupational safety research, representing a fundamental requirement. According to Russian ventilation design standards (SP 60.13330.2020), minimum air exchange rates for intermittently occupied spaces are at least 20 m^3/h, which is below international recommendations. Particular risk arises in densely intermittently occupied spaces: cinemas, theaters, airport and railway lounges, and shopping centers. Brief exposure does not eliminate transmission risk, as viruses remain infectious in aerosols for several hours [48]. High COVID-19 viral concentrations detected in canteens, conference halls, and restrooms confirm cross-transmission during brief exposures [49, 50].

Recommended minimum airflow rates for outbreak prevention must account for pathogen virulence. To determine standard airflow when addressing the SARS-CoV-2 delta variant, it may be necessary to establish higher exchange rates incorporating optimal indoor air velocity requirements for infection control [51].

Air Exchange Configuration Schemes

Controlling airflow patterns indoors is essential for maintaining high air quality. Research demonstrates that changes in overall and local infection risks from airborne transmission under different air distribution schemes are complex and non-linear [52].

Mixed air distribution with «top-to-top» supply and exhaust achieves uniform temperature and pollutant dispersion within the space under ideal conditions. While this approach dilutes aerosol concentrations, insufficient air exchange may accelerate pathogen spread throughout the space [53]. High airflow volumes in compact areas like densely-seated cafés and restaurants often necessitate close proximity between supply and exhaust vents. Supply air entering the space fails to reach work areas due to immediate capture by exhaust vents. This effect is called «short air circulation». Stagnation areas are formed in the work area with elevated temperatures and contaminant levels.

Displacement ventilation supplies air to the work area with upper-level exhaust. Thermal buoyancy forms vertical convection currents, stratifying temperature and contaminants along room height. Displacement ventilation effectiveness against viral transmission depends on positioning between infected individuals and other people in the room. When people remain seated ⩾1.5 m apart (in case of COVID-19), displacement ventilation reduces infection likelihood more effectively than mixing ventilation; however, effectiveness reverses when distances decrease [54].

Complex schemes combining mixed air distribution with personalized ventilation demonstrate superior effectiveness [53]. Personalized supply air delivery directly to breathing zones reduces cross-infection risk by ⩽50% [53, 55].

DISCUSSION

The majority of reviewed articles outline significant impact of the ventialtion system efficacy on the risk of respiratory infection spread. There is an insufficient body of research regarding aerosol viability dynamics of viral infections under varying air pollution levels. The reviewed research sample reveals no recommended mobility range for reducing contamination likelihood. More extensive research is needed on local humidifier use and their effects on respiratory virus viability. Discrepancies were identified between international and domestic regulatory requirements for maintaining comfortable indoor environmental conditions and air quality standards.

CONCLUSION

Compelling and sufficient evidence exists for aerosol transmission of viral respiratory infections, underscoring the urgent need for interdisciplinary research on how microclimate parameters and engineering system operation affect disease spread.

Based on theoretical studies, a set of practical recommendations has been compiled to reduce outbreak likelihood in public and residential buildings.

1. Optimal relative humidity levels should be maintained indoors (40%–60%). Local drum-type humidifiers can reduce infectious loads indoors by purging fine particulate matter and suppressing viral pathogen viability when properly operated.

2. The recommended air exchange rate per person is at least 30 m^3/h.

3. During transitional and cold seasons—peak periods for respiratory disease transmission—control for ventilation system efficacy should be intensified (including operational checks and design compliance), ductwork and equipment cleaning and disinfection should be conducted, and timely filter replacements should be ensured.

4. Personalized ventilation systems allow reducing viral aerosol transmission risk.

ADDITIONAL INFORMATION

Authors'contribution. D.V. Abramkina — literature review, collection and analysis of literary sources, writing the text and editing the article; V. Verma — literature review, collection and analysis of literary sources, preparation and writing of the text of the article. All authors confirm that their authorship meets the international ICMJE criteria (all authors have made a significant contribution to the development of the concept, research and preparation of the article, read and approved the final version before publication).

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ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ

Вклад авторов. Д.В. Абрамкина — обзор литературы, сбор и анализ литературных источников, написание текста и редактирование статьи; В. Верма — обзор литературы, сбор и анализ литературных источников, подготовка и написание текста статьи. Все авторы подтверждают соответствие своего авторства международным критериям ICMJE (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией).

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AUTHORS' INFO

***Darya V. Abramkina,** Cand. Sci. (Engineering), Assistant Professor;
address: 26 Yaroslavskoye hwy, Moscow, Russia, 129337;
ORCID: 0000-0001-8635-1669;
eLibrary SPIN: 2376-9125;
e-mail: dabramkina@ya.ru

Vishal Verma, Graduate Student;
ORCID: 0009-0006-5290-9162;
e-mail: vishalverma2k16@gmail.com

ОБ АВТОРАХ

***Абрамкина Дарья Викторовна,** канд. техн. наук, доцент;
адрес: Россия, 129337, Москва, Ярославское ш., д. 26;
ORCID: 0000-0001-8635-1669;
eLibrary SPIN: 2376-9125;
e-mail: dabramkina@ya.ru

Верма Вишал, аспирант;
ORCID: 0009-0006-5290-9162;
e-mail: vishalverma2k16@gmail.com

* Corresponding author / Автор, ответственный за переписку