Photochemistry and Photobiology, 2021, 97: 493–497

Special Issue Invited Review

Air Disinfection for Airborne Infection Control with a Focus on COVID-19: Why Germicidal UV is Essential†

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Received 7 January 2021, accepted 16 March 2021, DOI: 10.1111/php.13421

ABSTRACT

Aerosol transmission is now widely accepted as the principal way that COVID-19 is spread, as has the importance of ventilation—natural and mechanical. But in other than healthcare facilities, mechanical ventilation is designed for comfort, not airborne infection control, and cannot achieve the 6 to 12 room air changes per hour recommended for airborne infection control. More efficient air filters have been recommended in ventilation ducts despite a lack of convincing evidence that SARS-CoV-2 virus spreads through ventilation systems. Most transmission appears to occur in rooms where both an infectious source COVID-19 case and other susceptible occupants share the same air. Only two established room-based technologies are available to supplement mechanical ventilation: portable room air cleaners and upper room germicidal UV air disinfection. Portable room air cleaners can be effective, but performance is limited by their clean air delivery rate relative to room volume. SARS-CoV-2 is highly susceptible to GUV, an 80-year-old technology that has been shown to safely, quietly, effectively and economically produce the equivalent of 10 to 20 or more air changes per hour under real life conditions. For these reasons, upper room GUV is the essential engineering intervention for reducing COVID-19 spread.

INTRODUCTION

It is not an exaggeration to claim that the most effective, evidence-based, cost-effective, safe and available engineering intervention to disinfect air is being largely ignored during a lethal viral pandemic spread predominantly by the airborne route. That intervention is germicidal ultraviolet (GUV) air disinfection (1).

Given the current COVID-19 pandemic, this perspective will focus on SARS-CoV-2 virus transmission, but GUV is effective against all known microbial pathogens (2). GUV is widely used for potable water disinfection where its efficacy against a wide range of water-borne pathogens is well established (3). Because GUV works primarily by causing damage to nucleic acids (DNA or RNA), universally present in pathogenic microbes, its efficacy against protozoa, fungi, bacteria and viruses is assured, with some variability in the dose required (4). Fungal spores are among the hardest pathogens to inactivate, but GUV is effective in reducing mold growth in air conditioning coils and drip pan surfaces (5). Although there is some potential among microbes to repair nucleic acid UV damage (photoreactivation), tests in biological test chambers and field studies shows no significant resistance to GUV microbial inactivation (6). Drug resistant pathogens, such as multidrug resistant tuberculosis, are fully UV susceptible (1).

AIRBORNE TRANSMISSION AND THE ROLE FOR IN-ROOM AIR DISINFECTION

For many months early in the pandemic, the predominant transmission pathways of COVID-19 were unclear and largely attributed to large droplets and surface contact spread (7). Determining exactly how respiratory viruses transmit from person to person is challenging. The mode of spread of common upper respiratory viral infections and seasonal influenza have long been controversial—large respiratory droplets and surface contact spread versus airborne spread by minute respiratory droplets (8). Not only is the distinction blurred in most cases, many respiratory infections spread by all 3 pathways. Now, well into the epidemic, the evidence suggests less transmission by large (ballistic) droplets and surfaces, and more by the airborne route. The Washington State Chorus transmission event has proven informative (9). Careful interviews with members showed that social distancing and contact precautions largely precluded significant large droplet and surface contact spread, and that the extensive transmission of COVID-19 and 2 deaths were almost certainly the result primarily of airborne transmission. Likewise, Jones has attributed only 8% of transmission among healthcare workers to surface contact—initially said to be a major pathway of transmission (10). The great seasonal changes in transmission between warmer and colder months is largely attributable to indoor airborne transmission, although proximity indoors also favors large droplet and surface contact spread (11).

For airborne infections, the most common way to reduce risk indoors is dilution and removal of infectious particles in room air through ventilation (12). Very large rooms (an auditorium or sports arena) reduce airborne infection risk indoors in the short

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†This article is part of a Special Issue dedicated to the topics of Germicidal Photobiology and Infection Control

run by dilution in large volumes of air regardless of ventilation —similar to being outside. Ultimately, natural or mechanical ventilation of rooms of any size is commonly used to dilute and remove air contaminants (13).

Although SARS-CoV-2 is now believed to be predominantly airborne spread, it does not appear to be spread though ventilation systems, as might be true for a few other airborne infections, such as TB and measles. The reason likely is do with the relatively large dose required for infection, and possibly because of the instability of the virus in air (14). Compared to SARS-CoV-2, for example, *Mycobacterium tuberculosis* is protected by a thick waxy coat and is quite stable in air. Moreover, the infectious dose of *M. tuberculosis* is as little as a single infectious droplet containing one or just a few bacilli (15). In contrast, the infectious dose of SARS-CoV-2 is believed to be somewhere between 300 and 1000 viruses (14). Unlike TB, billions of SARS-CoV-2 particles can be released by an infectious person, albeit for just a few days. It is likely that dilution in room air explains a proximity risk gradient initially attributed primarily to (and indistinguishable from) close range ballistic large droplets. Once exhausted into the room ventilation return ducts, infectious droplet nuclei are further diluted by air from other rooms, filtered, even if crudely, and very likely returned to occupied rooms at concentrations largely below the infectious dose and possibly damaged by recirculation. A recent literature review could find no reports of recirculated COVID-19 transmission (16).

The implication of this local, in-room transmission pattern is that the current focus on high-level air filtration in central HVAC systems is unlikely to be very helpful for COVID-19 mitigation (17). There are other reasons to filter recirculated air, airborne particulates and pollen, for example. But, even if recirculation of active SARS-CoV-2 virus were well documented, it is little comfort to persons sharing a room with an unsuspected, infectious COVID-19 source case to know that the air will be disinfected only after it leaves the room. To be highly effective, air disinfection must occur in the same room occupied by an infectious source and persons at risk of infection.

For much of the world, especially in warm climates, room air disinfection is by natural ventilation. HVAC systems are rare, and unlikely to be well-maintained in resource-limited settings. They are often neglected in resource-rich settings. Natural ventilation can be extraordinarily effective in reducing the risk of transmission of airborne infections, such as TB (18). Its limitations are that buildings are not always designed for natural ventilation, and it is often sub-optimal in practice. Windows are often closed at night and during inclement weather. Wind direction and speed are often variable, and both severe air pollution and intolerable heat are increasingly requiring that widows be closed in favor of air conditioning in settings like India. The most common and growing type of air conditioning, ductless or split systems, provide no outside air ventilation. The result of closing windows and turning on ductless air conditioning is a steep rise in rebreathed air fraction (RAF)—that fraction of a breath recently exhaled by others—a good correlate of risk of airborne infection (19). RAF is reasonably well estimated by ambient CO_2 levels (20). A recent demonstration showed a doubling of RAF and risk of infection within an hour of closing a window and turning on the split system AC (19).

ALTERNATIVES OR SUPPLEMENTS TO NATURAL VENTILATION

Industrialized countries in temperate and cold climates tend to prefer mechanical ventilation (HVAC) systems in public buildings. Generally, HVAC systems are expensive to install, operate and maintain and should be designed into the building at the time of construction. HVAC system fresh air delivery rates are designed for occupant comfort—odor control, CO_2 removal, temperature and humidity control. A well-designed and maintained HVAC system can perform these functions well. However, HVAC systems are not designed for airborne infection control—except in hospitals with airborne isolation rooms built for that purpose. Comfort level ventilation may be as little as 1 or 2 air changes per hour (ACH), depending on room or building occupancy, whereas CDC recommends 6–12 ACH for respiratory isolation and procedure rooms (21). Most HVAC systems in public buildings do not have the duct or blower capacity to be increased to 6 ACH (22).

One ACH is defined as having occurred when a volume of air equal to the volume of the room is delivered, and an equal volume of well mixed air is exhausted from the room. In a well-mixed room, one ACH removes approximately 63% of the air and air contaminants, including airborne pathogens, a second ACH removes 63% of what remains—a total of 86% removal, and so on. However, when infectious particles are being continuously generated in an occupied room, the calculation of ventilation efficiency is not so simple, and the mass balance Wells-Riley equation is used to estimate the difference between generation and removal rates of infectious particles. When the mass balance approach is used, with good estimates of the rate of infectious particle generation, even 6 to 12 ACH may be inadequate to prevent transmission, depending on the duration of exposure (22).

Only a fraction of HVAC air is normally outside (fresh) air—the rest being recirculated air from other parts of the building. For comfort purposes, recirculated air dilutes odors, humidity, and other airborne contaminants to tolerable levels throughout the building. As noted above, for a few highly transmissible airborne pathogens like TB and measles, ventilation systems have been implicated in transmission despite dilution. So far, that does not appear to be the case for COVID-19. If 10–20% of ventilation is outside air the rest recirculated, high level air filtration (MERV 13 or above) converts 100% of the air to the equivalent of outside air. However, it does not increase the volume of dilutional ventilation in the room—thereby reducing risk of transmission. In fact, if higher-level filtration increases flow resistance and, depending on fan load capacity, can reduce room ventilation, making transmission in the room more, not less likely.

Apart from natural and mechanical ventilation, only two practical and proven methods of supplemental air disinfection exist: upper room germicidal ultraviolet fixtures, and room air cleaners (using filters, UV or other means of disinfection). Portable room air cleaners seem like a simple solution, and are being widely marketed for COVID-19, but their clean air delivery rate (CADR) often results in room air changes equivalent to 1 or 2 per hour, depending on room volume—inconsequential protection against most airborne infections. Since most filters and UV systems employed for air disinfection remove or inactivate close to 100% of airborne pathogens, CADR is essentially equivalent

to the flow rate delivered by the device. For less efficient filters, CADR reflects both flow and filter efficiency. Dividing the CADR flow rate per hour by the room volume results in the equivalent ACH (EqACH). Larger, high-output machines can produce the desired 6 to 12 ACH, but noise, drafts and recapture of just processed air (short-circuiting) limits the practical utility of room air cleaners in many settings—large volume rooms in particular. That said, they are often the only workable solution for some situations, for example, a poorly ventilated gym with ceilings too low for germicidal UV. Some RACs are better designed than others to minimize recapture, drafts and noise, and provide useful CADR. Generally, it does not matter if air disinfection is accomplished by filters, enclosed GUV, cold plasma or other technologies. What matters in applying portable room air cleaners is CADR relative to room volume, recapture, drafts and noise.

WHY UPPER ROOM GUV IS SO EFFECTIVE AND COST-EFFECTIVE COMPARED TO OTHER TECHNOLOGIES

In contrast to mechanical ventilation and room air cleaners, upper room GUV air disinfection with good air mixing has been shown under real-life conditions to produce the equivalent of adding as much as 24 room air changes per hour, quietly, safely and sustainably (1). Under high-risk conditions, especially where few buildings have efficient mechanical ventilation systems, the only practical approach to the environmental control of airborne infection is upper room GUV. GUV is also used for room surface disinfection, but that application uses direct, high-intensity UV in unoccupied rooms, for example, between the admission of new patients.

Upper room GUV is so highly effective because such large volumes of room air are decontaminated at one time—the upper two feet (22% of room volume), for example, of a room with a nine-foot ceiling. Convective air currents generated by room occupant body heat is highly effective in mixing room air between the upper and lower room, but low-velocity ceiling fans assure mixing silently and inexpensively, contributing to the superior performance of upper room UV compared to other approaches to room air disinfection. Air in occupied rooms is also effectively mixed by occupant movement, ventilation diffusers, and supply air temperature gradients. As long as room air is well-mixed, fan direction and speed are not critical. Although microbes have less expose time with rapid transit through the upper room, vertical recirculation with fast mixing assures more frequent upper room exposure with a similar UV dose over time. In an unpublished study, Volchenkov and Jensen, then with the CDC, aerosolized test bacteria and spores into a test patient room in a TB hospital in Vladimir, Russia. They compared the effectiveness and the cost effectiveness of upper room UV to mechanical ventilation and three different room air cleaners, including the expensive plasma apparatus used in the Soyuz Space Capsule. The results, shown below (Fig. 1), were compared both by the dollar cost (at that time in Russia) of one equivalent ACH, and in the cost-effectiveness, considering the amortized cost of installing and running mechanical ventilation. They showed that upper room was by far the least expensive way to disinfect air, per eqACH, and also the most cost effective by a factor of more than nine.

WHAT ARE THE BARRIERS TO WIDER IMPLEMENTATION OF GERMICIDAL UV FOR COVID-19 AND OTHER CURRENT AND FUTURE AIRBORNE INFECTIONS?

It is remarkable that a technology as safe and effective as upper room germicidal UV is not routinely in use in buildings where airborne infection is likely. Until the COVID-19 pandemic, those might have included healthcare facilities, homeless shelters, nursing homes and jails/prisons. But this and the ongoing threat of pandemic influenza have shown the necessity of air disinfection in a wider variety of public settings to reduce community transmission. Homes are not normally considered as priorities for air disinfection since persons continuously living together have a shared risk profile and environmental interventions are likely, at best, to delay transmission, not prevent it entirely, when a household person is infectious.

The sale of questionable UV products, stimulated by pandemic COVID-19, is another barrier to the legitimate use of both time-tested and new, evidence-based UV devices. UV wands of any wavelength and 222 nm UV portals designed for surface decontamination, for example, are products that defy logic and could be dangerous. Wands are often sold for home use where they are likely to be both ineffective and dangerous. Although there are legitimate, evidence-based uses for UV surface decontamination—decontaminating hospital rooms between patients, for example, UV is not an ideal surface decontaminant, requiring strategies to expose pathogens in shadowed surfaces with UV doses known to be effective. Walking into a 222 nm UV portal and spinning around for 20 s is unlikely to present a risk, but equally unlikely to provide any benefit whatsoever against an airborne respiratory pathogen.

Among the barriers to wider implementation of upper room germicidal UV (mercury and LED sources) are lack of awareness of the technology, misinformation about safety or efficacy, lack of technical experts to plan, install, commission, and maintain upper room UV systems. For newer whole room "Far UV," the current barriers include unfamiliarity with the technology, safety concerns, dosing guidelines, cost, availability and a very limited lamp life for krypton chloride sources. These issues are discussed in this collection of papers.

EFFICACY OF UPPER ROOM GERMICIDAL UV AND DOSING CONSIDERATIONS

The history of germicidal air disinfection has been well documented (23). Most efficacy is based on laboratory and biological test chamber studies using culture as an endpoint, but three human field trials merit mention. In 1942, Wells and Wells reported the application of upper room 254 nm germicidal UV lamps to reduce measles transmission in schools in two Philadelphia suburbs (24). Measles is the most infectious respiratory virus known, believed to be predominantly airborne. More recently, both Escombe in Peru and Nardell and colleagues in South Africa set up human-to-guinea pig TB transmission facilities where the concentration of infectious doses (quanta) in ward exhaust was quantified by measuring the TB infection rate of identical guinea pigs breathing air from TB wards on alternate days when upper room UV was on or off. Although the details of the experiments varied considerably, the results (with

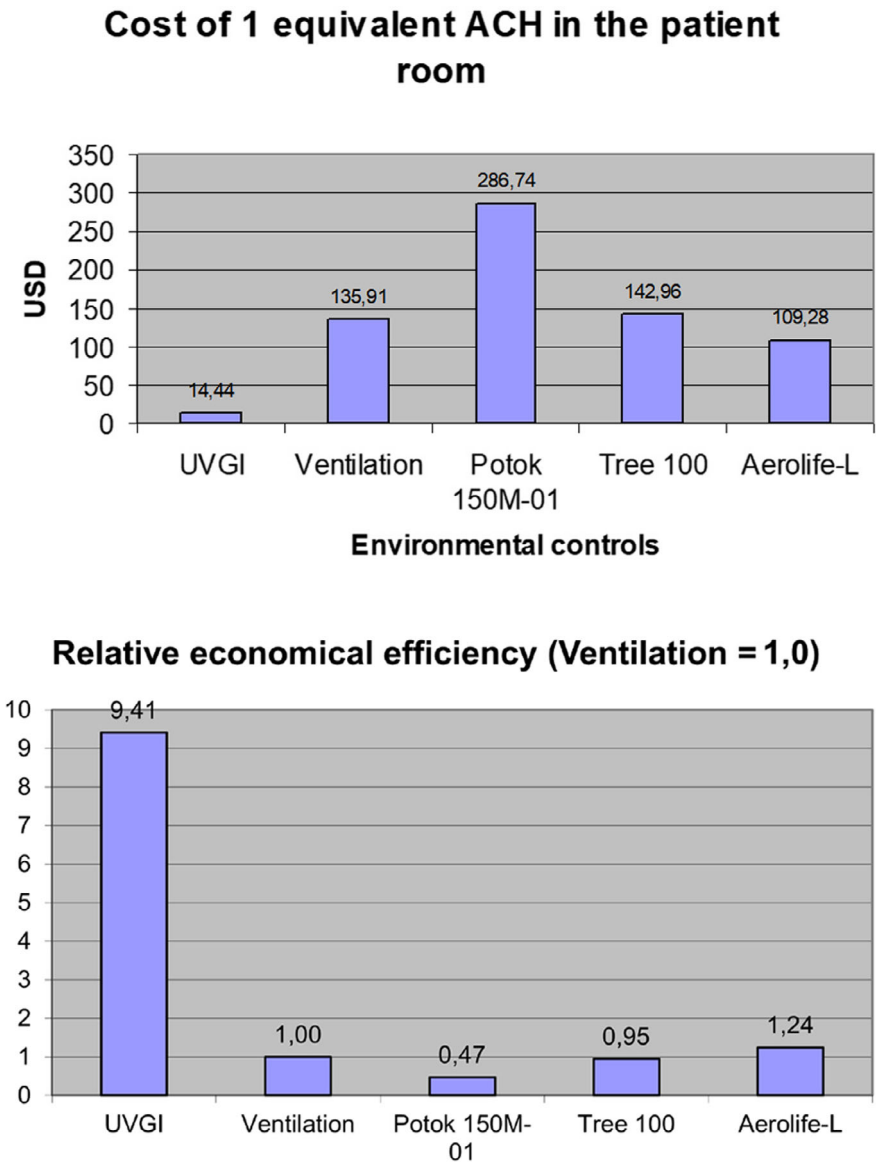

Figure 1. Unpublished experiment by Volchenkov and Jensen comparing upper room UV to mechanical ventilation and three different room air cleaners, the Potok model having been used in the Soyuz Space capsule. (Top) The cost of one ACH was calculated for each intervention. (Bottom) Ventilation is set as 1 for comparison purposes, and UV was more than 9 times cost-effective.

statistical corrections for more frequent unmeasurable double or triple infections under control conditions) showed approximately 80% protection in both settings (1,25). Whereas with surface disinfection it is common to expect pathogen reductions of 3 logs or more, these risk reductions of less than 1 log were considered excellent for air disinfection with ongoing pathogen generation. As noted above, greater and greater equivalent air changes (due to UV) are needed for smaller and smaller increments in protection. The equivalent air changes produced in the South African study was 24 in addition to 6 ACH produced by the ventilation system.

In the South Africa study, a detailed assessment of the UV installation allowed the authors to propose evidence-based guidelines—for the first time based on total fixture UV output (fluence) and total air volume treated. A second, as yet unpublished, study in South Africa using locally made fixtures at 1/3 less dose had similar results, allowing a reduction of the published 17 mW total fixture output per cubic meter room volume, to 12 mW m^{-3} room volume. Although these are a workable, evidence-based dosing guideline, further adjustments will likely be needed for very distinctive architectural features, like the very high ceilings of an atrium or big box store. An important factor in UV fixture deployment is average ray length, since UV photons/rays are active until absorbed. A computer assisted lighting program, Visual™, has been adapted and validated for use with UV (26). It has the ability to estimate average UV fluency rates anywhere in the treated space if the fixtures used have been fully characterized by gonioradiometry. The ceiling fans used in the South African study produced a calculated 57 vertical air changes per minute between the upper and lower room. However, as mentioned, fan speed and direction is not critical, and we recommended at least 25 vertical air changes per minute (1).

Dosing for Far UV is less complicated because it need not be confined to the upper room and occupant safety is less of a concern due to extremely limited tissue UV penetration (27). Currently, levels are being applied that are likely to result in actual human exposure within the published ACGIH TLV guide dosing. Actual exposure, however, must account for time-motion reduction in eye and skin exposure as occupants move within rooms. For example, a worker moving in and out of a portion of a room treated with 222 nm UV, spending only a fraction of 8 h exposed, and even less directly on eyes or skin, should not be subjected to the full 8-h TLV as if exposure were continuous stare time at the fixture. In an upper room, 254 nm UV personal monitoring study of nurses, patients, teachers, office workers and other occupants, First and colleagues found no 8-h exposure greater than 1/3 of the TLV despite estimates from point eye-level measurements that indicated potential over-exposure (28). Additional time-motion research is needed in applying exposure limits to UV in order to obtain maximum safe UV protection from potentially lethal pathogens. Other papers in this collection deal with UV eye and skin safety in detail.

SUMMARY—WHY GERMICIDAL UV IS ESSENTIAL FOR AIRBORNE INFECTION CONTROL

Germicidal UV, primarily upper room UV, has for over 80 years provided a safe and highly effective way to disinfect air in occupied rooms where person to person transmission is likely to occur. Quantitatively, where applicable, no other technology approaches the equivalent air changes per hour that can be produced by upper room UV, silently, safely and cost-effectively. For COVID-19, it is essential that engineering strategies target transmission in occupied rooms—more so than in the ventilation system, given the paucity of evidence of recirculated virus. Barriers that need to be addressed include increased public and professional awareness of how it works, its safety and efficacy. Training and certification of more UV technicians are needed. Time-motion exposure research is needed to rationally apply current exposure guidelines, assuring both UV safety and optimal protection from airborne pathogens.

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