Energy Implications of Using Upper Room Germicidal Ultraviolet Radiation and HVAC Strategies to Combat SARS-CoV-2

Belal Abboushi, Gabe Arnold, Jason Tuenge, Tim Salsbury: Pacific Northwest National Laboratory
Jason DeGraw: Oak Ridge National Laboratory
Ed Nardell: Harvard Medical School

ABSTRACT

Upper Room Germicidal Ultraviolet (UR-GUV) radiation had been used to neutralize pathogens for many decades before the COVID-19 pandemic. UR-GUV has recently been recommended by the CDC as a method to slow the spread of the SARS-CoV-2 virus. Other recommended mitigation strategies include an increased air change rate, increased introduction of outdoor air, and improved HVAC filtration. Increasing the introduction of outdoor air and improving filtration assume that SARS-CoV-2 virus recirculates within HVAC systems, remains infectious, and contributes importantly to transmission. Most evidence to date found that transmission of SARS-CoV-2 virus occurs in the room where the infectious source and susceptible occupants breathe the same air. Nevertheless, this paper maintains the assumption of infectious SARS-CoV-2 recirculation for the purposes of comparing germicidal efficacy and energy use in published studies of four mitigation measures: UR-GUV, increased air change rate, increased introduction of outdoor air, and improved in-duct filtration. The reviewed studies found that the germicidal efficacy of UR-GUV equates to that of multiple air changes using pathogen-free air, and is more effective at reducing infection risk than MERV 13 filtration. Regarding energy use, UR-GUV uses substantially less energy than mechanical air changes or increasing the introduction of outdoor air. Limitations of reviewed comparisons, application considerations, and future research steps are discussed.

1. Introduction

COVID-19 spreads from one person to others via infectious aerosols or droplets with transmission almost exclusively occurring indoors (Greenhalgh et al. 2021). To reduce airborne transmission in buildings, several environmental mitigation strategies have been recommended such as upper room GUV (UR-GUV) which irradiates the upper room volume with no direct irradiation to the occupied zone (CDC 2021), increasing the air change rate in healthcare facilities and schools (CDC 2003; Jones et al. 2020), increasing the outdoor air (OA) fraction above code as much as the system or space allows, and using high-efficiency in-duct filters with a minimum efficiency reporting value (MERV) 13 (ASHRAE 2021). OA fraction is the ratio of the volumetric flow rate of outdoor air to the total supply airflow rate, so increasing OA fraction reduces the fraction of recirculated air (ASHRAE 2022). Figure 1 shows the four mitigation strategies that will be reviewed and discussed in this paper.

These strategies rely on different assumptions related to intra- and inter-room transmission. Improving filtration and increasing OA fraction assume substantial recirculation of SARS-CoV-2 virus in a still infectious state and that air recirculated through HVAC systems constitutes a substantial portion of transmission within buildings with HVAC systems. However, two years into the COVID-19 pandemic, there is little evidence that SARS-CoV-2 virus recirculation does contribute importantly to transmission compared to direct person-to-person transmission between occupants in rooms. While the absence of convincing reports of HVAC-mediated transmission of COVID-19 is not by itself proof that it is not occurring at some level, the absence of credible case reports strongly suggests that recirculated virus is unlikely to be nearly as important as intra-room transmission. Reports of HVAC-mediated transmission of other airborne infections such as measles and tuberculosis are easily cited from outbreaks in schools (Riley, Murphy, and Riley 1978), on ships (Houk 1980), in an office building (Nardell et al. 1991), and in clinics (CDC 1989), to name a few examples. Nevertheless, for this review of the literature on the germicidal efficacy and energy use comparisons of four interventions (increasing air change rate, increasing OA fraction, improved in-duct filtration, or UR-GUV), we will assume that SARS-CoV-2 recirculation *does occur* and that these are all potentially effective mitigation strategies.

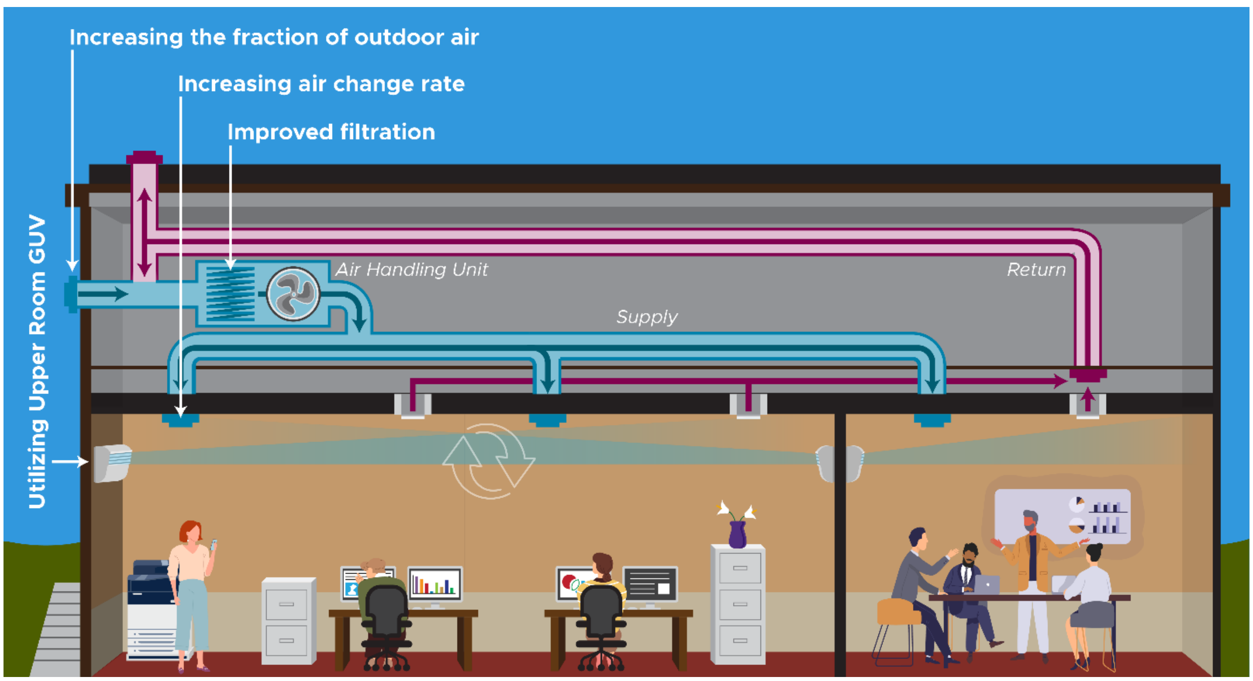

Figure 1: A diagram of the four mitigation strategies reviewed in this paper (illustration by Cortland Johnson, Pacific Northwest National Laboratory).

Making changes to HVAC operation or implementing new mitigation strategies can substantially increase building energy consumption compared to a pre-COVID baseline. For example, increasing the OA fraction to 100% across the U.S. commercial building stock would increase annual energy use by 24.5%, which comprises of 75.2% increase in gas consumption and 8.4% increase in electric consumption, as shown in Figure 2 (CaraDonna and Trenbath 2021). The same study showed that applying MERV 13 filtration across the U.S. commercial building stock would increase annual energy use by 0.8%.

For US schools, improving in-duct filtration to MERV 13 and increasing the air change rate to reduce infection risk below 1% would increase the annual energy cost per square meter by about fivefold (Cai et al. 2022). Given these considerable negative impacts on energy use and greenhouse gas emissions, it is important to consider alternative or complementary energy-efficient mitigation strategies that are effective at reducing infection risks.

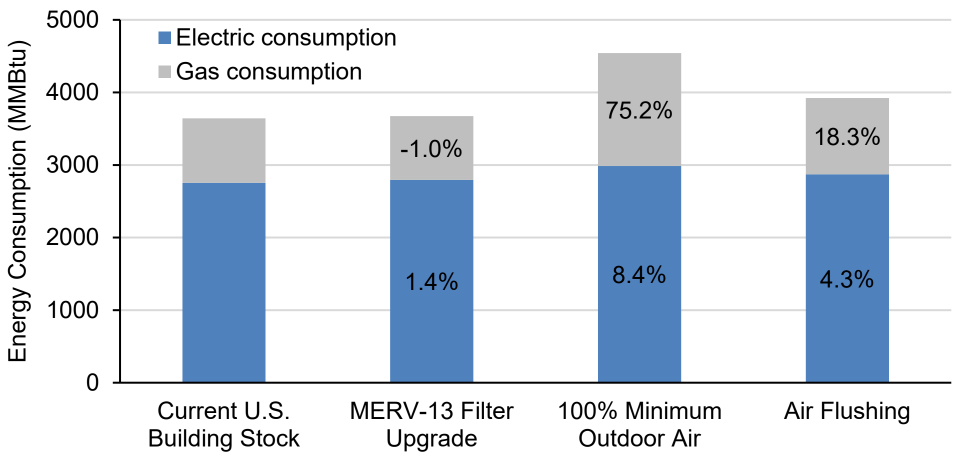

Figure 2: The percent increase in annual energy using MERV 13, 100% OA, or air flushing compared to current U.S. building stock (CaraDonna and Trenbath 2021).

Selecting energy-efficient and effective mitigation strategies is critical in spaces with high rates of pathogen emission (Noakes, Sleigh, and Khan 2012; Buonanno, Stabile, and Morawska 2020). As the generation rate of infectious particles increases, the required air change rate to reduce infection risk substantially increases (Qian et al. 2010; Nardell et al. 1991). Essentially, removal rates must exceed generation rates to reduce risks. This can increase energy use and pose challenges to existing HVAC systems that might not be sized to handle such high air change rates. UR-GUV can be used in combination with other mitigation strategies with the potential to deliver high levels of air disinfection at a relatively low energy increase (Escombe et al. 2009; Mphaphlele et al. 2015; Noakes, Khan, and Gilkeson 2015; Reed 2010). Based on findings from Riley, Knight, and Middlebrook (1976), Nardell et al. (1991) estimated that UR-GUV can routinely achieve air disinfection rates equivalent to 10-20 air changes per hour (ACH).

This paper reviews previous studies that evaluated the germicidal efficacy and energy use of four mitigation strategies: UR-GUV, increasing OA fraction, increasing HVAC air change rate, and improved filtration. Other mitigation strategies were not reviewed in this paper. This review included studies that evaluated at least two of the four strategies. Studies that evaluated only one strategy were included if they used metrics that describe efficacy in relation to other strategies. Where possible we focused on studies related to SARS-CoV-2. The paper discusses the efficacy, energy use, metrics used, and underlying assumptions. It also outlines future research areas needed to facilitate the selection of mitigation strategies with minimum or no energy penalty. Intra-room airborne transmission is the focus of the paper.

2. Germicidal Efficacy

Previous studies reported the efficacy of UR-GUV in terms of equivalent air changes ($eACH_{\text{UR-GUV}}$): the number of air changes per hour in a well-mixed room that would be required to reduce the concentration of a viable airborne pathogen to the same degree as the UR-GUV irradiation alone (First et al. 1999). Note that this equivalency is limited to air disinfection.

In decay experiments —where the emission stops and the decay in the concentration of infectious particles is monitored— Equation 1 can be used to estimate the time needed to achieve different levels of removal efficiency using different air change rates (Mutchler 1973; CDC 2003). In this equation, *t*1 and *t*2 are the initial and final time points in minutes, and *C*1 and *C*2 are the initial and final concentrations of contaminant, respectively. Equation 1 can be rearranged and expressed in terms of $eACH_{\text{UR-GUV}}$ (Equation 2) where *t* is the time in hours.

$$t2 - t1 = -60 \ln\left(\frac{C2}{C1}\right)/\text{ACH} \qquad (1)$$

$$eACH_{\text{UR-GUV}} = -\ln\left(\frac{C2}{C1}\right)/t \qquad (2)$$

The calculation of $eACH_{\text{UR-GUV}}$ using Equation 2 assumes that the source of infectious particles stops emission, hence it does not apply to situations with continuous generation of infectious aerosols that would occur in a continuously occupied space (Nardell 2021; CDC 2003). Under realistic conditions, the removal efficiency of one air change can be affected by uneven mixing (Brickner et al. 2003), in-duct filter efficiency for removal of a certain pathogen, and the OA fraction (Bohanon and Zaatari 2020). Deviations in these factors are not accounted for in Equation 2.

Estimates of $eACH_{\text{UR-GUV}}$ in different studies will be affected by variability in experimental conditions such as the assumed virus UV susceptibility constant (which has been denoted as *Z* or *k* and is a function of UV spectrum, target pathogen, and other environmental conditions such as humidity), irradiance in the upper room volume and how it was measured, in-room air mixing, and room geometry. Hence, the overall relative efficacy of UR-GUV compared to other strategies is of higher significance than absolute $eACH_{\text{UR-GUV}}$ values.

To demonstrate achievable $eACH_{\text{UR-GUV}}$ levels, consider the following example: using concentration decay data from a recent simulation study (Jones et al. 2021), we used Equation 2 and estimated $eACH_{\text{UR-GUV}}$ of 7 and 14 for conditions with mean UR-GUV irradiance of 14.5 and 29 $\mu W/cm^2$, respectively. These $eACH_{\text{UR-GUV}}$ estimates are in line with an estimate of 11 $eACH_{\text{UR-GUV}}$ by another simulation study (Beggs and Avital 2020). Compared to Beggs and Avital who assumed a *Z* constant of 0.038 m^2/J and a mean irradiance of 50 $\mu W/cm^2$, Jones et al. assumed a slightly higher *Z* constant of 0.056 m^2/J and lower mean irradiance (N. Jones, pers. comm., February 15, 2022). Beggs and Avital also calculated another $eACH_{\text{UR-GUV}}$ estimate of 109 based on a higher *Z* constant of 0.38 m^2/J. This shows that it is important to check the assumed *Z* constant when comparing $eACH_{\text{UR-GUV}}$ estimates between different studies.

The estimates by Beggs and Avital used a related formulation (Equation 3) that uses the ratio between the height of the UV zone (h_{uv}) and the room height (h_r) to determine particle residence time in the UV zone. In Equation 3, *E* is mean irradiance [W/m^2]. We added the 3600 multiplier to convert the air change estimate from per second to per hour. Overall, the estimates from Jones et al. (2021) and Beggs and Avital (2020) showed higher germicidal efficacy for UR-GUV compared to air changes using the HVAC system.

$$eACH_{\text{UR-GUV}} = 3600 \times Z \times E \times \frac{h_{uv}}{h_r} \qquad (3)$$

A recent laboratory study that investigated the efficacy of UR-GUV using viable SARS-CoV-2 virus utilized four circulating fans and estimated 50 $eACH_{\text{UR-GUV}}$ (Signify 2021; Innovative Bioanalysis 2020). While the Z constant was not reported in this study, mean irradiance was 4 µW/cm^2 (M. Creusen, pers. comm. January 5, 2022), which is lower than that used in the Jones et al. and Beggs et al. studies. The impact of using the circulating fans on $eACH_{\text{UR-GUV}}$ and energy use deserves further investigation to determine whether it is critical to achieving high $eACH_{\text{UR-GUV}}$ levels.

One of the benefits of using the $eACH_{\text{UR-GUV}}$ metric is that it can be used to calculate infection risk. For example, assuming $eACH_{\text{UR-GUV}}$ of 12, Shen et al. (2021) estimated mean infection risk reductions based on the probability of infection and reproduction number. They found that UR-GUV resulted in 59% mean reduction, which is higher than mean reductions achieved using 100% OA (27%), doubling the supply airflow rate (37%), or the use of a MERV 13 filter (21%). The assumption of 12 $eACH_{\text{UR-GUV}}$ appears reasonable in relation to those reported in other studies, such as Jones et al. (2021) and Beggs and Avital (2020).

Another metric, Effectiveness, is often reported in continuous generation studies (see Table 3 in NIOSH 2009; Miller et al. 2002; First et al. 2007). Effectiveness represents the fraction of infectious particles neutralized after UR-GUV application (Equation 4). In this Equation, $C_{uv\ on}$ and $C_{uv\ off}$ represent the concentration of pathogens with and without UR-GUV, respectively. The ratio between $C_{uv\ on}$ and $C_{uv\ off}$ represents the fraction of infectious particles surviving after UR-GUV application and can be used to calculate $eACH_{\text{UR-GUV}}$ in continuous generation experiments, as described by First et al. (2007), using Equation 5.

$$Effectiveness = 1 - \frac{C_{uv\ on}}{C_{uv\ off}} \qquad (4)$$

$$eACH_{\text{UR-GUV}} = \frac{Effectiveness}{\frac{C_{uv\ on}}{C_{uv\ off}}}\ \text{ACH} \qquad (5)$$

While this review focused on intra-space transmission, it is important to note that the impact of mitigation strategies on inter-space transmission might be different. Pease et al. (2021) estimated the probability of infection for a source room and connected rooms using different mitigation strategies. For the source room, increasing the air change rate from 3 ACH to 12 ACH reduced the probability of infection risk by 4% in that room. Meanwhile, in connected rooms, a lower air change rate of 1.8 ACH resulted in the lowest probability of infection for connected rooms. The higher air change rates increase the rate by which infectious particles were being spread from the source to connected rooms.

Instead of increasing the air change rate, UR-GUV can be installed in all critical spaces to inactivate pathogens originating from other connected rooms. A previous simulation study estimated that UR-GUV installed in four adjacent patient rooms and the connecting corridor reduced the number of new tuberculosis infection cases and used less energy than a scenario with 6 ACH (Noakes, Khan, and Gilkeson 2015).

Table 1 shows a summary of the efficacy of UR-GUV compared to other mitigation strategies as reported in simulation-based studies. This shows that UR-GUV had the highest efficacy and that improved filtration had a slightly lower efficacy than 100% OA.

Table 1: Summary of the germicidal efficacy of UR-GUV, mechanical air changes, in-duct filtration, or increased introduction of OA as reported in simulation-based studies.

Study	Simulation Assumptions	Findings
Beggs and Avital 2020	*E*= 50; *Z*= 0.038 or 0.38	$eACH_{\text{UR-GUV}}$= 11; 109 for the two Z constants, respectively
Jones et al. 2021	*E*= 14.5 or 29; *Z*= 0.056; decay	$eACH_{\text{UR-GUV}}$= 7; 14 for the two *E* values, respectively†
Shen et al. 2021	12 $eACH_{\text{UR-GUV}}$; continuous generation *q*= 58 to 610	Mean risk reduction was 59% for UR-GUV, 37% for doubling supply airflow rate, 27% for 100% OA, and 21% for MERV 13
Noakes, Khan, and Gilkeson 2015	*E*= 20; *Z*=0.4; continuous generation *q*=12	UR-GUV installed in all connected spaces resulted in a smaller number of new infection cases, compared to 6 ACH.
Azimi and Stephens 2013	Continuous generation *q*= 100	MERV 13-14 filter offers the highest risk reduction at the lowest cost, compared to increased fraction of OA and air change rate
Faulkner et al. 2022	Continuous generation *q*=25	Compared to a baseline with MERV 10 filtration, the use of 100% OA coupled with MERV 10 reduced mean virus concentration by 11%, compared to 10% using MERV 13.

† Values calculated from data shared by the authors courtesy of Nathaniel Jones, Paul Lynch, and Arup.
E refers to mean irradiance in the upper room volume [$\mu W/cm^2$], and *Z* is the virus susceptibility constant [m^2/J].
q is the quanta generation rate [hr^{-1}].

Table 2 shows laboratory or field studies that examined the performance of UR-GUV. We only identified one study that examined viable SARS-CoV-2 virus in a laboratory setting, hence field studies that examined Tuberculosis were included because they may be relevant to the current discussion given the similarity in *Z* value between Mycobacterium tuberculosis and SARS-CoV-2 (NIOSH 2009; Buonanno, Stabile, and Morawska 2020). Overall, across all studies, UR-GUV was consistently found to provide higher levels of eACH or reductions in infection risk than air changes by the HVAC system, air filtration in HVAC system, or increased fraction of OA.

Table 2: Summary of laboratory and field studies examining the efficacy of UR-GUV for neutralizing SARS-CoV-2 or Mycobacterium tuberculosis.

Study	Experimental conditions	Findings
Signify 2020	SARS-CoV-2; *E*= 4; decay	eACH of UR-GUV= 50
Mphaphlele et al. 2015	Mtb; *E*= 6; continuous generation	eACH= 24; 80% reduction in TB infection
Escombe et al. 2009	Mtb; *E*= 25; continuous generation	73% reduction in TB infections when UR-GUV was on compared to without UR-GUV

The letter *'E'* refers to mean irradiance in the upper room volume [$\mu W/cm^2$].

3. Energy Implications

In this section, we review the energy implications of utilizing UR-GUV, increased air change rate, increased introduction of OA, or improved in-duct filtration. Most studies did not include a complete comparison between the four mitigation strategies; for example, some studies only compared UR-GUV to increased introduction of OA. Another challenge is that previous studies used different metrics to evaluate the annual energy use of mitigation strategies: percent increase in energy, total energy cost, or energy cost per eACH. Table 3 shows a summary of reviewed studies and their findings.

Overall, the studies consistently found lower energy use or energy cost for UR-GUV or MERV 13 filtration, compared to increasing the fraction of outdoor air or increasing air change rate. This is expected given that heating, cooling, and fan energy are typically higher than the energy needed for UR-GUV fixtures.

Table 3: Summary of energy use for the four mitigation strategies as reported in previous studies.

Study	Space/ building type	Location	Findings
Faulkner et al. 2022	Office space	Denver, CO	Annual energy using 100% OA was 49% higher than that needed using MERV 13.
Noakes, Khan, and Gilkeson 2015	Hospital wards	London, UK	Annual energy using 6 ACH was approximately 28% higher than that needed using 3 ACH and UR-GUV in all spaces
NYSERDA 2021a	University buildings	Not reported	Annual energy increased by 6.5% when maximizing OA fraction, 0.1% using MERV 13, or 0.6% using UR-GUV in critical spaces§
NYSERDA 2021b	Medical center	Albany, NY	Annual energy increased by 0.4% when maximizing OA fraction, <0.01% using MERV 13, or 0.01% using UR-GUV in critical spaces§
Azimi and Stephens 2013	Office space	Phoenix, AZ; Houston, TX; Chicago, IL; Charlotte, NC	Annual costs per eACH for MERV 13 were about \$120, compared to \$367 for Charlotte, \$416 for Houston, \$469 for Chicago, and \$543 for Phoenix using 100% OA†
Ko et al. 2001	Waiting room	Boston, MA	Annual costs were \$2,000 for six additional ACH, compared to \$100 for UR-GUV
Brickner and Vincent 1997	Isolation room	Los Angeles, CA; New York, NY; Dallas, TX; Miami, FL	Annual energy costs using 100% OA at 12 ACH were \$1,328 for Los Angeles, \$1,730 for New York, \$4,203 for Dallas, and \$6,866 for Miami. The annual energy cost for two 17W UR-GUV fixtures would be about \$18‡

† Annual costs of filtration included labor, filter, and fan energy costs.

‡ Calculations assumed \$0.06/kWh for electricity and \$0.55 per 100 ft^3 for natural gas.

§ The estimates are compared to a pre-COVID baseline. UR-GUV estimates were based on a 40 W fixture that covers about 300 ft^2 for 10 hours daily.

As shown in Table 3, Azimi and Stephens (2013) compared strategies using energy cost per unit removal rate (eACH). This metric allows for normalized comparisons between different strategies assuming recirculation of viable pathogens. To illustrate comparisons using this metric, we used data from two other studies (Brickner and Vincent 1997; Ko et al. 2001) and calculated annual energy cost per eACH. Figure 3 shows annual energy per eACH for 100% OA, MERV 13, or UR-GUV based on these three studies. This shows smaller energy costs for UR-GUV and MERV 13 compared to 100% OA.

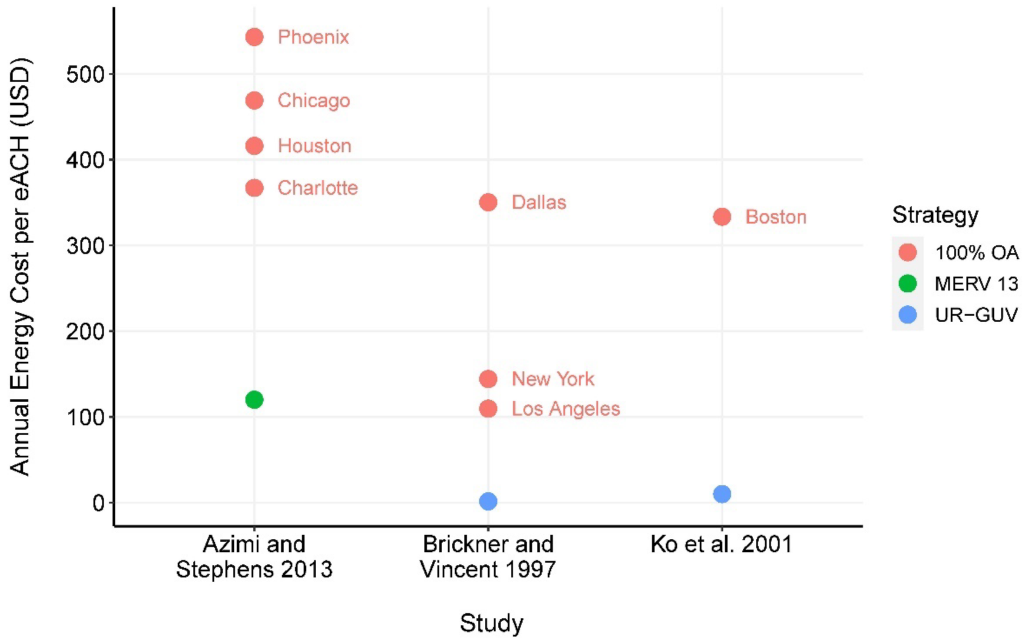

Figure 3: Annual energy cost per eACH for three mitigation strategies as reported by Azimi and Stephens (2013), and calculated using published data in the other two studies. The city names are shown for 100% OA strategy. The energy cost estimates for UR-GUV in Brickner and Vincent (1997) and Ko et al. (2001) assumed 12 and 10 $eACH_{UR\text{-}GUV}$, respectively, as estimated in these two studies. The estimate shown for MERV 13 from Azimi and Stephens (2013) included labor and filter costs.

Assuming viral recirculation, two strategies can be estimated to be equally effective at reducing virus concentrations, but one uses substantially less energy than the other. For example, in an office building, the use of 100% OA (coupled with baseline MERV 10 filtration) resulted in a similar reduction in virus concentration to that achieved only using MERV 13, but the latter strategy used substantially less energy (Faulkner et al. 2022). This aligns with results from another study that found MERV 13-14 filters offer the highest risk reduction at the lowest cost, compared to increasing the fraction of outdoor air and air change rate (Azimi and Stephens 2013). Any improvements beyond MERV 13-14 approximately double the annual cost and do not lead to substantial reductions in infection risk.

The higher energy use needed for conditioning OA was also demonstrated in two reports by NYSERDA for university buildings and a healthcare center (NYSERDA 2021a,b). The NYSERDA reports showed that the energy use of UR-GUV was similar or slightly higher than that using MERV 13. The energy use for UR-GUV or MERV 13 was considerably smaller than that needed to maximize the introduction of outdoor air.

The consequences of increasing the introduction of outdoor air depend on climatic variations (Figure 3). Heating or cooling-dominated climates are more likely to increase energy use (Risbeck et al. 2021). To demonstrate this, consider a hypothetical isolation room in four US cities (Los Angeles, CA; New York, NY; Dallas, TX; and Miami, FL). To deliver 12 ACH in an isolation room, Brickner and Vincent 1997 showed high energy costs needed for 100% OA that ranged from $1,328-$6,866, compared to $18 energy cost for UR-GUV. Among the four cities considered, the energy costs were highest for Miami, FL due to high cooling loads. Instead of implementing 12 ACH (CDC requirement for airborne infection isolation room (CDC 2003)), an alternative that is more energy-efficient and more effective at reducing viable pathogens is to combine 6 ACH from the HVAC system with UR-GUV, which would result in about 50% reduction in energy cost.

To reduce energy use associated with the increased introduction of OA, this strategy may be only implemented under specific climatic conditions that do not excessively increase energy use. For instance, in Denver, CO., Faulkner et al. (2022) recommended that 100% OA is only used in the summer months because it substantially increases heating energy use if utilized in the colder months.

4. Discussion

As mentioned earlier, comparing the energy implications of enhanced ventilation (improved in-duct filtration, increased OA fraction, and increased air change rate) to UR-GUV makes sense only with the assumption that all four approaches are likely to be equally effective in reducing the transmission of SARS-CoV-2 virus. However, that is not likely to be the case. If infectious SARS-CoV-2 is not recirculated through HVAC ducts, and there is little evidence of inter-room transmission more than two years into this pandemic, then return air already is virus-free and neither increased outdoor air nor improved filtration is likely to result in greater air disinfection. We discuss current recommendations from an energy perspective as if they were equivalent, but point out these limitations in greater detail below.

4.1—Limitations of the Presented Comparisons

A first step in making equitable energy use comparisons among competing strategies is to establish that they are equally effective, or at least enable comparison of their efficacy in terms of a common metric (e.g., eACH). Important factors are not documented in some studies, confounding comparisons. For example, studies often report neither UV irradiance nor fluence rate, but when irradiance is calculated or measured, the shape and orientation (e.g., horizontal plane facing zenith, vertical plane facing west, sphere) of the represented surfaces are sometimes unclear. In addition, studies conducted in the field or laboratories often lack details regarding measuring equipment and its calibration.

Once the efficacy of different strategies is quantified on a common scale, their respective energy use can be compared. Viewed in terms of cost/benefit analysis, the energy costs of different strategies are fairly simple to determine relative to quantifying the benefits. Although estimating energy use for UR-GUV systems is relatively straightforward, some factors can complicate analysis. For example, when fans are needed to sufficiently mix room air, their energy use should be considered. In addition, it is common that studies report rated power for UV lamps, rather than input power for the complete fixture (*i.e.*, without consideration for ballast losses). However, more significant challenges are encountered when estimating energy use for enhanced-ventilation strategies. Building HVAC systems span multiple spaces, some of which might not be included in a pathogen-mitigation strategy, complicating system boundaries. Furthermore, the energy implications of increased OA content depend on the season and local climate. Despite the uncertainties, however, UR-GUV again consistently appears to outperform increasing OA fraction, this time in terms of minimizing energy use.

4.2 Intra- and Inter-Space Transmission

Two potential modes of viral particle transit are relevant for buildings that contain a collection of different occupied spaces. The first is the transmission from an emitter (infected person) to others within a space and the second is the transit of viral particles from an infected space to other non-infected spaces via a centralized ventilation system. Viral transmission within single spaces can involve a broader portion of the viral particle size spectrum (Pease et al., 2022) and may also involve fomites from surface contact (Asadi et al., 2020). In contrast, transit of viral particles through a centralized ventilation system from one room to others is easier to model and can be approximated quite well using well-mixed assumptions (Vlachokostas et al., 2022). The latter assumes that viral particles survive transit through the ventilation system still infectious and at concentrations likely to reach the dose required for human infection.

Mitigation strategies for reducing infectivity risk can be localized to individual spaces or applied at a centralized level — if viable viral material is recirculated. Both approaches will impact intra- and inter-space transmission, and science-based comparisons should involve quantifying and combining both types of risks. For example, the use of centralized filtration is likely to have a small/negligible and lagging effect on near-field transmission but a much larger effect on transmission between spaces. In contrast, UR-GUV may have a greater impact on intra-space transmission. The distinction between in-room and centralized mitigation strategies is therefore important in evaluating both the costs and benefits of the different approaches.

To date, there is little or no convincing epidemiological evidence for SARS-CoV-2 recirculation (CDC 2021). In contrast, evidence of measles and TB transmission throughout buildings causing infection among occupants without direct person-to-person contact is readily available both as reported observations and as staged experiments (Escombe et al. 2009; Mphaphlele et al. 2015; Riley, Murphy, and Riley 1978). Most evidence indicates that the risk of COVID-19 transmission among room occupants is primarily in the room where an infectious source is generating clouds of infectious particles that can be inhaled before they are diluted, removed, or are inactivated (Greenhalgh et al. 2021).

Although both intra- and inter-space transmission might be possible, one approach is to prioritize mitigation measures that address the predominant transmission mode. While it is possible to for example compare the cost of adding MERV 13 filters to achieve the equivalent of 6 to 12 ACH outdoor air, that is true only if SARS-CoV-2 is substantially recirculated in an infectious state and if recirculated virus contributes importantly to transmission. If for example it is shown that all viral material in recirculated air without enhanced filtering is not viable in terms of causing infection, the addition of enhanced filtering might have other benefits in terms of air quality but would increase energy use without any reduction in transmission.

4.3 Virus Emission Rate

The 6-12 ACH of germ-free air that has been traditionally recommended by the CDC for airborne infection isolation rooms and procedure rooms in healthcare facilities appears to be based on air change rates that result in 1 or 2 log reductions in the concentration of air contaminants – but without ongoing generation. With an ongoing generation of contaminants much higher ventilation rates are required for similar reductions (Nardell et al. 1991). With omicron variants where viral production rates equivalent to measles occur, dilution and removal rates must exceed production rates to reduce the risk for room occupants. This may require the equivalent of 50 to 150 ACH – well beyond the capacity of most HVAC systems – and all but the most advanced germicidal UV systems.

4.4 Considerations for Increasing Introduction of OA

It is widely agreed that ventilation is an effective countermeasure to prevent transmission of COVID-19, with significant portions of the guidance on pandemic response focused on improving ventilation rates. However, even in that guidance, it is recognized that additional OA is not always possible and that tradeoffs must be considered (ASHRAE 2021). In many of the climate zones of interest, it is difficult to economically provide above-minimum OA for much of the year. The outdoor air is simply too cold, too hot, or too humid. In some situations (e.g., if a building is too close to a cooling tower) it may not be possible to provide good ventilation even in normal situations. Ventilation is even more problematic when outdoor air quality is low and potential contaminants of concern are present. The increasing frequency of fires in the American west has for example been a cause of growing concern. It is therefore legitimate to look for energy-efficient strategies like UR-GUV that provide protection equivalent to higher OA fractions.

4.5 Considerations for UR-GUV Application

Safety is a primary design consideration for UR-GUV systems. There are three main bands of UV (UV-C, UV-B, UV-A) covering the region of 100 to 400 nm in the electromagnetic spectrum with the UV-C range as the most effective for the inactivation of infectious pathogens (Sliney 2013; IES 2021). UV-B and UV-A reach the germinative layer, and UV-B does so at higher energy, resulting in it being most strongly associated with an increased risk for skin cancer; in contrast, UV-C is absorbed in the superficial layers of the skin and eyes, and accidental exposure to unsafe levels typically results in temporary photokeratitis of the eyes and erythema of the skin (IES 2021). Most commercially available UR-GUV systems produce almost all of their energy in the UV-C band for improved efficacy and because they are safer for building occupants. Nevertheless, UR-GUV systems must be carefully designed to not expose occupants to irradiance above threshold values (ACGIH 2022). Similarly, building operation and maintenance staff must be properly trained and equipped to maintain UR-GUV systems. Another consideration for UR-GUV application is that UV energy can degrade building materials over time. Polymer-based materials including some types of glass, plastics, and paints are especially susceptible. Degradation of these materials can affect the strength, color, and texture of the materials. Though there is significant data available about UV degradation of materials that occurs from sunlight outdoors, little data is available specifically for the degradation of materials from the UV-C band. UV-C is not present in sunlight that reaches the ground. More data is needed to understand the susceptibility of existing and new building materials to UV-C energy so that UR-GUV systems can be installed without damaging indoor surfaces.

A specific bandwidth of UV-C from 200 to 230nm (often called "Far UV-C") can have greater germicidal efficacy, and its higher threshold limit values further enhance its potential effectiveness (ACGIH 2022). Direct-irradiation Far UV-C can disinfect air in much of the occupied space between occupants, doesn't depend on airflow, and may be safer than conventional 254 nm irradiation (Eadie et al. 2022). However, wavelengths below 240 nm generate some ozone, so adequate ventilation must be ensured.

5. Conclusion and Next Steps

The review of previous research studies in this paper indicates that — among the four strategies— UR-GUV is the most effective at reducing infection risk and viable virus concentration. Furthermore, the energy use of UR-GUV was found to be lower than increasing the HVAC air change rate or the OA fraction.

To realize the UR-GUV opportunity, additional research and development is needed to fully develop, validate, and deploy the technology. As much of the existing research is simulation-based, field-based evaluations and demonstrations of UR-GUV efficacy and energy use are needed. To support this, there is a need for development of a common analysis framework that will enable more confident comparisons of different studies and applications and enable incorporation of new data over time. This can support a larger-scale meta-analysis that can aggregate available data both simulated and measured into a robust dataset to support technology deployment. Field evaluations should consider assessing not only the efficacy and energy use of different mitigation measures, but also assess and quantify corollary benefits such as reduced absenteeism resulting from reduced infections.

Application guidance informed by research is also needed. Mitigation measures are unlikely to be applied singularly. A combined application of UR-GUV, increased introduction of OA, increases in air change rate, and improved filtration will be more likely in most commercial buildings. There is a need for further study to determine which combination of mitigation measures are the most efficient and effective combinations. There is a lack of a standardized method for risk-benefit analysis of the different mitigation measures to determine optimal combinations. There is also a gap in application guidance for target levels of reduced infection risk. What is an acceptable level of transmission risk reduction for a particular application, perhaps as a target eACH level? This is a critical need to support the design and optimization of transmission mitigation measures.

Finally, more research is needed to understand, quantify, and combine the multiple risks of infectivity stemming from both intra- and inter-space transmission for different release scenarios and then determine how different proposed strategies reduce these risks. We also note that these risk mitigation strategies would be specific to virus type; for SARS-CoV-2 they may depend on the variant in circulation. Beyond research, a robust education effort will be essential for practitioners to be able to understand and deploy UR-GUV technology effectively and safely.

References

ACGIH. 2022. "2022 Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs)". ACGIH. Cincinnati, OH.

Asadi, S., Bouvier, N., Wexler, A. S., & Ristenpart, W. D. 2020. "The coronavirus pandemic and aerosols: Does COVID-19 transmit via expiratory particles?". Aerosol Science and Technology, 54(6), 635-638.

ASHRAE Epidemic Task Force. 2021. "Core Recommendations for Reducing Airborne Infectious Aerosol Exposure", https://www.ashrae.org/file%20library/technical%20resources/covid-19/core-recommendations-for-reducing-airborne-infectious-aerosol-exposure.pdf

ASHRAE. 2022. ASHRAE terminology: a comprehensive glossary of terms for the built environment. www.ashrae.org/ashraeterms. Accessed 3/18/2022.

Azimi, P., and B. Stephens. 2013. "HVAC Filtration for Controlling Infectious Airborne Disease Transmission in Indoor Environments: Predicting Risk Reductions and Operational Costs." Building and Environment 70: 150–60. https://doi.org/10.1016/j.buildenv.2013.08.025.

Beggs, C., and E. Avital. 2020. "Upper-Room Ultraviolet Air Disinfection Might Help to Reduce COVID-19 Transmission in Buildings: A Feasibility Study." PeerJ 8: e10196. https://doi.org/10.7717/peerj.10196.

Bohanon, H., and M. Zaatari. 2020. "Effect of Ventilation and Filtration on Viral Infection in Residences." ASHRAE Journal 62, (12): 38–45.

Brickner, P., R. Vincent, M. First, E. Nardell, M. Murray, and W. Kaufman. 2003. "The Application of Ultraviolet Germicidal Irradiation to Control Transmission of Airborne Disease: Bioterrorism Countermeasure." Public Health Reports 118, (2): 99–114. https://doi.org/10.1016/S0033-3549(04)50225-X.

Brickner, P., R. Vincent. 1997. "Stopping the spread of Tuberculosis by use of ultraviolet germicidal irradiation (UVGI) and ventilation." Report to NYSERDA. Albany, NY.

Buonanno, G., L. Stabile, and L. Morawska. 2020. "Estimation of Airborne Viral Emission: Quanta Emission Rate of SARS-CoV-2 for Infection Risk Assessment." Environment International 141: 105794. https://doi.org/https://doi.org/10.1016/j.envint.2020.105794.

Cai, J., S. Li, D. Hu, Y. Xu, and Q. He. 2022. "Nationwide Assessment of Energy Costs and Policies to Limit Airborne Infection Risks in U.S. Schools." Journal of Building Engineering 45, 103533. https://doi.org/10.1016/j.jobe.2021.103533.

Cara Donna, C., and K. Trenbath. 2021. "ComStockTM/COVID-19: U.S. Commercial Building Stock Analysis of COVID-19 Mitigation Strategies." Golden, CO. https://www.nrel.gov/docs/fy21osti/79335.pdf.

CDC. "Appendix B. Air." Environmental Infection Control Guidelines, 2003. https://www.cdc.gov/infectioncontrol/guidelines/environmental/appendix/air.html#tableb1.

CDC. "Ventilation in Buildings," 2021. https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html.

CDC. 1989. "Mycobacterium Tuberculosis Transmission in a Health Clinic -- Florida, 1988." Atlanta, GA. https://www.cdc.gov/mmwr/preview/mmwrhtml/00001377.htm.

Eadie, E., W. Hiwar, L. Fletcher, E. Tidswell, P. O'Mahoney, M. Buonanno, D. Welch, C. Adamson, D. Brenner, C. Noakes, and K Wood. 2022. "Far-UVC (222 nm) Efficiently Inactivates an Airborne Pathogen in a Room-Sized Chamber." Scientific Reports 12 (1): 1–9. https://doi.org/10.1038/s41598-022-08462-z.

Escombe, A. R., D. Moore, R. Gilman, M. Navincopa, E. Ticona, B. Mitchell, C. Noakes, et al. 2009. "Upper-Room Ultraviolet Light and Negative Air Ionization to Prevent Tuberculosis Transmission." Edited by Peter Wilson. PLoS Medicine 6, (3): e1000043. https://doi.org/10.1371/journal.pmed.1000043.

Faulkner, Cary A., John E. Castellini, Wangda Zuo, David M. Lorenzetti, and Michael D. Sohn. 2022. "Investigation of HVAC Operation Strategies for Office Buildings during COVID-19 Pandemic." Building and Environment 207 (PB): 108519. https://doi.org/10.1016/j.buildenv.2021.108519.

First, M., E. Nardell, W. Chaisson, and R. Riley. 1999. "Guidelines for the Application of Upper-Room Ultraviolet Germicidal Irradiation for Preventing Transmission of Airborne Contagion -- Part 2: Design and Operation Guidance." In ASHRAE TRANSACTIONS - 1999 WINTER MEETING. Chicago, IL: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA (US).

First, Melvin, Stephen N. Rudnick, Kevin F. Banahan, Richard L. Vincent, and Phillip W. Brickner. 2007. "Fundamental Factors Affecting Upper-Room Ultraviolet Germicidal Irradiation—Part I. Experimental." Journal of Occupational and Environmental Hygiene 4 (5): 321–31. https://doi.org/10.1080/15459620701271693.

Greenhalgh, Trisha, Jose L Jimenez, Kimberly A Prather, Zeynep Tufekci, David Fisman, and Robert Schooley. 2021. "Ten Scientific Reasons in Support of Airborne Transmission of SARS-CoV-2." The Lancet 397 (10285): 1603–5. https://doi.org/10.1016/S0140-6736(21)00869-2.

Houk, V N. 1980. "Spread of Tuberculosis via Recirculated Air in a Naval Vessel: The Byrd Study." Annals of the New York Academy of Sciences 353: 10–24. https://doi.org/10.1111/j.1749-6632.1980.tb18901.x.

IES. 2021. "RECOMMENDED PRACTICE: ULTRAVIOLET GERMICIDAL IRRADIATION (UVGI)." New York, NY, USA. IES.

Innovative Bioanalysis. 2020. "Efficacy of a Wall Mounted UV Device Against Aerosolized SARS-CoV-2." Costa Mesa, CA. https://www.assets.signify.com/is/content/Signify/Assets/philips-lighting/global/20210301-innovative-bioanalysis-report-sars-cov-2.pdf.

Jones E, Young A, Clevenger K, Salimifard P, Wu E, Luna ML, Lahvis M, Lang J, Bliss M, Azimi P, Cedeno-Laurent J, Allen JG. 2020. "Healthy Schools: Risk Reduction Strategies for Reopening Schools." Harvard TH Chan School of Public Health Healthy Buildings Program. Boston, MA. https://schools.forhealth.org/risk-reduction-strategies-for-reopening-schools/.

Jones, N., P. Lynch, J. Hewlings, J. Boyd, R. Seffinger, D. Lister, and R. Thomas. 2021. "Simulation of COVID-19 Ultraviolet Disinfection Using Coupled Ray Tracing and CFD." In Building Simulation 2021. Bruges, Belgium.

Ko, Gwangpyo, H. Burge, E. Nardell, and K. Thompson. 2001. "Estimation of Tuberculosis Risk and Incidence under Upper Room Ultraviolet Germicidal Irradiation in a Waiting Room in a Hypothetical Scenario." Risk Analysis 21, (4): 657–74. https://doi.org/10.1111/0272-4332.214142.

Miller, S., M. Hernandez, K. Fennelly, J. Martyny, J. Macher, K. Elmira, P. Xu, P. Fabian, J. Peccia, and C. Howard. 2002. "Efficacy of Ultraviolet Irradiation in Controlling the Spread of Tuberculosis." Washington, DC.

Mphaphlele, M., A. Dharmadhikari, P. Jensen, S. Rudnick, T. van Reenen, M. Pagano, W. Leuschner, et al. 2015. "Institutional Tuberculosis Transmission. Controlled Trial of Upper Room Ultraviolet Air Disinfection: A Basis for New Dosing Guidelines." American Journal of Respiratory and Critical Care Medicine 192, (4): 477–84. https://doi.org/10.1164/rccm.201501-0060OC.

Mutchler J. 1973. Principles of ventilation. In: The industrial environment—its evaluation and control. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, Public Health Service, Center for Disease Control, National Institute for Occupational Safety and Health, DHEW (NIOSH) Publication No. 74–117.

Nardell, E. 2021. "Air Disinfection for Airborne Infection Control with a Focus on COVID-19: Why Germicidal UV Is Essential†." Photochemistry and Photobiology 97, (3): 493–97. https://doi.org/https://doi.org/10.1111/php.13421.

Nardell, E., J. Keegan, S. Cheney, and S. Etkind. 1991. "Airborne Infection: Theoretical Limits of Protection Achievable by Building Ventilation." American Review of Respiratory Disease 144, (2): 302–6. https://doi.org/10.1164/ajrccm/144.2.302.

National Institute for Occupational Safety and Health (NIOSH). 2009. "Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings." Washington, DC.

Noakes, C., M. Khan, and C. Gilkeson. 2015. "Modeling Infection Risk and Energy Use of Upper-Room Ultraviolet Germicidal Irradiation Systems in Multi-Room Environments." Science and Technology for the Built Environment 21, (1): 99–111. https://doi.org/10.1080/10789669.2014.983035.

Noakes, C., P. Sleigh, and A. Khan. 2012. 2012. "Appraising Healthcare Ventilation Design from Combined Infection Control and Energy Perspectives." HVAC&R Research 18, (4): 658–70. https://doi.org/10.1080/10789669.2011.592054.

NYSERDA (New York State Energy Research and Development Authority). "FlexTech Energy Efficient Indoor Air Quality Study for A Higher Education University" Albany, NY, 2021a.

NYSERDA (New York State Energy Research and Development Authority). “FlexTech Energy Efficient Indoor Air Quality Study for Albany Medical Center” Albany, NY, 2021b.

Pease, L., N. Wang, T. Salsbury, R. Underhill, J. Flaherty, A. Vlachokostas, G. Kulkarni, and D. James. 2021. “Investigation of Potential Aerosol Transmission and Infectivity of SARS-CoV-2 through Central Ventilation Systems.” Building and Environment 197: 107633. https://doi.org/10.1016/j.buildenv.2021.107633.

Qian, Hua, Yuguo Li, W.H. Seto, Patricia Ching, W.H. Ching, and H.Q. Sun. 2010. “Natural Ventilation for Reducing Airborne Infection in Hospitals.” Building and Environment 45 (3): 559–65. https://doi.org/10.1016/j.buildenv.2009.07.011.

Reed, N. 2010. “The History of Ultraviolet Germicidal Irradiation for Air Disinfection.” Public Health Reports 125, (1): 15–27. https://doi.org/10.1177/003335491012500105.

Riley, E C, G Murphy, and R L Riley. 1978. “Airborne Spread of Measles in a Suburban Elementary School.” American Journal of Epidemiology 107 (5): 421–32. https://doi.org/10.1093/oxfordjournals.aje.a112560.

Riley, R., M. Knight, and G. Middlebrook. 1976. “Ultraviolet Susceptibility of BCG and Virulent Tubercle Bacilli.” American Review of Respiratory Disease 113, (4): 413–18. https://doi.org/10.1164/arrd.1976.113.4.413.

Risbeck, M., M. Bazant, Z. Jiang, Y. Lee, K. Drees, and J. Douglas. 2021. “Quantifying the Tradeoff between Energy Consumption and the Risk of Airborne Disease Transmission for Building HVAC Systems.” Science and Technology for the Built Environment 28, (2): 240–54. https://doi.org/10.1080/23744731.2021.1984171.

Shen, J., M. Kong, B. Dong, M. Birnkrant, and J. Zhang. 2021. “A Systematic Approach to Estimating the Effectiveness of Multi-Scale IAQ Strategies for Reducing the Risk of Airborne Infection of SARS-CoV-2.” Building and Environment 200: 107926. https://doi.org/10.1016/j.buildenv.2021.107926.

Signify. 2021. “Disinfecting the Air We Breathe with UV-C Light,” https://www.signify.com/global/our-company/blog/innovation/uv-c-air-we-breathe.

Sliney, D., 2013. “Balancing the Risk of Eye Irritation from UV-C with Infection from Bioaerosols.” Photochemistry and Photobiology 89 (4): 770–76. https://doi.org/10.1111/php.12093.

Vlachokostas, A, Burns, CA, Salsbury, TI, et al. 2022. “Experimental evaluation of respiratory droplet spread to rooms connected by a central ventilation system”. Indoor Air 32: e12940. doi:10.1111/ina.12940