CENTER FOR GLOBAL HEALTH DELIVERY
HARVARD MEDICAL SCHOOL

PROCEEDINGS

Keeping Public Spaces Safe: Germicidal Ultraviolet Light for Air Sanitation During COVID-19

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Keeping Public Spaces Safe: Germicidal Ultraviolet Light for Air Sanitation During COVID-19

WEBINAR PROCEEDINGS

Date of Meeting

February 25, 2021

Rapporteurs

Dr Anna Nicholson, Doxastic

Jon Weinisch, Doxastic

Hosts

Center for Global Health Delivery at Harvard Medical School

Advance Access & Delivery

The Belfer Center's Middle East Initiative at the Harvard Kennedy School

Harvard Global Health Institute

Contents

Abbreviations

AA&D	Advance Access and Delivery
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CDC	Centers for Disease Control and Prevention
EqACH	equivalent air changes per hour
HVAC	heating, ventilation, and air conditioning
TB	tuberculosis
UR-GUV	upper room germicidal ultraviolet light
UV	ultraviolet light
WHO	World Health Organization

1 Introduction

On February 25, 2021, the Center for Global Health Delivery at Harvard Medical School, Advance Access & Delivery, the Belfer Center's Middle East Initiative at the Harvard Kennedy School, and Harvard Global Health Institute, hosted the virtual webinar *Keeping Public Space Safe Germicidal Ultraviolet Light for Air Sanitation During COVID-19*. The meeting convened a panel of engineers and infectious disease experts to discuss the safety profile and evidence base supporting the use of upper room germicidal ultraviolet systems (UR-GUV).

For decades, UR-GUV has been a powerful tool for airborne infection control, and it has recently gained popularity as a possible measure to stop the spread of the SARS-CoV-2 virus in public spaces. The goals of this webinar were to generate awareness around this technology, to discuss the safety implications, and to advocate for its widespread use for the COVID-19 pandemic. The webinar began with a discussion about the safety profile of UR-GUV, followed by an examination of basic science questions about how aerosols cause infection and an overview of the theory behind using UR-GUV. The focus then shifted to considering how this technology can be integrated into a total-building infection control program, including common design principles for how to practically apply UR-GUVG in multiple settings.

The webinar was co-hosted by Salmaan Keshavjee, professor in the Department of Global Health and Social Medicine and Department of Medicine at Harvard Medical School and director of Harvard Medical School's Center for Global Health Delivery–Dubai, and Tom Nicholson, executive director at Advance Access & Delivery. Featured speakers included:

- David Sliney, chair of photobiology committee of the Illuminating Engineering Society
- Don Milton, University of Maryland School of Public Health
- Ed Nardell, Harvard T. H. Chan School of Public Health
- Bill Bahnfleth, Institutes of Energy and the Environment at Penn State University
- Paul Jensen, independent consultant at Final Approach Inc. and CDC retiree

Opening remarks

Keshavjee opened the webinar by explaining that Harvard Medical School's mission is to nurture a diverse, inclusive community dedicated to alleviating suffering and improving health and wellbeing. The Harvard Medical School's Center for Global Health Delivery contributes to this mission through a focus on the last phase of healthcare delivery, working to ensure that the fruits of modern medicine reach people in communities where they live and work. For many years, the Center for Global Health Delivery has been working to stop the spread of tuberculosis (TB), a disease that has been curable since the late 1940s yet kills 1.5 million people each year - 4,000 people per day. The use of infection prevention and control measures that stop airborne transmission has long been a part of the strategy for stopping TB transmission. Like TB, COVID-19 is an airborne disease. When the COVID-19 pandemic began, Keshavjee and his colleagues realized that lessons learned from TB control may be highly relevant for making public spaces safer. COVID-19 is largely transmitted through the air via droplets and aerosols. As yet, little infection prevention and control has been deployed in public spaces, and there is great opportunity in the use of UR-GUV for COVID-19 infection prevention and control.

Furthermore, the Center for Global Health Delivery is focused on health equity. The response to the COVID-19 pandemic has not fully utilized all layers of technology that can be used to make people safe. Particularly, there has been a gap in the response in terms of making public spaces (eg, schools, courthouses, gyms, and other congregate settings) safe. An estimated 34%-42% of workers deemed essential have continued working (outside their home) throughout lockdowns; these include medical personnel, transit workers, grocery store workers, first responders, teachers, students, critical office workers, and many others. These workers are likely to have annual household incomes under $40,000 per year, and survey data suggest that half of these workers would not be able to pay an unexpected $500 medical bill expense in full at the time of service. Many of these individuals who have been working throughout the pandemic are living on the margins, said Keshavjee. Despite the widespread use of lockdowns, along with other interventions, there has been little investment in appropriate environmental interventions to ensure that essential workers are able to function safely in public spaces. He pointed out that the pandemic response has been focused on layers of intervention that rely on individual behavior and have varying efficacy for stopping COVID-19 transmission, such as masks and social distancing. Yet the response has failed to make use of interventions that are known to be effective and do not rely on individual behavior, such as ventilation and UR-GUV. Certain environmental interventions may greatly contribute to stopping the spread of COVID-19 and for this reason, a panel of experts was convened to discuss the engineering and interventions associated with UR-GUV.

Nicholson explained that Advance Access and Delivery (AA&D) is a global health nonprofit with partners and programs around the world. AA&D has a focus on TB and other diseases of poverty, along with a focus on the looming challenges of non-communicable diseases around the world. He noted that the impetus for the webinar was related to the organizers' experiences working on TB control at global health delivery organizations and academic centers. The emergence of COVID-19 necessitated a quick transition toward working on airborne infection control in the US, a need that would not have been conceivable previously. Throughout the COVID-19 pandemic, many of the webinar's organizers and speakers have been working to share information about infection control, including information about UR-GUV, and to facilitate the installation of UR-GUV in congregate and institutional settings. This work has included advising schools, homeless shelters, and houses of worship. It has been challenging but rewarding to see these places become safer for those who congregate, worship, and work in these spaces, said Nicholson. While discussing UR-GUV with policymakers, building managers, state and county health directors, and tribal health authorities, it has become clear that an overview of the current scientific understanding of UR-GUV is needed, along with a clear overview of how UR-GUV can be used to fight COVID-19. He expressed his hope that the contents of the webinar will be synthesized with practical guidance on integrating the design of UR-GUV into building plans and retrofitting this technology into existing buildings.

2 On the principles and safety of upper room germicidal ultraviolet lighting

In his presentation on the principles and safety of upper room germicidal ultraviolet lighting, David Sliney, chair of the photobiology committee of the Illuminating Engineering Society, defined the concepts of "germicidal radiation," or "germicidal light," and discussed how UV-C can be used as a germicidal light, and addressed safety and exposure concerns related to ultraviolet light and UR-GUV applications.

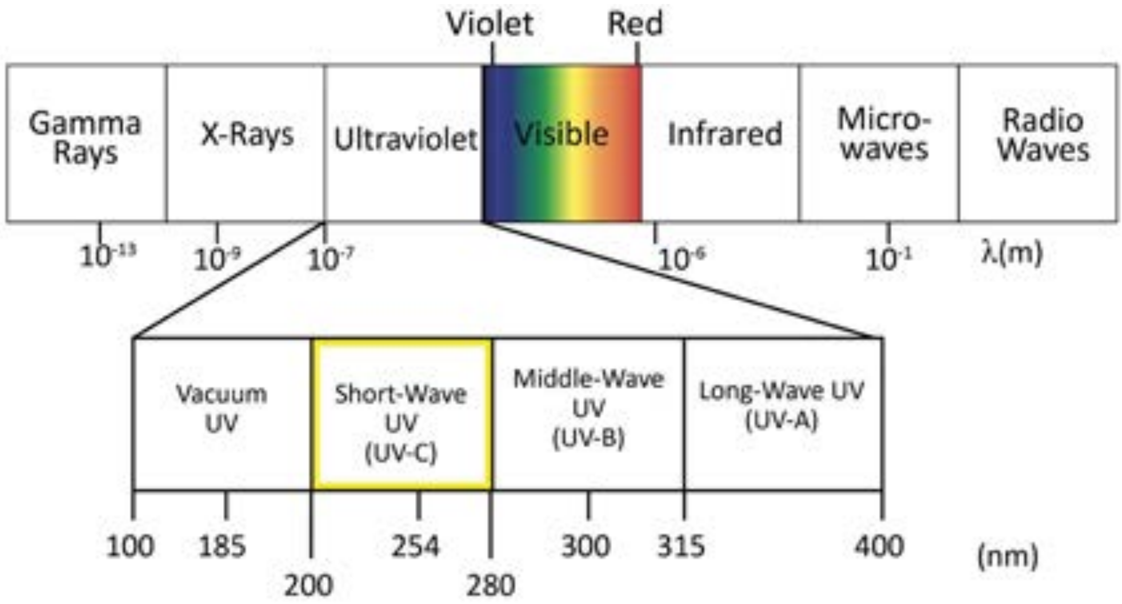
2.1 What is germicidal light?

Sliney explained that germicidal light typically refers to the shortest wavelengths of the optical spectrum, which is ultraviolet radiation. In photobiology, the ultraviolet band is divided into three photobiological spectral bands known as UV-A, UV-B, and UV-C (see Figure 2-1). UV-A is used for fluorescence detection, insect light traps, and various specialized applications; it is relatively safe in comparison to shorter wavelengths. UV-B radiation is the shortest part of the sunlight spectrum outdoors. They are less effective than UV-C at disinfecting air, but they have effectiveness, especially during the summer months when UV-B frequently inactivates viruses in outdoor air. However, UV-C is the only effective means for disinfecting indoor air. Data point to the fact that UV-A, UV-B, and violet light have only marginal effects in terms of inactivating microbes. Further, the shorter wavelengths (eg, UV-C) have the highest photon energies.

The germicidal application of ultraviolet light is an old technology, Sliney explained. During the mid-20th century, it was common to see UR-GUV used in hospitals, bathrooms, medical clinics, and other public areas in the US. This approach fell out of favor as highly effective vaccines and antibiotics were developed. In fact, the use of UR-GUV has become so uncommon that the COVID-19 pandemic has necessitated a near-reinvention of UR-GUV technology. When appropriately designed and installed, UR-GUV technology has been effective as a means of microbial disinfection. It is among the only reliable methods for air disinfection.[1] The outbreak of COVID-19 has resulted in the marketing and scale-up of numerous UR-GUV products, ranging from handheld disinfecting wands to large-scale robotic applications, and some of these products work well.

1 Sliney noted that gas can be used for air disinfection; however, this approach requires that those present in the space being disinfected have respiratory protection.

Figure 2-1. The ultraviolet portion of the electromagnetic spectrum



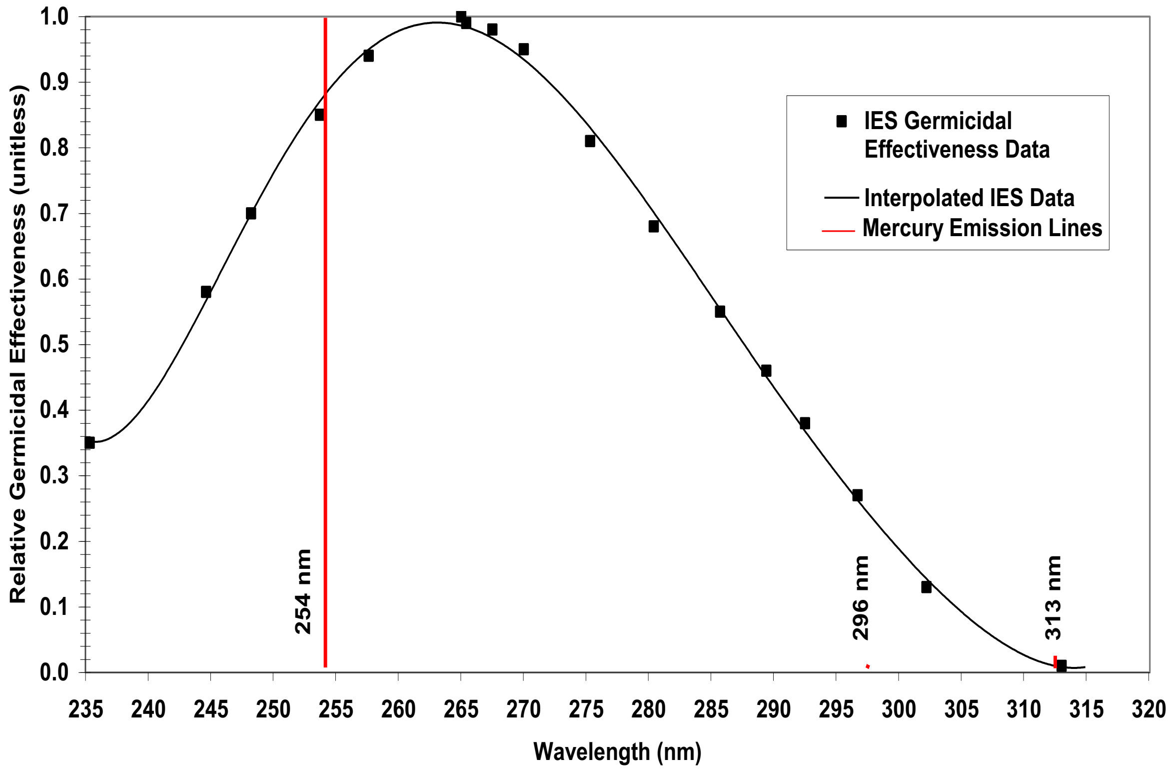
Sources: Sliney pre sentation; https://www.ies.org/standards/committee-reports/ies-committee-report-cr-2-20-faqs/

2.2 How ultraviolet light works as a disinfection technology

The key target molecules for UV-C are DNA and RNA, Sliney explained. In photobiology, certain wavelengths are more effective than others for any given application; this is represented using action spectra. Each bacterium, and some viruses, are susceptible to UR-GUV depending on their action spectrum. While the action spectra of these bacteria and viruses vary somewhat, those that are susceptible are generally susceptible to the emission line (254 nm wavelength) of the most commonly used ultraviolet germicidal lamp—the low-pressure mercury lamp (see Figure 2-1). For instance, *E. coli* bacteria was a common target of GUV in the 1940s and 1950s. These lamps have an effectiveness of >80%, but in recent years, there has been growing interest in other lamps to address bioaerosols with action spectra with wavelengths less than 254 nm. A 2015 study found evidence that the Krypton Chloride lamp, which operates at 222 nm-207 nm wavelengths, may be used in germicidal applications.[2]

2 Beck et al 20f15

Figure 2-2. Germicidal spectrum for inactivating *E. Coli*



Notes: IES=Illuminating Engineering Society (past handbooks)
Source: Sliney presentation

2.2.1 Traditional UV-C safety issues

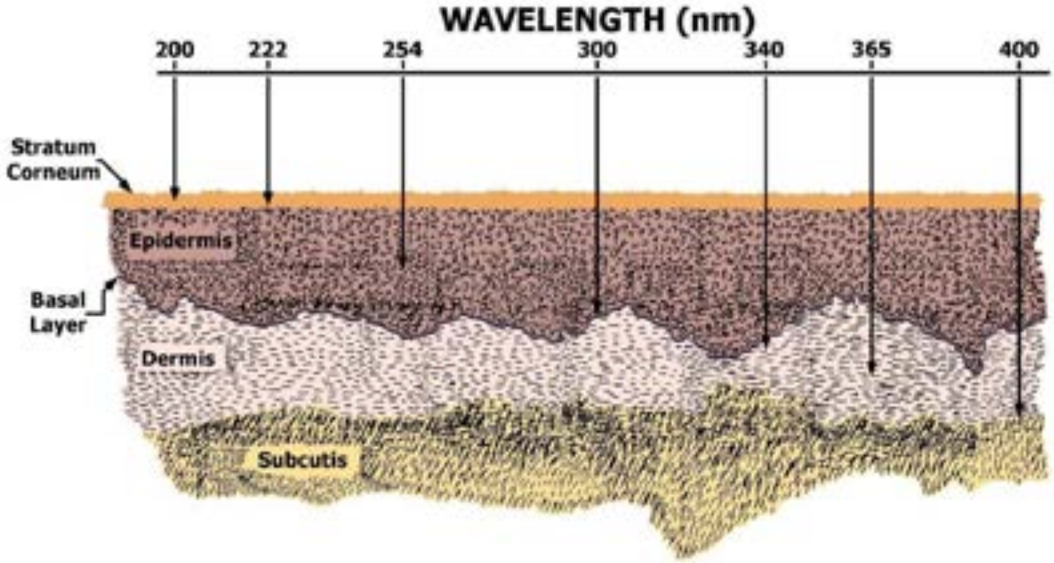
Sliney acknowledged that safety concerns are often raised when discussing UR-GUV, and that ultraviolet safety is an important consideration in its use. There are two effects commonly associated with the accidental exposure of skin and eyes to ultraviolet light. Photokeratitis (also known as "welder's flash" and "snow blindness") may occur when the eye is accidentally exposed to ultraviolet light. Common symptoms of this condition include photokeratoconjunctivitis (reddening of the eye) and irritation similar to the sensation of having sand in the eye. Similar to sunburn, photokeratitis does not present immediately after exposure to ultraviolet light, but several hours after exposure. Photokeratitis may be painful, but the condition is transient and does not pose a risk so great as to preclude the use of UR-GUV altogether. Erythema (ie, the reddening of the skin) can occur after exposure to ultraviolet light on the skin. The symptoms can be severe if the skin is exposed to UV-B rays, similar to sunburn, but erythema is mild when the skin is exposed to UV-C at the low doses used in UR-GUV. This is because UV-C rays are only superficially absorbed, while UV-B rays can deeply penetrate the skin.

The most pressing safety concern in the use of ultraviolet light is the potential for delayed effects of ultraviolet exposure, Sliney explained. Specifically, exposure to UV-B light may cause skin cancers. UV-B in sunlight is known to penetrate to the basal (germinative) layer of epidermis, and solar UV-B is recognized as the cause of most skin cancers. While UV-C photons are highly energetic and dangerous to living cells, the living cells of the skin epidermis are protected by the filtration of the outermost layers of skin. That is, UV-C is heavily absorbed in the superficial epidermis and stratum corneum. The action spectrum associated with safe human exposure limits is designed to protect against the more sensitive ocular effects and peaks at approximately 270 nm, which is close to the peak of the previous action spectrum typically used for germicidal applications.

Sliney considered the question of whether there is a realistic risk of skin cancer due to the use of UR-GUV.[3] He invoked the first law of photobiology, which states that photons must be absorbed and reach their target molecules to produce an effect. The highly energetic nature of UV-C is often a cause for concern, and many have questioned why UV-C is not highly phototoxic and more closely associated with severe skin cancer risk. The reason UV-C is not exceedingly phototoxic is that UV-C photons do not typically penetrate into the basal, germinative layer of the epidermis, where new cells are created. Only approximately 1 of 1,000 UV-C photons penetrate to the basal layer of the skin, or germinative layer. New cells are created in this layer and move to the surface within a couple of weeks. These cells die and become the outermost protective layer, known as the stratum corneum. Sliney pointed out that light with a 222 nm (KrCl) wavelength only slightly penetrates into the epidermis (the outermost living layer of the skin).[4] In comparison, UV-B penetrates to the basal layer of the epidermis. Understanding the action spectra is key in photobiology, said Sliney, and the action spectrum for non-melanoma skin cancers induced by ultraviolet light reveals that the most dangerous wavelengths are those close to 300 nm. The risks associated with ultraviolet light exposure are far lower for wavelengths less than 300 nm (see Figure 2-3 and Figure 2-4). Further, the superficial risks of ultraviolet light exposure (ie, the risk of erythema and photokeratitis) decrease dramatically at wavelengths below 270 nm (see Figure 2-4).[5] Thus, UV-C lighting applications for UR-GUV, which typically use 254 nm, are unlikely to pose a considerable long-term risk for causing non-melanoma skin cancers.

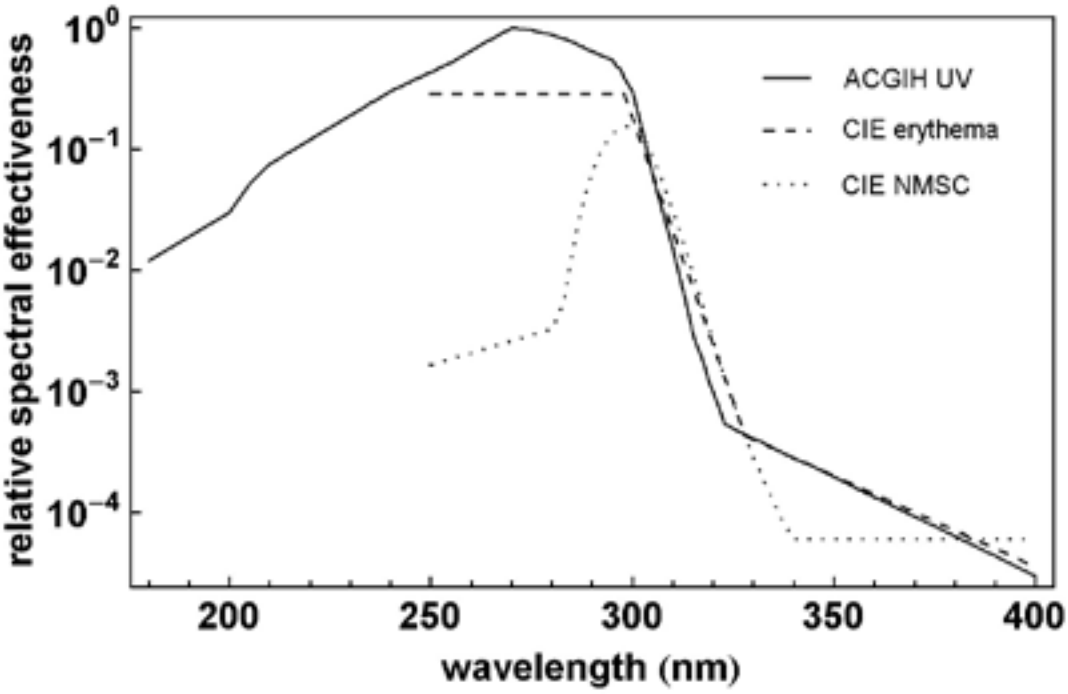
3 CIE 2010; Sliney 2013; Sliney and Wolbarsht 1980
4 Beck et al 2015
5 CIE 2010; Sliney 2013; Sliney and Wolbarsht 1980

Figure 2-3. Penetration of UV wavelengths into the skin



Source: Sliney presentation

Figure 2-4. Relative spectral effectiveness of ultraviolet light



Notes: CIE=International Commission on Illumination. ACGIH=American Conference of Governmental Industrial Hygienists UV Hazard Action Spectrum; CIE erythema=International Commission on Illumination standard action spectrum for erythema; CIE NMSC=CIE International Commission on Illumination Standardized Action spectrum for non-melanoma skin cancer.
Source: Sliney presentation

2.2.2 Exposure limits and safety standards for ultraviolet lamps and lamp systems

Sliney described the standards used to ensure the safe use of UR-GUV. Exposure to ultraviolet light can be limited either by emission control, such as by an enclosure, or by exposure control, such as by a shield or other protection of persons. Emission limits are employed within product safety standards. These limits are often referred to as "accessible emission limits", and the measurement conditions for these limits are specified based on pre-determined human exposure conditions. A bare germicidal light could be potentially dangerous, but exposure is limited by the design of fixtures and appliances, such as louvered devices that limit exposure to the upper areas of a room. Exposure limits are the standards used to ensure the safety of persons potentially exposed to ultraviolet light, such as those in the lower part of a room where UR-GUV is present. These limits are embedded within occupational safety standards and are measured at the location of exposed persons. For instance, in the case of a room with UR-GUV deployed, exposure would be measured at the location of persons in the lower part of the room, and in an occupational setting where welding occurs, exposure limits would be measured and used to determine the safe distance between the welding and unprotected persons.

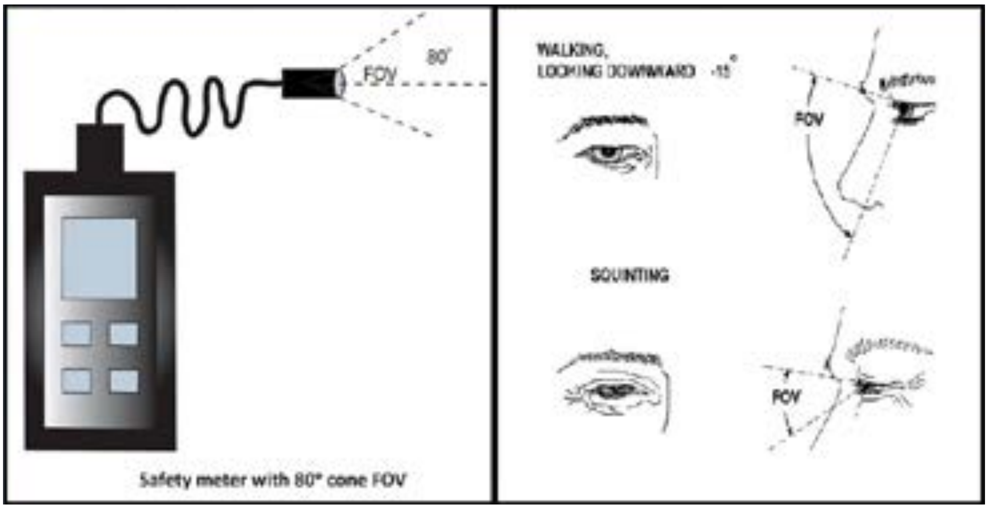
Sliney discussed the typical emissions of low-pressure mercury germicidal lamps, since these are the lamps most often used for UR-GUV applications.6 These lamps emit several monochromatic lines at varying wavelengths between 254 nm and 405 nm, but 90% of these emissions are at the 254 nm wavelength. He noted that new lamps are forthcoming, including the aforementioned Krypton Chloride lamp, which operates at a peak 222 nm wavelength, and other LED lamps operating at longer UV-C wavelengths.

Next, Sliney explained how ultraviolet safety measurements are made. Specially designed UV-C meters are used to measure ultraviolet exposure that are calibrated for the particular wavelength of the lamp or LED being used. These measurement instruments are designed with an 80-degree field of view to account for the fact that the biological effects of light are most severe when the light encounters an individual directly, rather than at an oblique angle (see Figure 2-5). Further, the human eye's upper field of view is limited to between 45 degrees and 50 degrees, and overhead down-lighting fixtures are normally above this field of view. The epidermal skin tissue receives little from obliquely incident rays because of exponential absorption in the stratum corneum and the outermost epidermis, and the oblique rays are also much more reflected (Fresnel reflection) compared to direct incidence.7

Sliney presented an example of the exposures associated with a typical UR-GUV application (see Figure 2-6) and discussed the approach to UR-GUV safety that would be used by an occupational safety professional or industrial hygienist for determining the relative risk in occupied spaces with UR-GUV. Time-weighted averaging is employed to assess risk from scattered UV-C. Above 7 feet, or 2.1 meters, there is a high intensity of UV-C. The fixtures used for UR-GUV have louvers that allow the light to be directed upwards, helping to ensure the lowest possible exposure for those standing and sitting below the fixtures. The placement of GUV in the upper room ensures minimal exposure to people standing and sitting in the lower part of the room. Those who are seated rather than standing have even lower exposure to UR-GUV.8

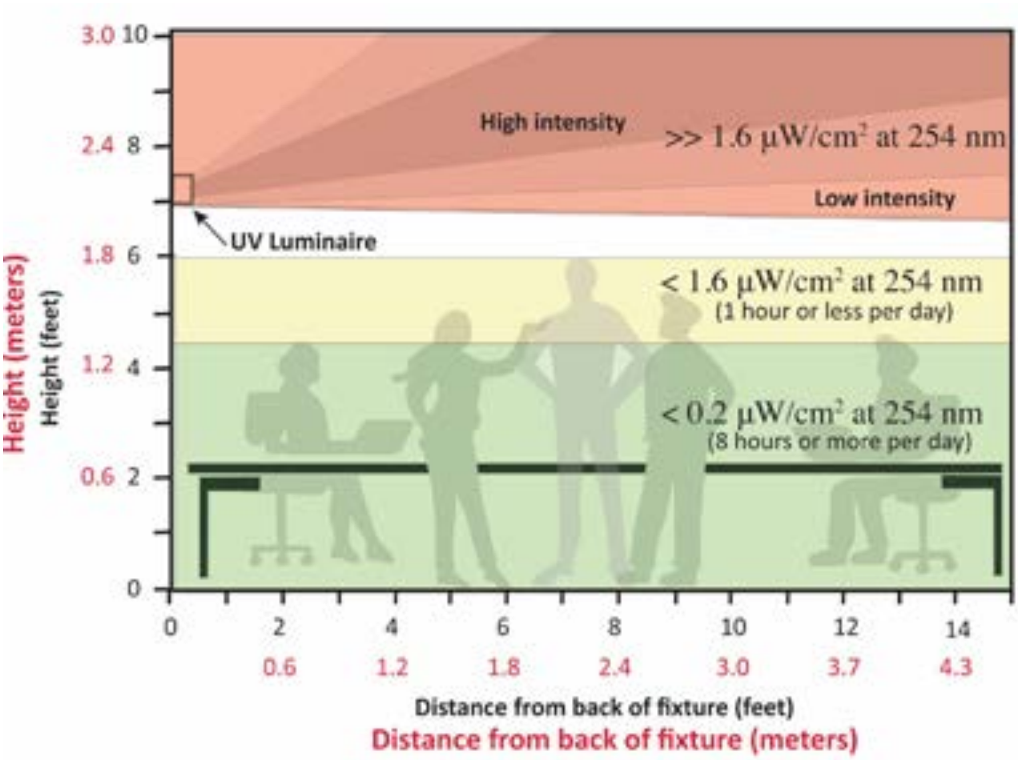
6 Sliney noted that these lamps can be powered with conventional wall plugs and are currently the most efficient available lamp for UR-GUV applications.
7 Sliney and Wolbarsht 1980
8 Exposure to UV-C in a room with UR-GUV will be highly correlated with the height of the room and the effective height of the individuals relative to the position of the UR-GUV fixture.

Figure 2-5. Ultraviolet safety meter with 80-degree cone field of view and human eye field of view



Notes: FOV=field of view
Source: Sliney presentation

Figure 2-6. Exposures for upper room UR-GUV using UV-C.



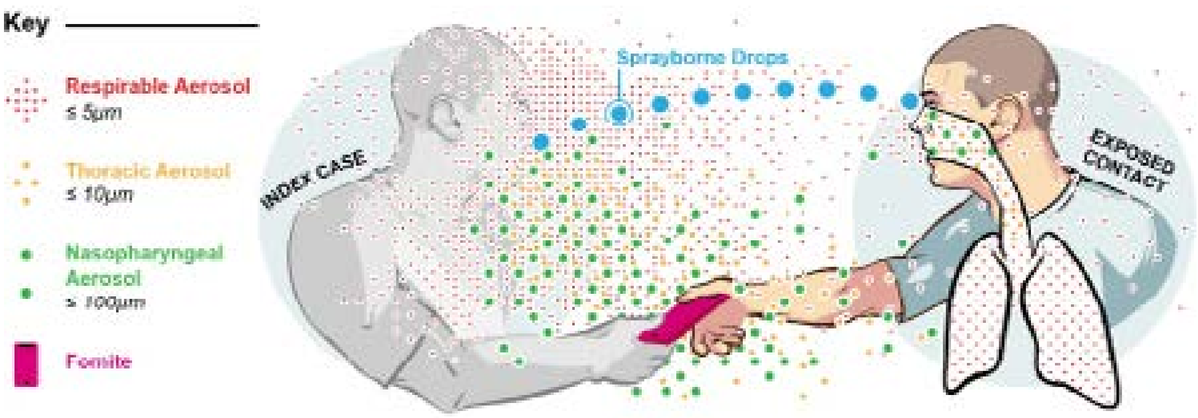
Notes: µW/cm²=Microwatts per centimeter squared; UV=ultraviolet
Source: Sliney presentation

3 How droplets and aerosols cause infection

3.1 Transmission modes of respiratory viruses

Don Milton, University of Maryland School of Public Health, explained that there are three general modes of respiratory virus transmission[9], as shown in Figure 3-1: touch, spray, and inhalation. Transmission by touch occurs when an individual touches a person or object (fomite) that has virus on its surface and then transfers the virus to the mucosal membranes via finger-to-eye, finger-to-nose, or finger-to-mouth transfer. Transmission by spray occurs when an individual is close enough to another individual that ballistic drops (droplets >100 μm in size) can fly from the index case and make direct contact with the eye, nostril, or mouth of a nearby individual. These ballistic drops can fly from the index case when they speak loudly, cough, or sneeze. Transmission by inhalation occurs when fine droplet aerosols that are exhaled by the index case then waft into the breathing zone of another person who then inhales them while breathing. Inhaled aerosols are categorized by size and how deeply into the respiratory tract they are able to penetrate: nasopharyngeal aerosols are relatively large (≤100 μm) and cannot penetrate beyond the nose and throat; thoracic aerosols are smaller (≤10-15 μm) and able to penetrate deeper into the individual's airway; and respirable aerosols (≤5 μm) are small enough that they can penetrate deeply into the individual's lungs, small airways, and air sacs.

Figure 3-1. Transmission modes of respiratory viruses.



Source: Milton presentation

3.2 The generation of respiratory particles

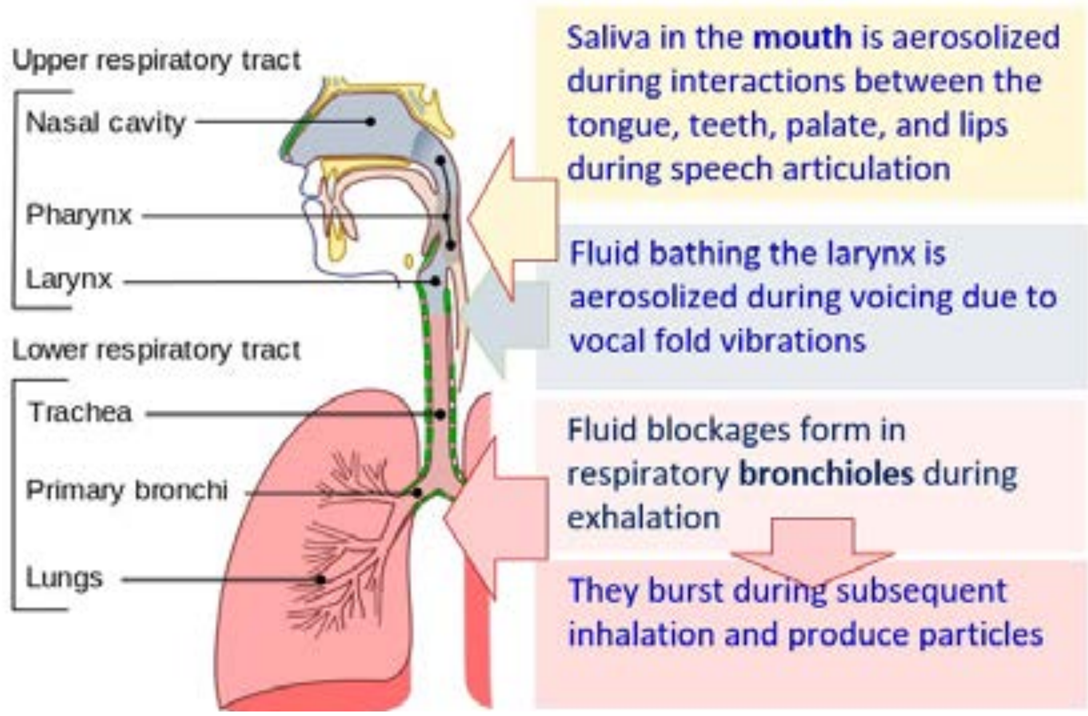
Milton discussed the generation of respiratory particles by comparing the respiratory tract to a series of nebulizers, as shown in Figure 3-2. First, fluid blockages form in the respiratory bronchioles deep in the lung during exhalation, which burst during subsequent inhalations thereby producing respiratory particles. Fluid bathing the larynx is also aerosolized during voicing due to vocal fold vibrations (eg, speaking and singing). Finally, saliva in the mouth is aerosolized during interactions between the tongue, teeth, palate, and lips during speech articu-

9 Li 2021; Milton 2020

lation; this process may create either large particle droplet spray or smaller particles that can remain suspended in air and follow air currents as true aerosols. Recent research has shown that surface deformations favor the production of very small aerosol particles and concentrate viruses and bacteria into tiny aerosol particles.[10]

Milton presented a visual representation of the mechanism of aerosol formation in the lung during breathing, as shown in Figure 3-3. The representation shows how fluid-lined small airways (bronchioles) can collapse so that a fluid film forms blocking the flow of air; when the collapsed airway reopens the film thins out and breaks, in a manner similar to a bubble popping, and emits tiny particles. This mechanism has been confirmed by having an individual exhale to residual volume, ie, blowing as much air out of their lungs as possible,11 then taking a deep breath. During this process, airways are closed off and then pop open, generating a large number of droplets in the breath, including a greater proportion of tiny aerosol particles than are produced during breathing at normal lung volumes. Research has shown that different breathing patterns and respiratory activities generate varying particle sizes.12 The smallest particles are produced by the bronchial fluid film burst mode, and these particles stay suspended in the air longest. The laryngeal vibration mode creates larger particles that stay suspended in the air for a shorter time, and the oral speech articulation movement mode creates the largest particles, which stay suspended in the air for the shortest duration. Some of these larger particles fly through the air with ballistic trajectories, he added.

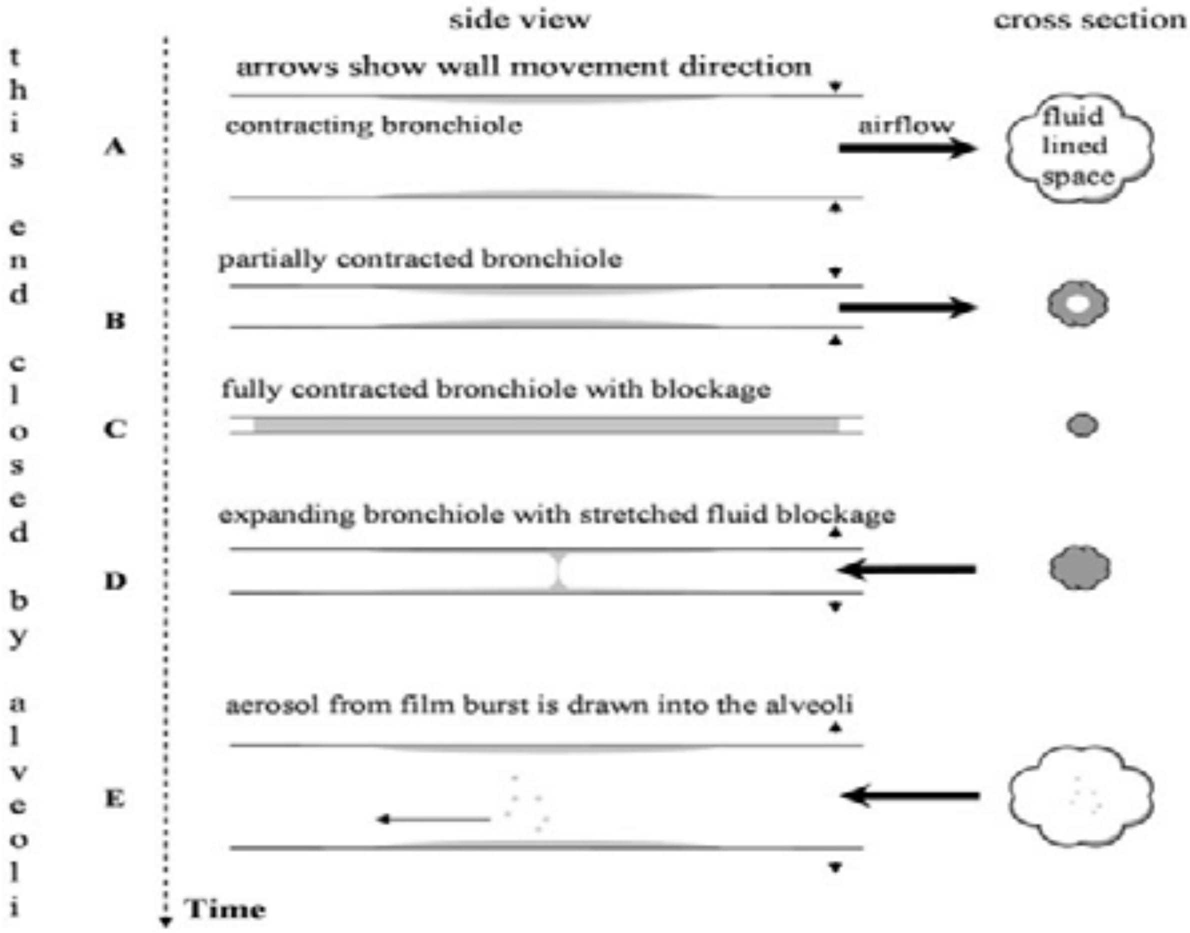
Figure 3-2. Generation of respiratory particles



Source: Milton presentation, courtesy of Lidia Morawska

10 Oratis et al 2020
11 Milton noted that this may occur naturally when a singer uses all of their breath to sing or when a lecturer forestalls their next breath in order to finish their sentence.
12 Morawska et al 2009

Figure 3-3. Mechanism of aerosol formation in the lung during breathing.



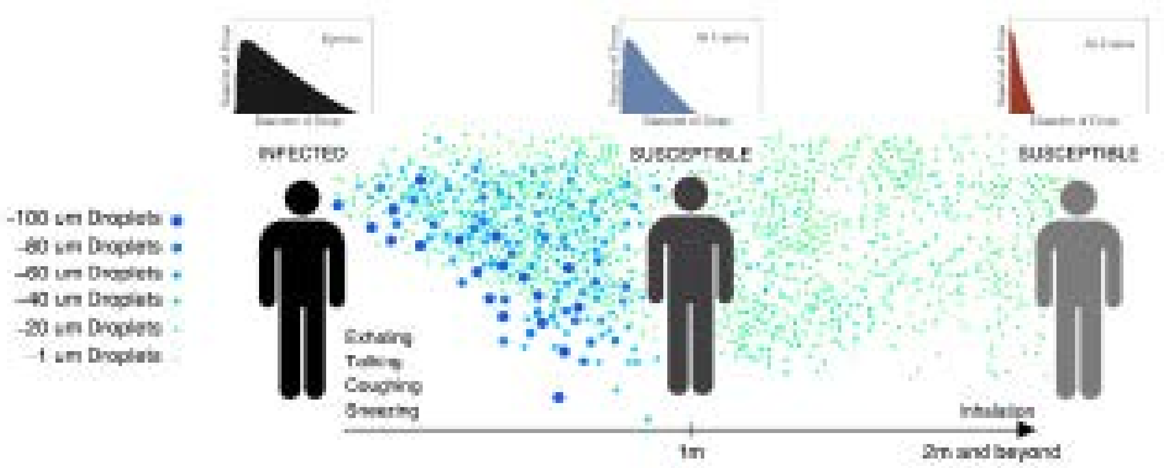
Sources: Milton presentation; Johnson and Morawska 2009

3.3 Size of virus-laden airborne particles and the flow of particles generated by respiratory activities

Milton discussed the size of virus-laden particles, focusing on SARS-CoV-2.[13] The SARS-CoV-2 "naked virus" is approximately 0.12 µm in diameter, but the virus travels through air in a droplet surrounded by water, mucus, and salts. Thus, virus-laden particles are larger than 0.12 µm. He added that particles with a diameter of greater than 1 µm could contain higher loads of SARS-CoV-2. When individuals congregate, they generate aerosols by talking, coughing, and breathing, and these droplets become aerosol particles and flow through the air.[14] The particles are more highly concentrated closer to the individuals generating them, and larger droplets typically remain closer to these individuals, because they settle out from the air more quickly than the smaller particles.

13 Ma et al 2021; Santarpia et al 2020
14 Balachandar et al 2020

Figure 3-4. Flow of particles generated by respiratory activities



Sources: Milton presentation; Balachandar et al 2020

3.3.1 Evidence on the spread of SARS-CoV-2 by respiratory particles

Milton discussed evidence on the spread of SARS-CoV-2 by respiratory particles and the air pathways that can facilitate airborne transmission of SARS-CoV-2-laden particles. A study conducted in a hospital room in Florida found that particles small enough to be inhaled deep into the lung were shown to be present in the air of a room that was 7 meters long by 3.5 meters wide.[15] Two patients were in the room, divided by a curtain, and two samplers were used to detect the presence of these small particles and demonstrate that they contained infectious virus.

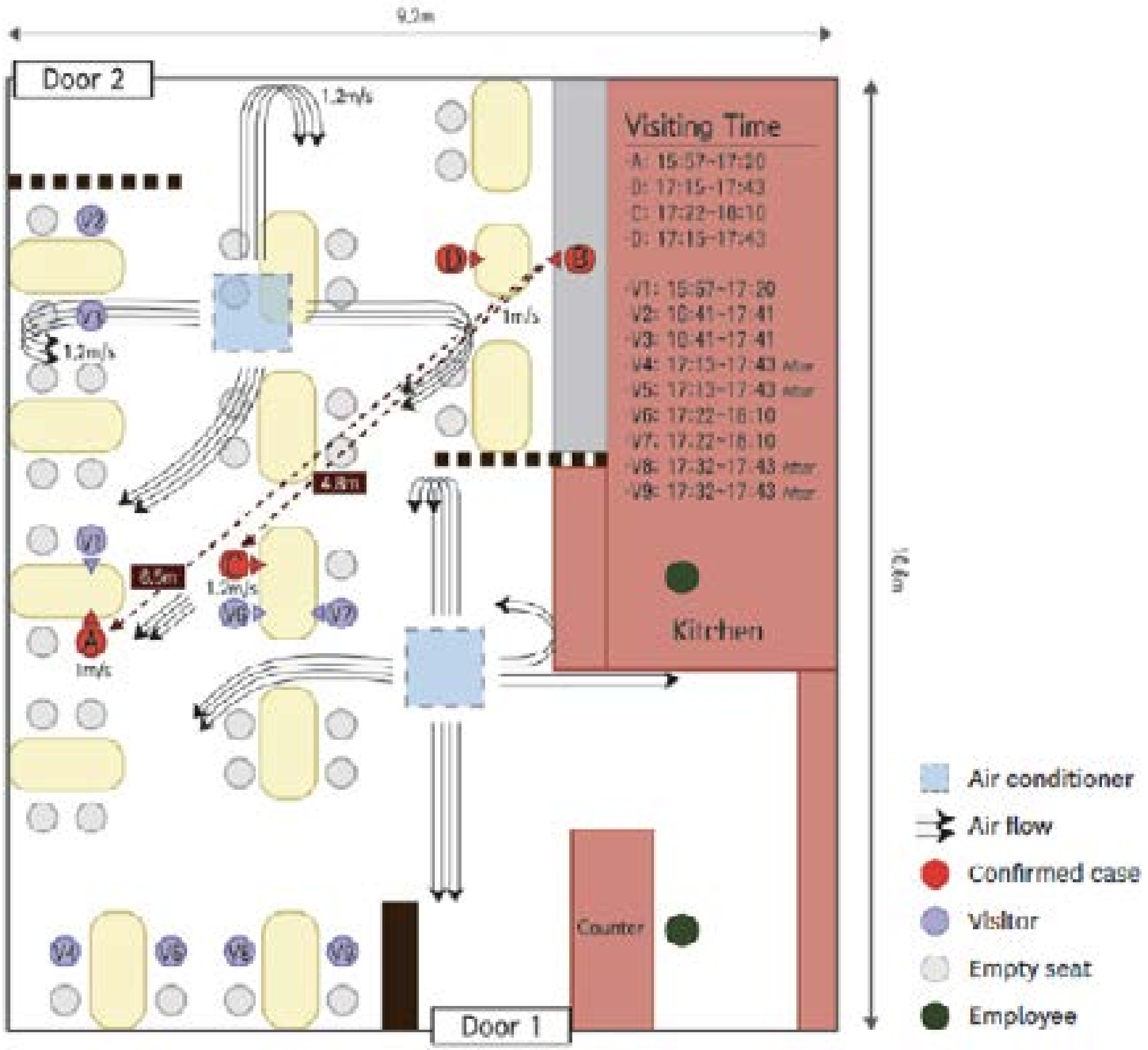
Multiple SARS-CoV-2 outbreaks in restaurants have been carefully studied. One of these studies used surveillance cameras to monitor the length of a patron's stay and the distance between patrons[16]; tracer gas was used to show that the building's ventilation system was essentially recycling the air in a loop around the dining room. Individuals were infected who did not come any closer than 4.6 meters from the index patient. Another study investigated transmission of SARS-CoV-2 in a restaurant in South Korea, as shown in Figure 3-5.[17] In this case, a diner (case A) finished eating and left the dining room using Door 1. Case A departed 5 minutes after the index case (case B) had entered the dining room using Door 2. These two diners used separate doors and sat at tables that were 21 feet apart, and they never traveled closer to one another than 21 feet. Yet, the investigation found that case A was infected with the SARS-CoV-2 virus by case B. This kind of transmission can only be explained by aerosol transmission, said Milton. While transmission may be more likely in close proximity to the index case, transmission is also dependent upon the airflow in settings where transmission occurs.

In closing, Milton reviewed the pathway of infectious aerosols (see Figure 3-6) and the implications for the transmission of SARS-CoV-2. Aerosols are generated in various areas of the respiratory tract and in different sizes depending on where and how they are generated. However, aerosols can also be generated by shaking out a sheet, flushing a toilet, or by other modes of indirect aerosolization. The behavior of infectious aerosol is determined by their size, their water

15 Lednicky et al 2020
16 Li et al 2020
17 Kwon et al 2020

content, temperature, relative humidity, air speed, how they were generated, and how quickly their biological agent decays. A study in New Orleans found that, at 23 degrees Celsius and 50 precent relative humidity, SARs-CoV-2 virus was capable of surviving for at least 16 hours.18 He noted that that even in a poorly ventilated room, a particle would be removed from the air within this 16-hour time frame. Where a particle lands is dependent upon its size. A large particle may land in a person's nose, but a smaller particle can likely enter deeper into the respiratory tract. The SARS-CoV-2 virus is capable of invading cells and initiating infection at either location.

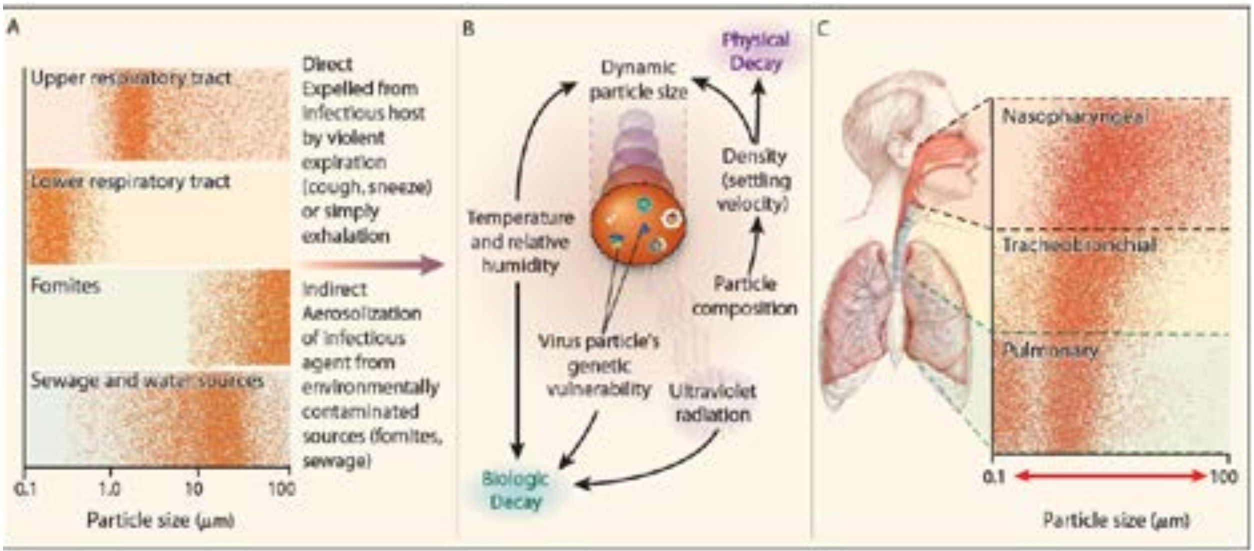
Figure 3-5. Transmission of SARS-CoV-2 in a restaurant 21 feet downwind of index case



Sources: Milton presentation; Kwon et al 2020

18 Fears et al 2020

Figure 3 6. The pathway of aerosol particles through the air.



Sources: Milton presentation; Roy and Milton 2004

4 Overview and theory of using upper room germicidal ultraviolet lighting

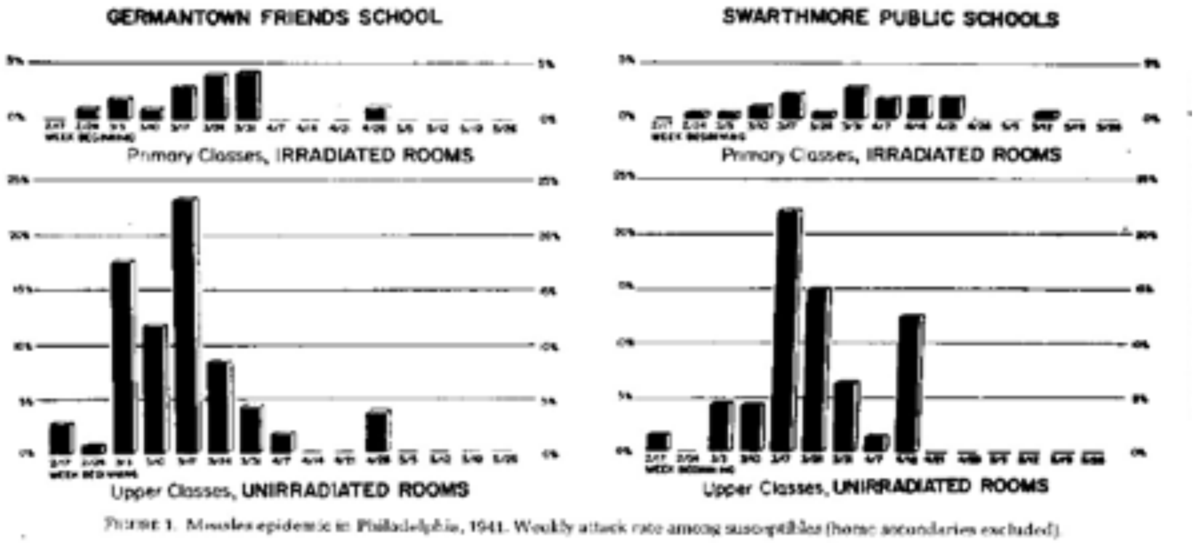
4.1 Background, history, and evidence of effectiveness

Ed Nardell, Harvard T. H. Chan School of Public Health, discussed the theory and application of UR-GUV from his perspective as a physician. He explained that he first encountered UR-GUV during a TB outbreak in a homeless shelter in Boston. TB is a strictly airborne infection, and it has long been known that TB is subject to environmental controls. Even though UR-GUV was not widely used during the 1980s when this TB outbreak occurred, Nardell participated in efforts to implement UR-GUV fixtures in the homeless shelter, and more research has been conducted on the use of UR-GUV in the years since. He pointed out that UR-GUV is not a new technology. Textbooks on the subject were written as early as 1946,[19] and in 1942, a study investigated the use of UR-GUV in day schools.[20] This study compared measles attack rates among students in primary classes with those in upper classes (see Figure 4-1). It was expected that students in the upper classes might have some immunity from prior exposure—but in fact, those in the primary classes with UR-GUV experienced less measles transmission. The UR-GUV fixtures used today are fairly similar to the UR-GUV fixtures used in the 1942 study. Nardell emphasized that this study may offer the best epidemiological evidence on the use of UR-GUV.

An observational study conducted from 1957 to 1958 investigated the effectiveness of UR-GUV for pandemic influenza. This was not a planned study, but the Livermore Veterans' Administration Hospital already had UR-GUV installed to control TB when an annual influenza pandemic struck. The pandemic influenza had an attack rate of 18.9%, but the attack rate among those in wards with UR-GUV was 1.9%.[21] The study concluded that UR-GUV was 90% effective among these patients. Nardell reiterated that this was neither a planned nor a controlled study, but he affirmed that this is a compelling finding in favor of the claim that UR-GUV can help prevent the spread of an airborne infection.

19 Luckiesh 1946
20 Wells et al 1942
21 In this case, there were 395 patients at risk in wards with no UR-GUV; 75 of these patients had serologically confirmed influenza. 209 patients were at risk in wards with UR-GUV; 4 of these patients had serologically confirmed cases of influenza.

Figure 4-1. Measles epidemic in Philadelphia, weekly attack rate among susceptible in 1941 (home secondaries excluded).



Sources: Nardell presentation; Wells et al *1942*

4.2 Applications of UV germicidal irradiation

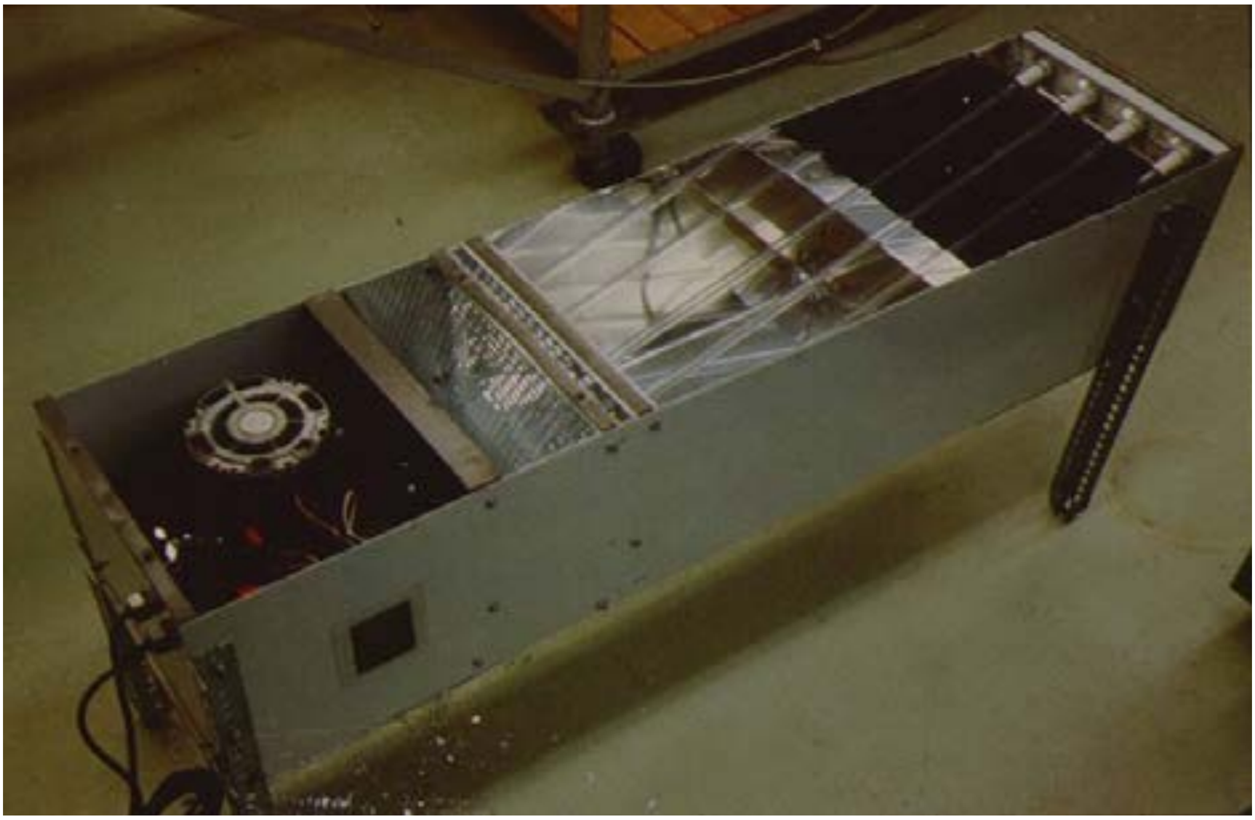
Nardell considered four applications of UV germicidal irradiation and the advantages and disadvantages of each application: (1) "UV in a box" room air cleaners, (2) UV in heating, ventilation, and air conditioning (HVAC) systems, (3) whole-room UV air disinfection, and (4) UR-GUV.

4.2.1 UV in a box, room air cleaners

"UV in a box" refers to the implementation of UV germicidal irradiation within ventilation ducts or portable air cleaners, said Nardell. These applications confine the UV germicidal irradiation device to an enclosure through which air is pumped. A portable air cleaner, such as the one shown in Figure 4-2, functions by sucking in air through an intake, blowing that air through a filter, and then pushing the air through a UV lamp chamber. The primary advantage of this application is its simplicity. The device needs merely to be plugged in in order to safely function. However, the primary disadvantage of this application is that it is difficult to move a sufficient quantity of air through a ventilation system or portable air cleaner in order to achieve a high number (between 6 and 12) of equivalent air changes per hour (EqACH).[22] This application is also susceptible to inefficiencies involving recapturing air that has just been decontaminated (ie, "short circuiting").

22 The concept of EqACH is defined by comparison with the actual air changes achieved by removing the air in a room. Further explanation is provided below in section 0.

Figure 4-2. Example: UV in a box with top cover removed



Source: Nardell presentation; photo courtesy of Paul Jensen

4.2.2 UV in HVAC systems

UV germicidal irradiation can be implemented within an HVAC system, Nardell explained. The advantage of this approach is that the UV germicidal irradiation is out of sight and completely safe. However, this approach only disinfects air after it leaves the room, and this approach is limited by the building's ventilation system. Furthermore, there is no evidence that SARS-CoV-2 recirculates between rooms and floors within a building. The virus certainly spreads across rather large distances within a room, and it has been found that it can be carried longer distances on the air currents produced by ductless air conditioning systems. Thus, it may be questioned whether using UV germicidal irradiation within an HVAC system would be effective for reducing SARS-CoV-2 transmission. The same concern applies to the use of higher-level filtration in ventilation systems.

4.2.3 Whole-room UV air disinfection

Whole-room UV air disinfection is used in operating rooms, autopsy rooms, and hospital rooms to prevent nosocomial infection in settings where individuals are wearing protective clothing or in unoccupied hospital rooms between patients, said Nardell. Traditionally, UV lights between 254 nm and 280 nm have been used, such as low-pressure mercury lamps and newer LED lamps. However, this form of UV is not an ideal surface disinfectant, as micro-shadows can protect pathogens from irradiation. This approach can be useful when combined with surface cleaning, and it has been shown to be effective in hospital rooms where robots move through rooms using high intensity UV germicidal lights. Whole-room UV air disinfection can now also be applied using the newly developed 222 nm UV lamps, which is far safer for direct human exposure due to its limited ability to penetrate the epidermis (see Figure 2-3). While 222 nm UV light is subject to the same limitations as 254 nm— ie, microbes protected in shadows – it may not penetrate soiled surfaces. Fortunately, surface contact is now believed to be less important than aerosol spread for SARS-CoV-2 mitigation. Currently, 222 nm UV lamps are relatively expensive and inaccessible. Nardell posited that 222 nm lamps will soon become more readily available and that the increase in availability will be accompanied by a reduction in the cost and an increase in the lamp-life of these sources.

4.2.4 UR-GUV

Finally, Nardell discussed the use of UR-GUV (see Figure 4-3), which generally employ lamps with wavelengths between 254 nm and 280 nm. This approach takes advantage of the large volume of air in the upper part of a room and uses this area as a disinfection chamber. The approach also allows air to mix with the lower part of the room. Even though this mixing occurs at a relatively low velocity, it can be an effective approach for air disinfection in the lower part of the room. The primary disadvantage of this approach is the need to confine irradiation to the upper room. Nardell described how UR-GUV functions with respect to the flow of air within a room. Warm, contaminated air naturally rises toward the upper area of a room, and disinfected air in the upper volume of the room is displaced and circulates back down to the occupied, lower area of the room. Paddle fans can be used to assure good air mixing. Low-velocity ceiling fans can be useful for this purpose.[23] The use of UR-GUV is also limited by the efficiency of fixture designs. Louvers are necessary for fixtures used in conventional low ceilings, but they work by absorbing a large fraction of useful UV, as shown in Figure 4-3.

Figure 4-3. Example of modern UR-GUV fixtures (louvered)

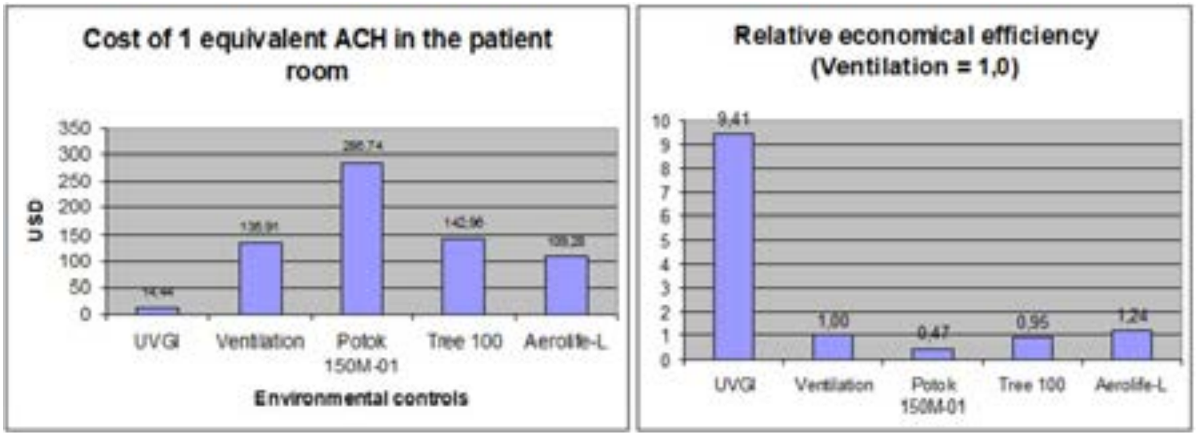
Source: Nardell presentation, courtesy of Charley Dunn, Lumalier

23 Nardell said that UR-GUV can be effective even without fans but improving air mixing in a room improves the disinfection of air in the lower portion of a room with UR-GUV.

4.3 Cost effectiveness of UR-GUV versus other room air cleaners

Nardell presented findings from an unpublished study conducted in Vladamir, Russia that evaluated the cost effectiveness of ventilation, room air cleaners, and UR-GUV. The study found that UR-GUV was the most cost effective both in terms of cost per EqACH in a patient room and in terms of relative economic efficiency. He added that the UR-GUV used in this study comprised standard lamps with a simple fixture design. The devices were made in Russia and were found to be approximately 9.5 times more cost effective than ventilation as a means of disinfecting large volumes of air.

Figure 4-4. Cost effectiveness of ventilation versus room air cleaners versus UVGI.



Note: UVGI=ultraviolet germicidal irradiation.
Source: Nardell presentation.

4.4 Key concepts of UV germicidal irradiation

Nardell reiterated the high-level concepts regarding the use of UV germicidal irradiation, such as in UR-GUV. The 254 nm wavelength is easily produced and well suited for UR-GUV application. This wavelength is more easily produced by low-pressure mercury vapor lamps.24 Soon, LED lights may be a viable alternative, which would reduce the environmental impacts of using mercury-containing lamps. Such LED lamps operate using a low current and could be powered by batteries or solar power. However, LEDs create a slightly longer wavelength (265 nm – 280 nm), which is somewhat less safe than the 254 nm lamps currently used. LED lamps for UV germicidal irradiation are being developed in response to the COVID-19 pandemic. They are not as efficient as mercury lamps, but they offer greater flexibility in terms of design and implementation. The power and cost limitations of such LED lamps are improving, he added.

Because UV germicidal irradiation uses UV-C, the risk of harmful skin and eye penetration is quite low. UV-C is highly reactive and absorbed by the outer dead layers of the skin. Eyes are relatively well-protected by the shape of the head and by eyelids, although mild eye irritation can occur with poor installations. Thus, exposure to UV-C radiation does not cause skin cancer or cataracts. Microbes are vulnerable to UV germicidal irradiation because of their tiny size and the exposure of nucleic acids to the UV germicidal light.

24 Nardell pointed out that low-pressure mercury vapor lamps are nearly the same as ordinary fluorescent lamps, except that they are made using a special kind of glass.

Nardell explained and discussed the importance of EqACH for air disinfection, pointing out that air changes are a limitation that is common to all air disinfections strategies. EqACH is a concept used to equate ventilation with the effects of UV germicidal irradiation. For example, the first air change in a room caused by ventilation may remove 63% of airborne contaminants, and each subsequent air change may remove 63% of whatever airborne contaminants remains from the previous air change. Whenever 63% of airborne contaminants are removed, by ventilation or by germicidal UV, it can be said that one equivalent air change has occurred. Thus, EqACH is a measure of the number of these equivalent air changes that occur per hour, and this measure can be used to describe the effectiveness of germicidal UV. Nardell noted that it becomes increasingly difficult to remove contaminants with each air change as contaminant concentrations fall. This is because each air change is removing the same proportion of the remaining contaminants as the last air change; thus, each air change removes a smaller absolute number of contaminants. In the case of UV germicidal irradiation, there are similar limitations, but because of the high EqACH UR-GUV can achieve, it is generally more effective than the alternative approaches. Additionally, in a room where virus-containing particles are continuously being generated, a considerably high level of air disinfection is required to keep the concentration of contaminants low. Given these considerations, an EqACH of between 6 and 12 is recommended, and in some cases an even higher EqACH may be necessary.

4.5 Evidence on the use of UR-GUV

Nardell discussed a study conducted in South Africa that investigated the use of UR-GUV to stop TB transmission from human patients to sentinel guinea pigs. The study was conducted in a facility with three patient rooms containing two patient beds each. Room air was vertically mixed with a ceiling fan. Exhaust air from the ward was delivered to one of two identical guinea pig chambers on alternating days. During 4 months of exposure, guinea pigs in one chamber only breathed air from the ward when room UR-GUV was on, and the other only breathed air from the ward on the alternate days when the UR-GUV was off. Guinea pigs are highly susceptible to TB, yet after several months of exposure, researchers found that the use of UR-GUV reduced the risk of TB transmission by 80%. This reduction in risk is comparable to adding 24 equivalent air changes to the existing six air change per hour ventilation, which would be difficult to achieve using ventilation or room air cleaners.

Nardell presented findings from a study of human exposures to UR-GUV. The study used personal eye-level monitors to measure UV exposure in various settings, including medical, educational, and office settings. The study found that individuals were only exposed to a small proportion of the allowable exposure limit, even though typical peak UV meter readings would have suggested that many of the installations were unsafe. This discordance owes to the fact that room occupants do not stare at fixtures for 8 hours; furthermore, he reiterated that the shape of the head and eyelids prevent excessive exposure to overhead UV – both indoor germicidal UV and outdoor solar UV. Nardell emphasized the importance of this finding for confirming the relative safety of UR-GUV.

In closing, Nardell affirmed that that UR-GUV is the most effective and efficient method of air disinfection for rooms where its use is feasible, and UR-GUV is safe for room occupants. One example of settings where UR-GUV is not feasible is rooms with low ceilings. He noted that LED lamps may soon become more common in UR-GUV and whole-room UV-C air disinfection, potentially replacing mercury lamps.

5 Integrating upper room germicidal ultra-violet lighting as part of a total-building infection control program

Bill Bahnfleth, Institutes of Energy and the Environment at Penn State University discussed how germicidal UV systems can be integrated into the overall context of infection control within a building. He noted that World Health Organization (WHO) and Centers for Disease Control and Prevention (CDC) have acknowledged the potential for airborne transmission of SARS-CoV-2. According to CDC, the virus most commonly spreads during close contact and less commonly spreads through contact with contaminated surfaces. However, airborne transmission can occur in enclosed spaces, during prolonged exposure to respiratory particles, and as a result of inadequate ventilation and air handling. Thus, HVAC systems can affect airborne exposures to SARS-CoV-2. He quoted Maria Neira, director of WHO Department of Public Health, Environmental and Social Determinants of Health, who said "ventilation represents a very important aspect, a very important factor to prevent the [SARS-CoV-2] virus from spreading indoors."[25]

5.1 Evidence of airborne transmission of viral particles in buildings

Numerous recorded instances of in-room airborne transmission suggest that airborne transmission is a pressing concern. One study investigated air handling units in a hospital in Oregon.[26] Researchers found that viral RNA penetrated through the air handling unit, which contained MERV 15 final filters. This finding strongly suggests that at least some proportion of viral aerosol is being recirculated in building systems. The reason that room-to-room transmission of SARS-CoV-2 has not been observed is likely due to the concentration of viral particles rather than the absence of viral particles.

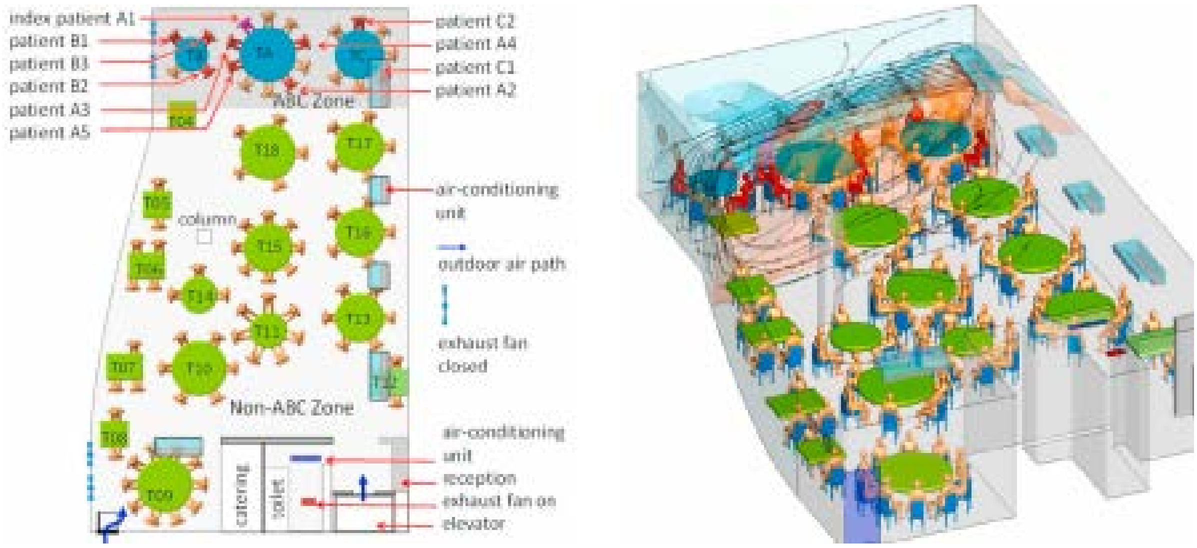
In one case, an index patient in a dining room infected nine restaurant patrons.[27] The dining room had split system air conditioning with strong in-space air recirculation (see Figure 5-1). There was no ventilation air supply. The dining room had four exhaust fans, but none were running at the time of transmission. The index case's visit was recorded on video, and no close contact with the infected individuals was recorded. The ventilation rate was measured at approximately 0.75L – 1L per second per patron. The study found that "aerosol transmission of SARS-Cov-2 due to poor ventilation may explain the community spread of COVID-19."

A recent study found strong implications of transmission of fecal aerosol through plumbing systems within a multistory building in South Korea (see Figure 5-2).[28] The study suggests that nine infections among three families were transmitted by the vertical alignment of the families' apartments and their bathrooms' connections to a shared plumbing stack. No evidence of transmission via elevator or other routes was found. It appears that the building's plumbing system created a natural ventilation shaft, and through the stack effect, air moved vertically from one apartment to another. Another study found that ten cases

25 More information about Neira's statement is available from https://www.youtube.com/watch?v=XJC1f7F4qtc (accessed March 5, 2021).
26 Horve et al 2020
27 Li 2021
28 Kang et al 2020

of COVID-19 were found in apartments along two plumbing natural ventilation shafts (see Figure 5-3). In this case, no backdraft damper was present, and no close contact among the cases could be identified. These cases, which suggest transmission via the effect of natural ventilation and the stack effect, are similar to the well-studied SARS outbreak in Amoy Gardens, said Bahnfleth.[29]

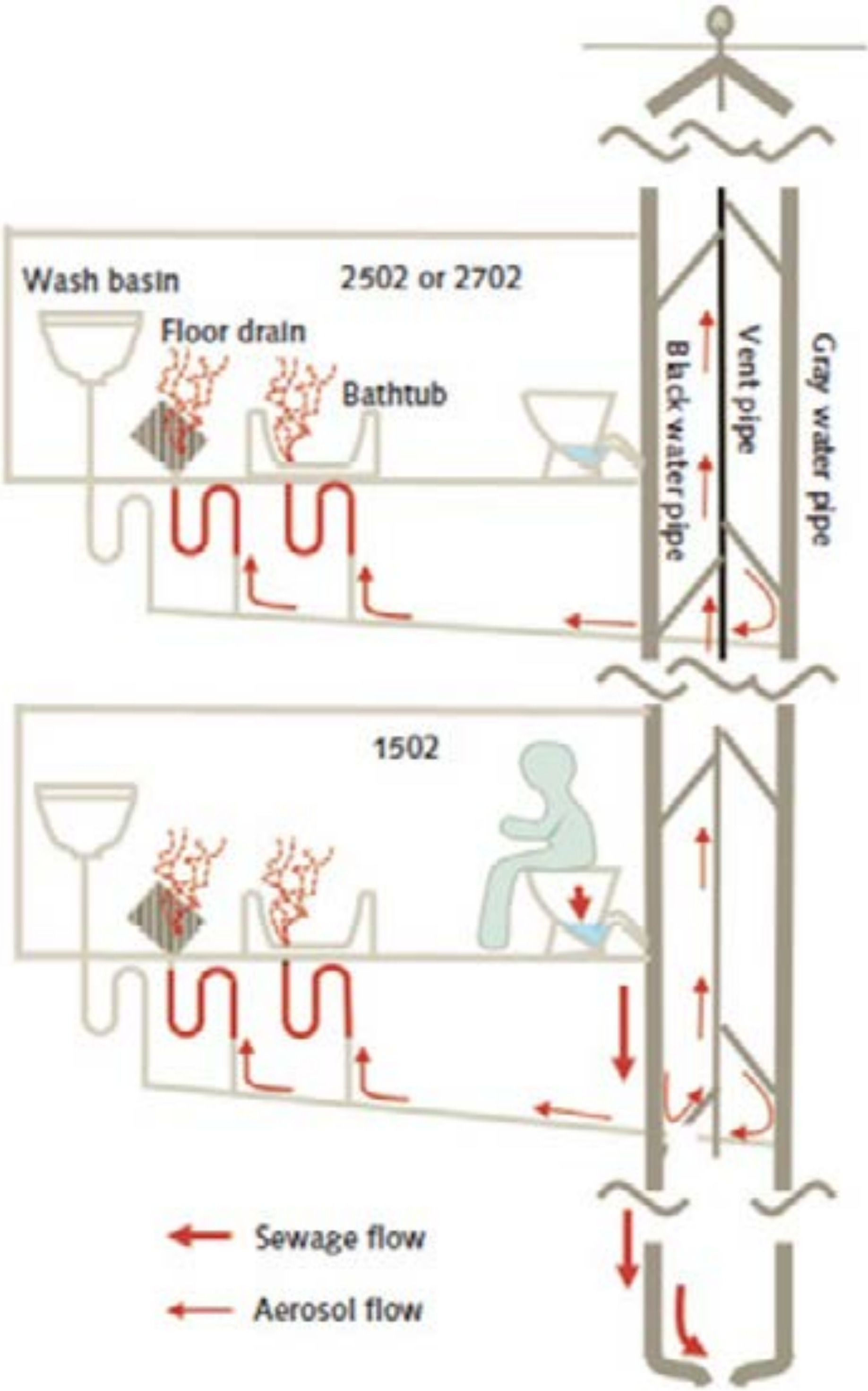
Figure 5-1. Restaurant air stream map.



Sources: Bahnfleth presentation; Li 2021

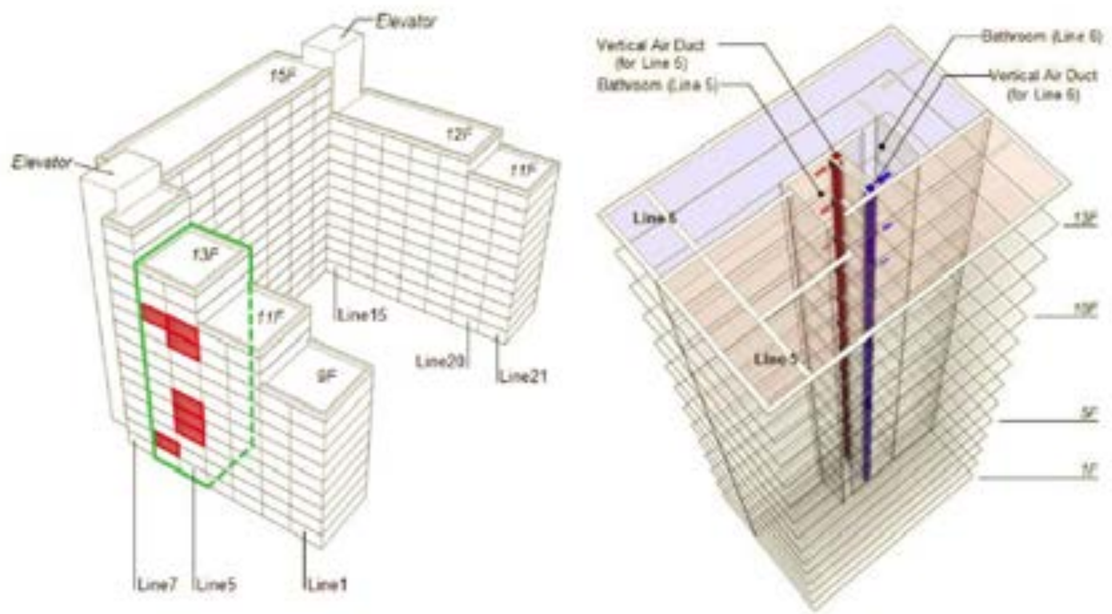
29 Ytu et al 2004

Figure 5-2. Fecal aerosol transmission suspected in apartment building incident



Sources: Bahnfleth presentation; Kang et al 2020

Figure 5-3. Possible aerosol transmission of COVID-19 through ventilation shaft



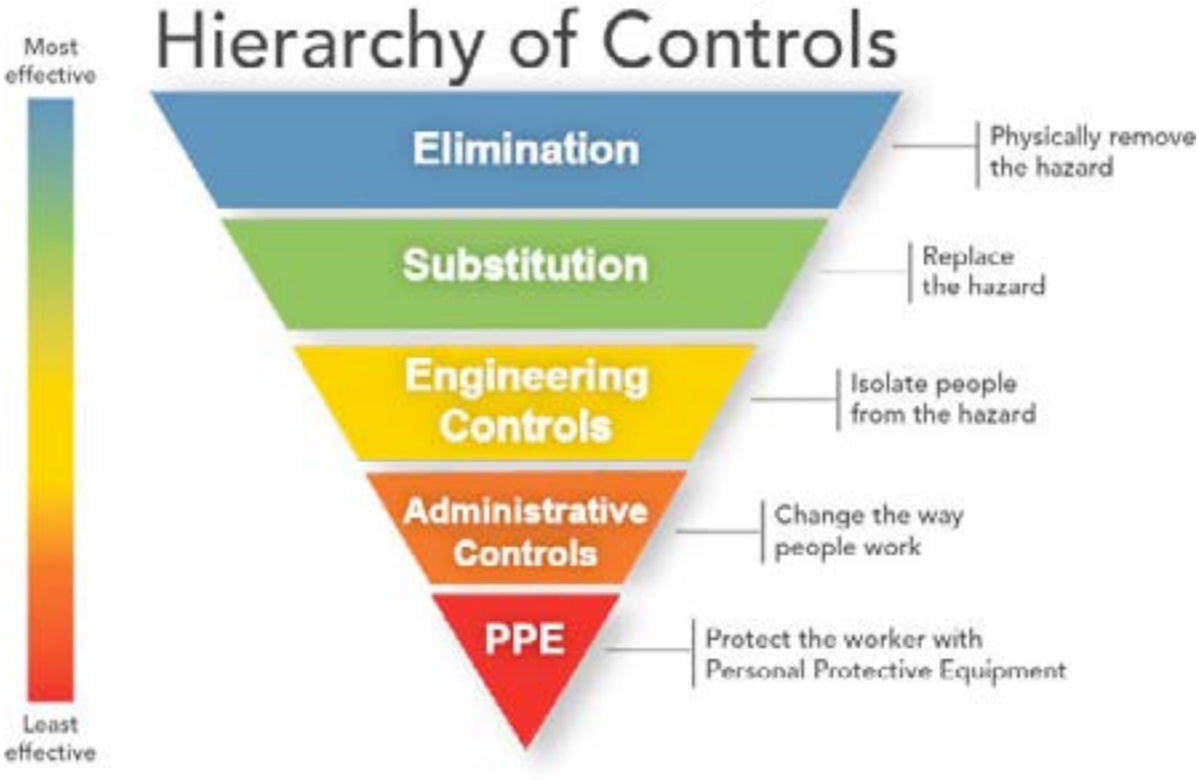
Note: The red boxes in column 13F indicate apartments where confirmed cases of COVID-19 were found.
Sources: Bahnfleth presentation; Hwang et al 2021

5.2 Engineering controls as part of a layered infection risk mitigation strategy

Bahnfleth explained that germicidal UV is an engineering control that should be implemented within a framework of a hierarchy of engineering controls that make up a risk management strategy, as shown in Figure 5-4. The hierarchy of control framework is arranged in terms of effectiveness. Engineering controls are those controls that isolate people from the hazard, and they are situated in the middle of this hierarchy. There are numerous engineering controls that can address the hazard of airborne transmission of disease, including ventilation, filtration, germicidal light, and so-called "additive" air cleaners. He explained that the generic category "air cleaners" may include germicidal light along with additive air cleaners. Additive air cleaners may include the addition of ions, hydrogen peroxide, or various radicals to the air. While additive air cleaners are currently being promoted strongly relative to UR-GUV, Bahnfleth suggested that additive air cleaners should not be considered as an engineering control or alternative to UR-GUV. This is because there is limited evidence for the effectiveness of additive air cleaners; further, he described the safety profile of these devices as incomplete, at best. He asserted that all viable engineering controls have applications in central and distributed air conditioning implementations. Thus, there is a high degree of flexibility in terms of how to address the engineering control layer of the hierarchy of controls risk management strategy.

Bahnfleth pointed out that engineering controls are only one layer within the hierarchy of controls. The implementation of engineering controls does not undermine the necessity or efficacy of other strategies, such as administrative controls (eg, social distancing) and personal protective equipment (eg, surgical masks or N95 respirators). In the context of the COVID-19 pandemic, engineering controls are aimed at reducing the concentration of active airborne viral particles (viral aerosols), that present risk to persons. However, the risk of transmission cannot be fully mitigated by reducing the concentration of viral particles (see Figure 5-5). When individuals are in close proximity to one other, the short-range transmission of viral aerosols may pose great risk, even when engineering controls are in place.[30] A single sneeze can travel up to 8 meters,[31] and the use of a mask can effectively diffuse the trajectory of ejected air and particles from an individual's mouth and nose.[32] Thus, social distancing and masks serve important functions within the hierarchy of controls layered approach to risk management.

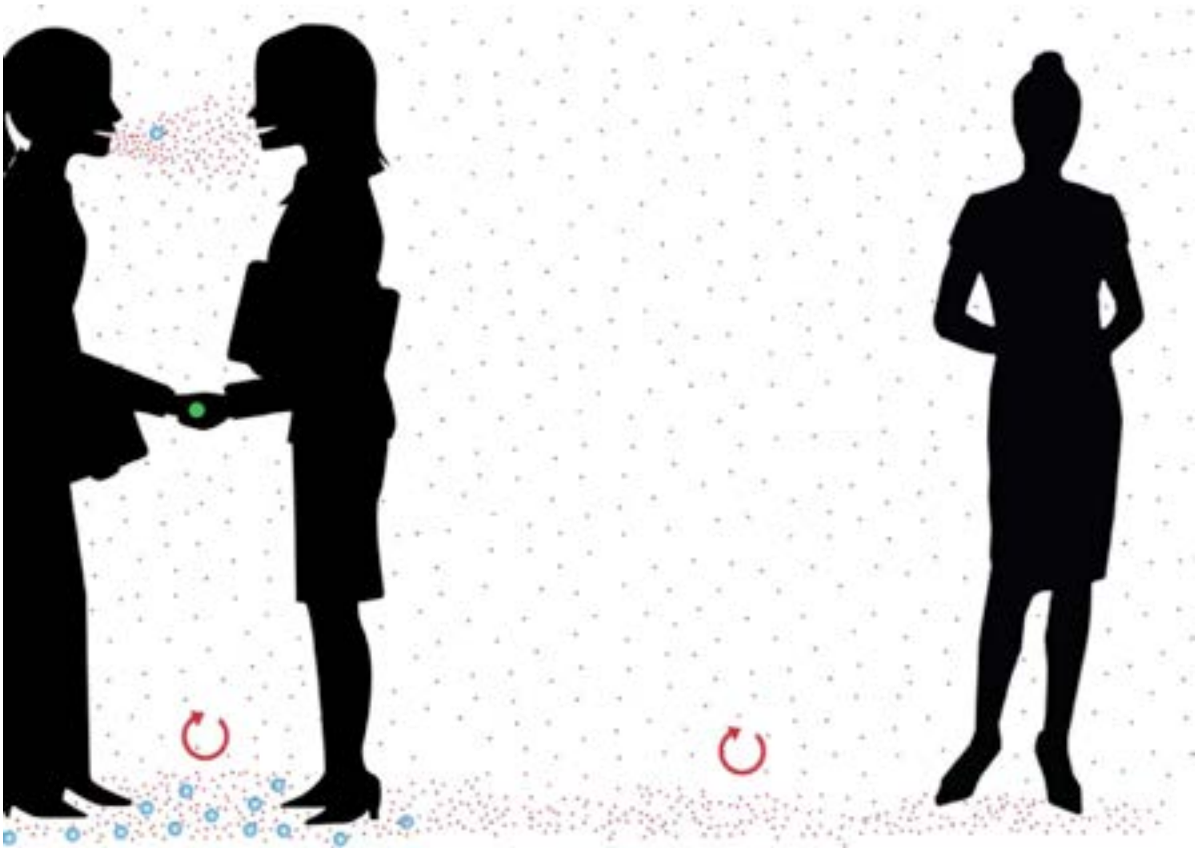
Figure 5-4. Hierarchy of controls.



Note: PPE=personal protective equipment.
Sources: Bahnfleth presentation, https://www.cdc.gov/niosh/topics/hierarchy/

30 Tang et al 2021
31 Bourouiba 2020
32 Staymates 2020

Figure 5-5. Range of respiratory particles and potential spread over distance.



Note: Blue particles represent droplets, typically >100-μm diameter, that fall to the floor under gravity within 2 m of the source. Red particles represent aerosols, typically <100 μm, that stay suspended for longer, but eventually fall to the ground if the air is motionless for long enough (at least 30 min).
Sources: Bahnfleth presentation, Tang et al 2021

5.3 Engineering controls reduce risk by reducing airborne concentration

To describe how requirements for engineering controls can be determined as part of a layered infectious aerosol risk management plan, Bahnfleth discussed the Wells-Riley model of airborne infection (see Figure 5-6), which has been used extensively during the COVID-19 pandemic. This model predicts the probability of new infections (P, ratio of new cases to number of susceptible persons) using a formula that includes the following variables: number of infectors (I), quanta emission rate (q, infectious doses per hour), pulmonary ventilation rate per susceptible person (p, meters cubed per hour), exposure time (t, hours), and flow rate of uncontaminated air (Q, meters cubed per hour). Increasing I, q, p, or t increase risk, while increasing Q decreases risk. Simply put, given the characteristics of the hazard source and occupancy, the uncontaminated airflow required to maintain safe concentrations (ie, achieve a target value of P) can be calculated. The necessary flow of uncontaminated air to achieve safe concentrations of airborne transmission hazards is simplistically interpreted as ventilation; however, uncontaminated air can be produced by other engineering controls, including filters and air cleaners. Ventilation and the effect of other controls are frequently expressed in units of EqACH. The effect of air cleaners such as UR-GUV can be determined and used to contribute to the total requirement for uncontaminated air. In fact, all contaminant removal mechanisms can be expressed as equivalent uncontaminated air flows and added together to reach the desired total of uncontaminated air flow, not only ventilation, filtration, and air disinfection, but also deposition of particles and natural inactivation.

Bahnfleth pointed out that building codes include ventilation requirements, and this required ventilation also contributes toward the calculation of the total uncontaminated air flow. However, for non-healthcare facilities, these ventilation rates are intended to address body odor control and other building-related contaminants, such as volatile organic compounds and particulate matter from indoor sources. Further, the required non-residential ventilation rates are far lower than the ventilation rates required for healthcare facilities.[33]

In both healthcare and non-healthcare buildings, filtration is required by ventilation standards in order to remove particulate matter from circulating air, Bahnfleth explained. However, the minimum filter efficiency required in residential and non-residential buildings (MERV 6 and MERV 8, respectively) is not effective for filtering particles the size of respiratory aerosols. These filters collect larger particles that may impair the function of HVAC equipment in the building. MERV 6 and MERV 8 filters have very limited ability to collect particles between 0.3μm and 3μm in size, but MERV 13 filters collect 50% or more of particles within the 0.3 – 1 μm size range and 85% or more in the 1 – 3 μm range, which includes most virus-containing particles. Thus, upgrading to MERV 13 filters will have a beneficial impact, but may not be sufficient to reduce the risk of infection transmission to an acceptable level, said Bahnfleth.

Figure 5-6. Well-Riley model of airborne infection.

$$P = 1 - \exp\left(-\frac{Iqpt}{Q}\right)$$

P = probability of new infections

I = number of infectors

q = quanta (infectious dose) emission rate [1/hr]

p = pulmonary ventilation rate per susceptible [m³/h]

t = exposure time [hr]

Q = flow rate of uncontaminated air [m³/h]

Source: Bahnfleth presentation

5.4 Using germicidal UV as an engineering control

Bahnfleth discussed application considerations for using germicidal UV light as a part of an engineering controls strategy. Germicidal UV light can be an effective supplement to other engineering controls, such as ventilation and filtration. As discussed above, the minimum levels of filtration and ventilation are generally not sufficient for effective aerosol risk mitigation. Minimum levels of ventilation and filtration provide approximately 3 EqACH, but at least 6 EqACH are required in order to achieve effective aerosol risk mitigation based on healthcare ventilation standards. It is possible to deploy germicidal UV light within an airstream, for example, in air handling units of central HVAC systems. This airstream approach is less expensive per treated unit of conditioned space than UR-GUV, but the clean air flow produced is ultimately limited to

33 Non-residential ventilation requirements are defined in ASHRAE 62.1. Healthcare ventilation requirements are defined in ASHRAE 170. More information about ASHRAE standards and guidelines is available from https://www.ashrae.org/technical-resources/standards-and-guidelines (accessed March 8, 2021).

the supply air flow rate, which is typically 5-6 ACH. In contrast, UR-GUV can be expected to have an effect equivalent to tens of EqACH and some systems have been measured to produce more than 100 each (Riley and Nardell 1989).

Bahnfleth discussed which settings are well suited for the use of UR-GUV as an engineering control. UR-GUV can be effectively deployed in densely occupied large spaces such as lunchrooms, restaurants, and auditoriums. In such settings, it may be sensible to invest in a more expensive but highly effective UR-GUV system. While fomite transmission is not a pressing concern in the COVID-19 pandemic, Bahnfleth added that germicidal UV light could be used to treat surfaces in settings where fomite transmission is a concern. This application of germicidal UV light for surface disinfection is well-established in healthcare settings and could be implemented in other types of facilities if far-UVC systems become widely available.[34]

Bahnfleth discussed key points from the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Epidemic Task Force's *Core Recommendations for Reducing Airborne Infectious Aerosol Exposure*.[35] First the recommendations call for adherence to public health guidelines, including personal protective equipment, administrative measures, circulation of occupants, hygiene, sanitation, and reduced occupancy. He noted that this recommendation is made in recognition of the importance of adhering to public guidance regarding the use of masks and social distancing. The Core Recommendations call for adherence to minimum ventilation requirements, as per applicable building code, but they call for filter upgrades in recirculating air streams. They also call for the use of a combination of ventilation, filters, and air cleaners in order to achieve risk reduction targets. This recommendation includes the use of added in-room air filtration and the use of germicidal UV light.

In closing, Bahnfleth reviewed the key considerations regarding the use of engineering controls to reduce the risk of viral transmission within buildings. Engineering controls address one aspect of infection risk, and they are situated within a hierarchy of controls that address multiple aspects of infection risk with varying degrees of effectiveness. While a baseline of ventilation and filtration is included in building codes, they are generally insufficient to reach desired airborne infection risk levels. Germicidal UV holds great promise as a supplementary engineering control when used in addition to ventilation and filtration. The choice between airstream germicidal UV and UR-GUV applications depends upon an analysis of the cost-performance tradeoff between the two technologies, but there is no doubt that the performance of UR-GUV is far better than that of airstream germicidal UV in a given space. The measurement of equivalent non-contaminated air flow (ie, EqACH) is the basis for the emerging method of designing a building's infection control program.

34 Buonanno et al 2020

35 More information about ASHREA Epidemic Task Force Core Recommendations for Reducing Airborne Infectious Aerosol Exposure is available from https://www.ashrae.org/file%20library/technical%20resources/covid-19/core-recommendations-for-reducing-airborne-infectious-aerosol-exposure.pdf (accessed March 8, 2021).

6 Practical application of upper room germicidal ultraviolet lighting

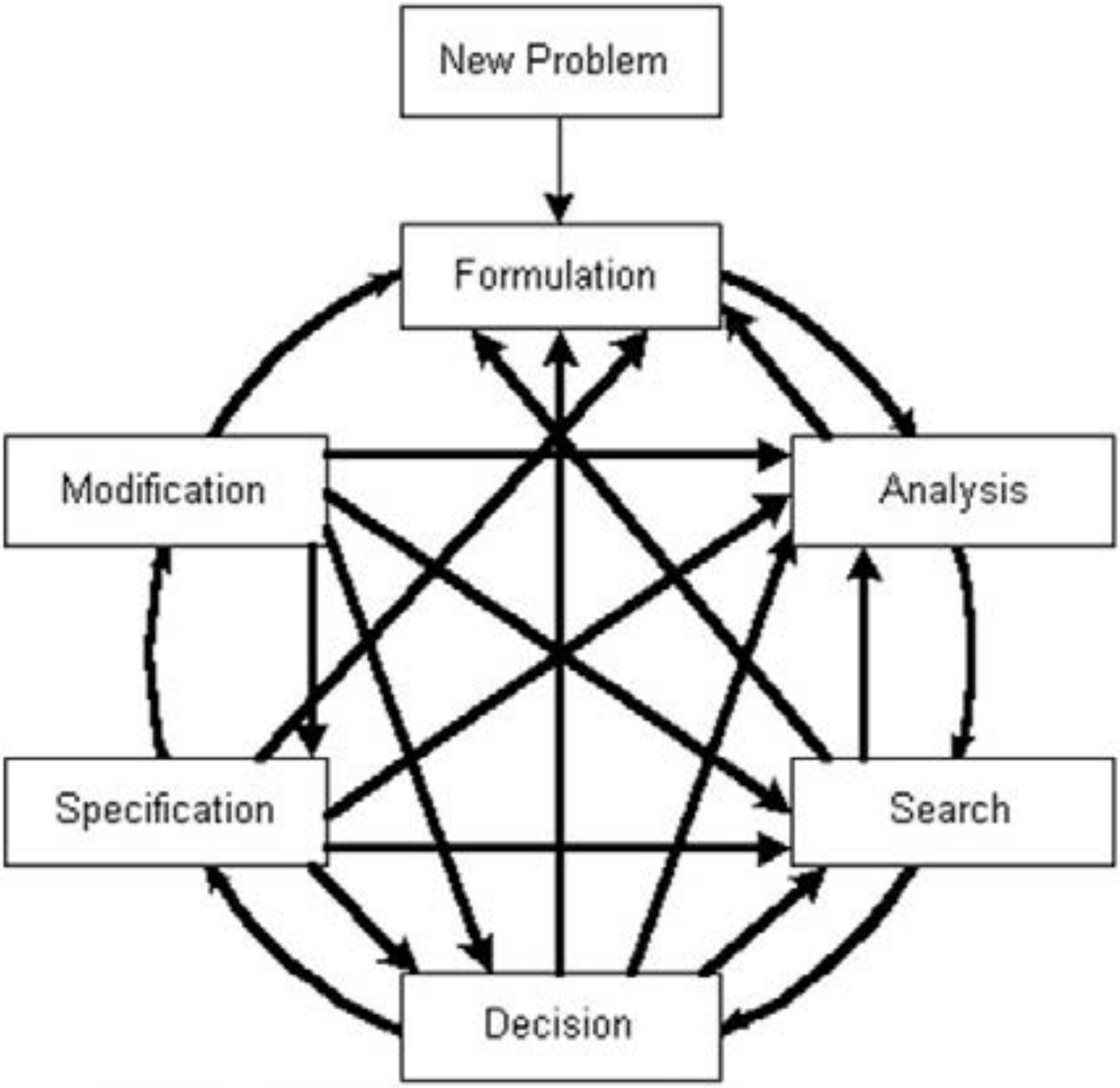
Paul Jensen, former lead for TB infection control and engineer at Infection Research and Programs Branch of the Division of Tuberculosis Elimination at US Centers for Disease Control and Prevention, and currently an Independent Consultant for FAI, discussed the process of implementing UR-GUV. He opened by invoking the concept that it is the dose that determines the poison. As Paracelsus said, "what is there that is not a poison? All things are poison, and nothing is without poison. Solely the dose determines that thing is not a poison."[36] With this in mind, Jensen explained that UR-GUV makes use of both the known harmful and safe exposures of UV-C. In the upper part of the room, UR-GUV creates a harmful area where the UV-C can inactivate viruses or bacteria. In the lower part of the room, it is necessary that the UV-C exposure is within the limits of safe exposure. This is related to the concept of the no adverse effect level.[37]

Jensen explained that the commissioning process for buildings and systems includes the provision of procedures, methods, and documentation requirements for each commissioning activity for project delivery from predesign through occupancy and operations.[38] He emphasized that the process includes every step from predesign through occupancy. In other words, the commissioning process is aimed at ensuring that the building actually performs as desired. Often, implementers are under the misconception that the commissioning process comprises only the acceptance or performance requirements; in fact, these are only one part of the overall commissioning process. The commissioning process includes an overview of required activities, a description of each process step's minimum activities, minimum documentation requirements, and acceptance requirements.

Jensen presented a visual representation of the commissioning process design cycle, as shown in Figure 6-1. He explained that the definition of each design step is not particularly important; the key point of the design cycle graphic is that at any given stage, it may be necessary to revert to a previous stage of the process. For instance, during the analysis process, it may become clear that it is necessary to return to the formulation stage, and during the modification process, it may be necessary to return to analysis, search, decision, or specification stages.

36 Grandjean 2016
37 Grandjean 2016
38 More information about ASHRAE's Commissioning Process for Buildings and Systems is available from https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/202_2018_a_20200630.pdf (accessed March 8, 2021).

Figure 6-1. Commissioning process design cycle



Source: Jensen presentation, Jensen and Tonies 1979

6.1 Installing UR-GUV at The Salvation Army Center of Hope, Oklahoma City, Oklahoma

Jensen discussed an example from the installation of UR-GUV at The Salvation Army Center of Hope in Oklahoma City, Oklahoma. The process began with a visual assessment of the arial view of the building, along with an assessment of the building plans. Next Jensen considered the microorganisms and diseases of concern. In this case, the risk of COVID-19, TB, and influenza transmission were of concern. The risk assessment also included a review of the epidemiological profile of the building's clients; this assessment determined whether clients were high-risk individuals, carriers of certain diseases, or immune-compromised individuals. In this case, the building was occupied by The Salvation Army staff, volunteers, and clients. The risk assessment also included an evaluation of the Infection Prevention and Control Plan that was already in place. This plan is comprised of policies and practices that are fully implemented to prevent and control infections. The Salvation Army Center of Hope in Oklahoma City offers a variety of services, including meals, food packets, utility and rent assistance, temporary housing, transition housing, and winter shelter. The delivery of these services includes much face-to-face interaction between staff and clients, and the risk assessment process included a description of which activities take place in which building areas.

Once the risk assessment was complete, a facility assessment was conducted. In any areas where UR-GUV systems may be beneficial, the feasibility of implementation had to be considered. This assessment considers ceiling height (physical ceiling height and effective ceiling height), limitations due to activities conducted in building spaces, electricity, and air mixing (ceiling fans and HVAC system). Once the facility assessment and risk assessment were complete, the room priority, room volume, calculated dosage, and cumulative dosage for each room were collected. Room priority was determined for each room on a scale of 1 to 3, where 1 was the highest priority. Jenson added that the facility's tornado shelter was not assigned a priority during the initial assessment, because staff did not anticipate needing to use that area of the building. However, during the winter this space was as a shelter and was fitted with UR-GUV. Room volume and calculated UV-C dosage were determined to estimate the amount of UV-C that would be necessary in each space.[39] At the time, AeroMed™ Technologies offered five different UR-GUV fixtures to cover a wide range of applications.[40] Using the room volume data and the UV-C output of the various available fixtures, cumulative dosages and fixture recommendations were established for each space. Once these initial recommendations were calculated, the physical layout process could begin.

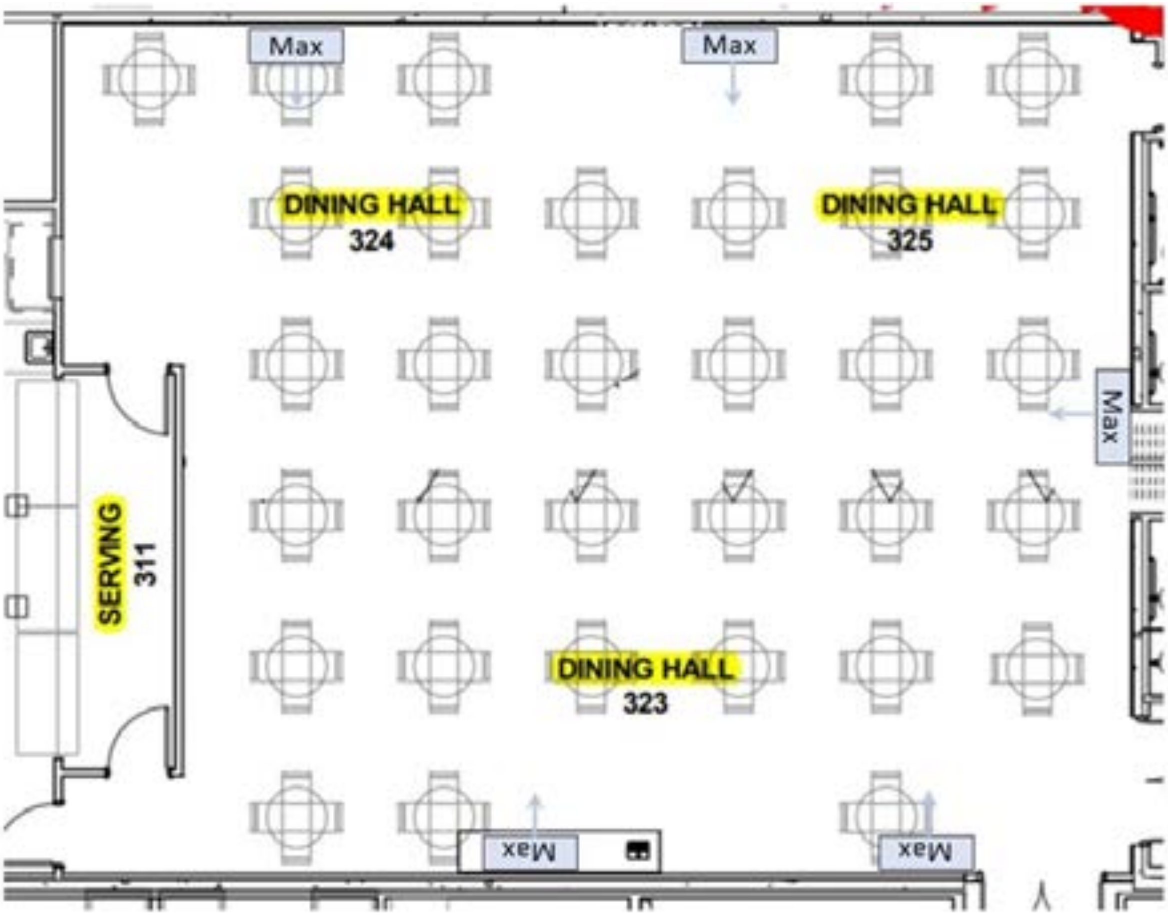
Jensen described the numerous considerations that had to be made while laying out the installation of UR-GUV in the dining hall of The Salvation Army Center of Hope. The dimensions of the room, including bump-outs and ceiling height had to be evaluated. For instance, the room had decorative, noise dampening panels hanging from the ceiling. Jensen and his associates had to determine whether to measure the ceiling from the base of these panels or from the height of the physical ceiling. They chose to measure from the bottom of these fixtures, in part, because the ductwork in the room blew down from above these fixtures, indicating good airflow in the room. In addition, it was impossible to irradiate the space between these panels and the physical ceiling. To ensure good airflow, they determined that the room's ventilation fans must always remain on, even during heating and cooling seasons. It was determined that AeroMed™ Max units (UV-C output = 1.21 Watts) would be installed (see Figure 6-2). However, there were various considerations that had to be made in order to successfully install these units in accordance with the layout, as the real-world conditions did not perfectly match the simple representation of the room layout. For example, one wall had a large television toward which occupants were likely to spend considerable time looking. Consequently, Jensen and his colleagues decided not to put any UR-GUV units on this wall. Instead, they located the UR-GUV on the rear and side walls. As the physical installation approached, decisions had to be made about the use of the space, the features and functions of walls, the potential for fixtures to block other room functions, and other related considerations. The resulting installation still achieved the sufficient UV-C dose needed to inactivate viruses and bacteria. Jensen added that installing the units is not particularly difficult in terms of labor in most scenarios and rooms; however, installers must apply a practical perspective to ensure that fixtures are deployed in a sensible and appropriate location. To assist with the installation process, a mobile app can be used to confirm that fixtures are installed in a neutral position. Jensen shared some insights from his

39 Jenson explained that he used the dosage requirements for TB irradiation in this installation. This is because COVID-19 is known to be more susceptible to UV-C than TB.

40 The output of fixtures available from AeroMed ranged from 0.35 Watts to 6.25 Watts. More information about AeroMed's germicidal UV fixtures is available from http://aeromed.com/upper_room_guv.html (accessed March 8, 2021).

own experiences in installing UR-GUV fixtures. A fixture with a short ray length, or a fixture that is installed close to a wall, can be pointed down a few degrees, while a fixture installed on a very high ceiling or casting its light a long distance can be pointed up a few degrees. These types of course adjustments may be necessary as part of the physical installation process, and they are made through communication and measurements made among the installers.

Figure 6-2. The Salvation Army diner UR-GUV installation layout



Notes: Max=AeroMedT™ Max UR-GUV fixture (output=1.21 Watts)
Source: Jensen presentation

6.2 Final acceptance/performance testing

Jensen described how UR-GUV installations are subjected to acceptance or performance testing, and he reiterated that this final process is not the entirety of the commissioning process but one step within the commissioning process, which spans from predesign to occupancy and operation. The process requires that installers measure UV-C exposure at standing eye-level height. For the tallest individuals, eye-level is between 5.5 feet (1.68 meters) and 5.9 feet (1.8 meters). Thus, installers use a pole to measure UV-C irradiance by affixing a UV-C detector on the pole at a height between 5.5 feet and 5.9 feet. In one location, this method yielded a measurement of 0.39 microwatts per square centimeter (see Figure 6-3). This is an acceptable and safe UV-C exposure measurement, said Jensen. He described the final acceptance/performance testing in a room with beds for clients. Clients would be standing in this room, he said, but the total time spent standing was expected to be fairly minimal. Even though UV-C exposure is expected to be low at the height of a bed, he and his colleagues tested the exposure at each bed just in case there were some reflections that increased potential exposure. In fact, they located one area where a high amount of UV-C was reflecting from overhead ductwork.

Figure 6-3. Measuring UV-C irradiance at eye height (5'6"), using a pole and UV-C radiometer

Source: Jensen presentation

6.3 UR-GUV operation and maintenance

Jensen discussed the details of operating and maintaining UR-GUV. The UV-C lamps and fixture reflectors must be cleaned regularly. Safety measurements should be periodically made to ensure that occupants are not being overexposed and/or the upper room is not being underexposed. He also discussed the lifecycle costs associated with UR-GUV (see Figure 6-4), which are mostly incurred during the operation and maintenance of the fixtures. These costs begin with planning and procurement costs, which include the costs of strategic planning, creating a master plan, design brief and design, construction, and commissioning. During the life of the fixtures, there will be recurring costs associated with operation and maintenance. At the end of a fixture's lifecycle, final costs associated with closure and disposal will be incurred. Over the life of a UR-GUV fixture, the total costs will amount to between two times and five times the initial capital costs. This must be kept in mind, as UR-GUV fixtures cannot be installed and then abandoned. They must be maintained and operated over the duration of their use and properly closed and disposed of when their use is discontinued.

Figure 6-4. Lifecycle costs of upper room germicidal ultraviolet lights.

Source: Jensen presentation, courtesy of SA Parsons and G Abbott

6.4 Conclusions

In closing, Jensen highlighted several points related to the practical application of UR-GUV. The building should be outfitted with high quality UV-C lamps and UR-GUV fixtures. These fixtures should be used as part of a well-conceived and thorough design, and they should be installed thoughtfully in accordance with that design. The final step of the commissioning process is final acceptance/performance testing, which must be performed to ensure the suitability of the UR-GUV installation. UR-GUV fixtures are not an alternative to proper ventilation or minimum fresh air requirements. Furthermore, the effectiveness of UR-GUV is reliant upon the effect of air mixing; thus, UR-GUV installation and design must include consideration of requisite air mixing. UR-GUV fixtures cannot be abandoned once installation is complete; they require ongoing maintenance and testing to ensure safety and functionality throughout their lifecycle. Accordingly, UR-GUV incur operation and maintenance costs for the duration of their lifecycle, and final closure and disposal costs will be incurred when their use is discontinued.[41]

41 Jensen noted that the StopTB Partnership has published helpful documents based on their experiences using UR-GUV to end TB transmission. More information is available from http://stoptb.org/wg/ett/resources.asp (accessed March 11, 2021).

7 Discussion

7.1 Determining the appropriate physical location of UR-GUV fixtures within a space

Keshavjee asked whether upper room UR-GUV is as effective in the center of a large room as it is around the perimeter. Nardell said that the relative location of the UR-GUV fixtures is less critical than the average irradiance in the upper room. Certain rooms are better suited for fixtures placed in the center of the room while other rooms are better suited for fixtures to be placed around the perimeter. Jenson emphasized that it is necessary to conduct room assessments prior to installation. During the installation process, hot spots or weak spots may be discovered. The aim when installing UR-GUV fixtures is to achieve a relatively uniform UV flux. Air mixing is also an important component. A study evaluating a methodology for quantifying the effect of room air ultraviolet germicidal irradiation on airborne bacteria found an 80% reduction in efficiency of germicidal UV without proper air mixing.[42] Another study found that air mixing could be achieved with an air velocity of 0.05 meters per second.[43] Nardell highlighted that occupants in a room contribute to air mixing through body heat, movement, and other activities. Still, mechanical air mixing is generally advised to ensure proper air mixing without leaving it to chance. Milton explained that in experimental settings heat boxes have been used to simulate human body heat. The simulated body heat increases EqACH; in one case the EqACH increased from 7 EqACH to 16 EqACH. However, a ceiling fan provides a far greater increase in EqACH, providing up to 90 EqACH. In some cases, a ceiling fan alone can increase the effectiveness of UR-GUV by a factor of 10. This is an important consideration for the cost and design of a UR-GUV installation. For example, adding ceiling fans to a UR-GUV installation could potentially double the initial installation cost. If this doubling of installation cost affords a 10-fold increase in UR-GUV performance, then a strong case can be made for the additional of ceiling fans to a UR-GUV installation.

7.2 Determining the impact of moisture on the effectiveness of germicidal UV

Keshavjee asked whether the moisture content of a room affects the performance of UR-GUV. Milton said that experiences with pox viruses indicate that moisture does impact the effectiveness of UR-GUV. Germicidal UV is more effective in the winter than in the summer, and this is thought to be related to the higher humidity during the summer. Bahnfleth noted some tension in findings related to this question. It has been found that increased humidity tends to decrease the rate constant for various pathogens. However, this is in contrast with the dictum stating that humidification can be used to reduce infection risk. Nardell suggested that the findings related to humidity and germicidal UV effectiveness may owe to some laboratory effect. Where UR-GUV is deployed, so long as particles are exposed to UV-C in the upper part of a room, it appears that UR-GUV remains fairly effective despite variations in humidity. A study in Lima, Peru found that the average humidity over 2 years was about 70%, yet researchers achieved about 80% effectiveness using UR-GUV.[44] Milton concurred, noting that variation in humidity may cause a reduction in EqACH from 1000 EqACH in winter to 100 EqACH in summer. Even at 100 EqACH, there is adequate air mixing to achieve the germicidal effect of UR-GUV.

7.3 Understanding the impact of UR-GUV on viral transmission via surfaces and air

Keshavjee asked about the percentage of airborne particles that reach the upper area of a room and the percentage of airborne particles that land and linger on fomites. Milton

42 Miller and MacHer 2000
43 Rudnick and First 2007
44 Escombe et al 2009

explained that the relevant question regarding fomites is what can be transferred from a surface to respiratory mucosa via contact. Regarding airborne particles, the relevant questions are what can be deposited in the respiratory tract by breathing, where it can be deposited, and how sensitive the deposit location is. This has not been studied extensively with SARS-CoV-2, but this phenomenon has been heavily studied with influenza. It takes a single influenza virus deposited deep into the lung to cause a severe flu with fever, chills, and systemic symptoms. It takes 100,000 influenza viruses instilled in the nose to cause a mild upper respiratory infection with no fever and no systemic symptoms. In fact, it is nearly impossible to cause fever by depositing flu virus in the nose. In order to deposit large amounts of virus into the nose an individual would likely need to intentionally do so. For instance, if an infected person sneezed into their hand and immediately rubbed their wet hand on another person's hand, that person may be able to deposit large quantities of virus if they put their finger in their nose while it was still wet with the moisture from the original person's sneeze.[45,46] This behavior may be a concern for small children, but this is not a plausible pathway for transmission among adults.

7.4 Determining the impact of air mixing and ventilation on the effectiveness of UR-GUV

Keshavjee asked whether low-velocity fans and related products have been evaluated or may be effective for controlling the spread of infection.[47] Jensen explained that the purpose of supplementing a UR-GUV with fans is to improve air mixing, overcome limitations in existing ventilation systems, or impact the temperature differentials (comfort) within a space. In a poorly ventilated space, a barrier of warm air can be created that prevents the mixing of air between the lower and upper spaces. Introducing mechanical mixing with fans can overcome this kind of air barrier between the lower and upper rooms. However, fans should be added in a way that improves or synergizes with existing ventilation, rather than interfering with ventilation. In some cases, existing ventilation systems may be altered to ensure good air mixing without adding ceiling fans. For example, it may be possible to achieve needed air mixing by changing the diffusers in the existing ventilation system and constantly running the ventilation system's fans.

7.5 Using UR-GUV in resource poor settings

Keshavjee asked about the power consumption of UR-GUV and whether battery-powered UR-GUV can be used in resource poor settings and settings where regular electrical supply is unavailable.[48] While there may not be any battery-operated UR-GUV systems sold as a package, Jensen said that existing backup generators or batteries-operated inverters could be used to power UR-GUV systems. These kinds of power sources are typically used to run incubators or freezers when other power sources are unavailable. The energy requirements for UR-GUV fixtures is low: 110V in the United States and 220V elsewhere. Some more expensive fixtures may be more energy efficient. For instance, there is a low-cost UR-GUV fixture available (approximately USD$150), with a UV-C output which is roughly half the output of the fixtures typically used in the US. This low-cost unit also consumes more power. This is another reason that both upfront and recurring costs should be considered when UR-GUV systems are being designed. Nardell added that if LED lamp technology improves, it is likely that portable UR-GUV fixtures that operate on DC current would become more readily available. Such units would likely be well suited to operate on battery and solar power. Jensen said that current UV-C LED technology is not ready

45 Milton explained that this method was discovered by researchers who were unable to transmit rhinovirus by contact with virus in the nose by other, less intentional means.
46 Dick et al 1987
47 Keshavjee noted that Big Ass Fans sells such products. More information about Big Ass Fans is available from https://www.bigassfans.com/ (accessed March 12, 2021).
48 A participant noted that portable, battery powered UV disinfection products are available for surface disinfection, such as UVHammer. More information about UVHammer is available from www.dimeruv.com/uvhammer/ (accessed March 12, 2021).

for widespread use. This is primarily due to the low UV-C output of these lamps. However, it is quite possible that this technology can rapidly advance, as LED technology for conventional lighting has advanced rapidly in recent years.

7.6 Understanding the relationship between ceiling height and the use or germicidal UV

Keshavjee about the relationship between the height of a ceiling, the volume of air in a room, and the effectiveness of UR-GUV. Jensen said that it is possible that a small amount of UV-C light emitted by UR-GUV systems can contribute to the disinfection of surfaces throughout a room; however, the primary function of UR-GUV is to disinfect air, not surfaces. Nardell said that higher ceilings contribute to dilution, which is beneficial for reducing viral transmission. High ceilings offer benefits for UR-GUV in that they allow for the use of simple fixtures and accommodate longer ray length. More work may need to be done to study the differences between the effectiveness of UR-GUV in rooms with higher or lower ceilings. It is possible that 222nm UV-C may also be applied for direct whole-room germicidal irradiation. Like UR-GUV, this may involve UV-C lamps placed high in a room, but these lamps could be used to irradiate most, or all, of the air in the room, rather than only the upper room. This approach reduces the need for air mixing and appears to be quite safe, but more research is needed to assess the efficacy of this approach.

A participant asked what dose of UV-C is required to inactivate virus embedded in aerosols and droplets. Jensen noted that UV-C light (222 & 254 nm) has been found to inactivate human coronaviruses efficiently and safely.[49]

Jensen added that UV-C output must be balanced with safety. It is possible to install UR-GUV in rooms with a ceiling height of 7’10” (2.39 m). However, these installations are time consuming and require tightly baffled fixtures, which result in reduced UV-C output. Thus, these installations may also require the use of more fixtures than would otherwise be required. For most installations, a 9’ ceiling affords easy installation and adjustment. Taller ceilings afford easier installation with less baffling. Regardless of ceiling height, moving air from occupied space to the irradiation zone is always a key factor.

7.7 Considering the lifecycle costs of UR-GUV systems

Keshavjee asked about the lifecycle costs for UR-GUV. Jensen explained that the costs of UR-GUV fall within ranges, depending on the specific case.[50] Materials from the ETTi website are available to help decision makers understand the upfront and lifecycle costs and to estimate the potential costs of installing UR-GUV systems in their settings.

7.8 Understanding the impact of filtration and deposition on airborne respiratory particles

A participant asked what proportion of airborne particles reach building air filters as opposed to landing on surfaces. Bahnfleth explained that this is impacted by many factors, but overall deposition, the process by which aerosol particles accumulate on surfaces, typically accounts for less than 1 EqACH. Given the requirements for air changes—both the building code requirements and the requirements for effective air mixing in UR-GUV contexts—deposition is neither insignificant nor sufficient. The primary shortcoming of most filtration systems is that they are not particularly efficient for removing respiratory droplets from the air. Regarding the effect of UR-GUV on particles that have been deposited on surfaces, he explained that if the concentration of active virions in the air is small, then the deposition rate is proportionally smaller. The SARS-CoV-2 virus can remain active on some surfaces for several days, and the US Centers for Disease Control and Prevention has identified fomite transmission as a possible mode of transmission of SARS-CoV-2. However, there has been scant evidence that

49 Buonanno et al 2020

50 More information about estimated lifecycle costs of UR-GUV systems is available from http://stoptb.org/wg/ett/assets/documents/ETTI_TechSheet_GUV_final%20version.pdf (accessed March 12, 2021).

fomite transmission is actually occurring or contributing to the spread of SARS-CoV-2.

7.9 UL safety listings for UR-GUV fixtures

A participant pointed out that the UL 1598, Annex L safety standard requires 0.2 microwatts/cm^2 at 7 feet measurement height for upper room UV products. It is not currently possible to bypass this requirement. He asked if UL is expected to change their current safety listing. Sliney acknowledged this consideration and suggested that the current UL listing is overly restrictive. The current standard is a tentative standard, and it seems that UL has erred on the side of caution. Still, UL will not currently certify UV-C products for electrical safety only. Jensen added that UL has announced that they are moving Annex L to UL Standard 8802 and are forming a committee to review and make changes as this consensus document goes through the ANSI/CSA development process. ASHRAE and others are represented on this new working group.

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