WHY GERMICIDAL UV IS EFFECTIVE

For all Known Human Airborne Pathogens

Background

In 1946, Matthew Lukiesh, the renowned General Electric lighting scientist, published a detailed study on the applications of germicidal UV, by then a common technology in the US and other industrial countries. In 1942, W.F. Wells and M.W. Wells, pioneer investigators of airborne disease transmission, published a controlled study of upper-room germicidal UV on measles transmission in two suburban schools outside of Philadelphia.[1] The final results are reproduced below in Figure 1, which is taken from from the Wells textbook.[2]

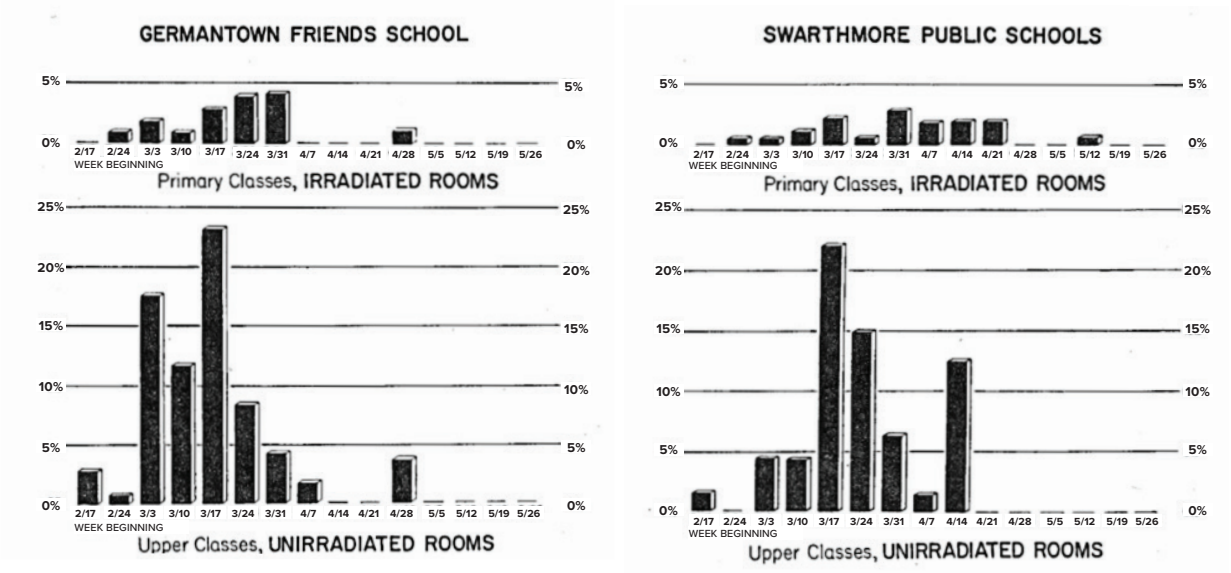

Figure 1 - Weekly Attack Rate Among Susceptibles (numbers of cases as a fraction of those still susceptible)

In Philadelphia that winter, the measles attack rate was high, as depicted by March transmission rates in the upper control classrooms in both Germantown and Swarthmore, Pennsylvania. Without UV, the attack rate among younger children, who were less likely to have been infected previously, was normally higher than in the control classes, so the primary classes were equipped with upper-room, 254 nm germicidal UV fixtures. The UV technology was very similar to current upper-room applications. *The results convincingly show that upper room UV could flatten the epidemiological curve of measles, the most infectious airborne viral respiratory pathogen known.*

Importance of understanding where transmission is occuring

At the time, before vaccines were commonly used for epidemic respiratory infections, and antibiotics were available for tuberculosis, there was great enthusiasm in public health for making air in indoor public spaces as safe to breathe as water disinfection made water safe to drink in technically advanced countries. Water and air are not analogous, however, since municipal water supplies are few whereas air is ubiquitous. Efforts to control measles transmission before immunizations also demonstrated the need to understand exactly where transmission is occurring to have an epidemiological impact. When the Philadelphia measles-in-school UV study was repeated in an upstate New York school and in urban London, the same results were not replicated, not because the UV application did not inactivate the virus, but because transmission occurred on school buses and in crowded urban tenements respectively. Wells intentionally selected a suburban setting outside of Philadelphia where children were commonly transported by parents and less likely to interact after school. **To be effective, air disinfection must be applied in the principal sites of transmission for each specific pathogen.**

How UV disinfection works

The mechanisms by which germicidal UV inactivates pathogens are well understood, at least for the longer wavelengths (254 – 280 nm). Depicted below (Figure 2) is a schematic of the effects of UV on nucleic acids – slightly different for bacteria and viruses containing DNA than for RNA viruses like the coronavirus family.

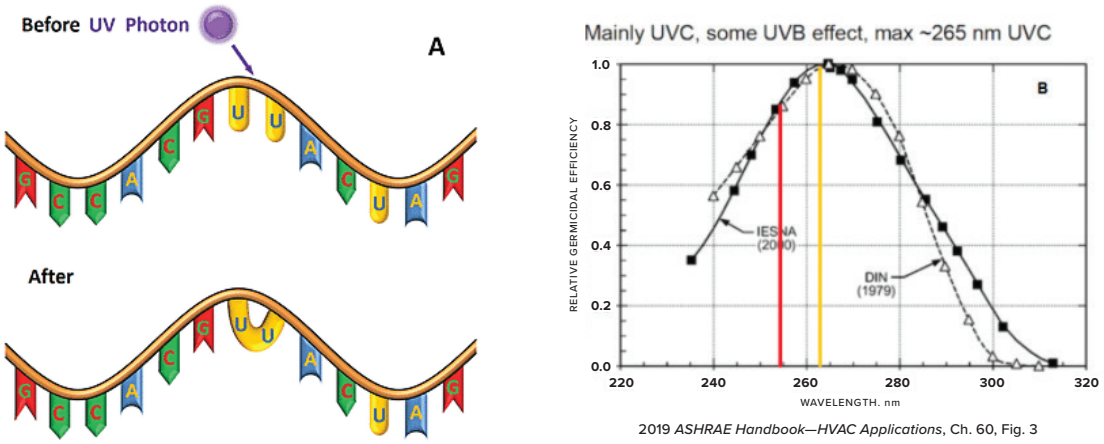

Figure 2 - UV-RNA-damaging mechanism and relative absorption spectra of RNA

Figure 2, left (A), depicts the impact of germicidal UV photon absorption on RNA, causing two Uracil nucleotide molecules to form a non-functional dimer. In DNA structure, Thymine replaces Uracil, so that UV germicidal photons cause Thymine dimers, called cyclobutene pyrimidine dimers (CPDs). These dimers effectively interrupt the replication of DNA/RNA by “tying a knot” and lead to bacterial cell death and viral inactivation. UV light also causes what are called 6-4 photoproducts (6-4 PPs), both of which distort DNA structure, introducing bends or kinks and thereby impeding transcription and replication. The right panel (B) shows the broad peak wavelength for nucleic acid UV absorption at about 260-265

nm wavelength (yellow line) and the peak wavelength generated by low pressure mercury UV lamps at about 254 nm UV (red line). Newer LED sources produce UV in the 255 to 275 nm wavelength.

Due to the presence of DNA or RNA, all human pathogens tested thus far are vulnerable to germicidal UV. There is a range of vulnerability depending on organism size, replication rate, and nucleic acid repair mechanisms. Environmental organisms, like fungi naturally exposed to light, have evolved more effective nucleic acid repair mechanisms than intracellular pathogens like viruses. Generally, viruses and rapidly replicating bacteria are easiest to inactivate with UV while slower growing mycobacteria are intermediate in resistance and fungi are most resistant to UV inactivation.

Pathogen vulnerability to UV is measured as a Z or K value - different terms used by different investigators. These values represent the relative UV dose required to inactivate 90% of test organisms under test conditions in air. Since these tests are not standardized, reported values vary with the technical differences between experiments, as pointed out in a recent review of vulnerability of the SARS-CoV-2 virus to germicidal UV[3]. This Covid-focused paper makes the point that viruses of similar size and structure exhibit similar UV susceptibility, allowing for experimental differences in testing. The available data reveals large variations, which are apparently not caused by the coronaviruses but by the experimental test conditions. When these variations are excluded as far as possible, it appears that coronaviruses are readily susceptible to UV. The upper limit determined for the log-reduction dose (90% reduction) is approximately 106 J/m2 (median), while the true value is probably only 37 J/m2 (median)[3].

Pathogen	Z-Value (m2/J)	Source
M. tuberculosis (Erdman strain)	0.230	CDC, need actual
Influenza A	0.138	Abraham 1979
SARS-CoV-1	0.321	Weiss 1986
Measles	0.105	DiStefano 1976
SARS-CoV-2	0.062 - 0.187*	See Note Heßling, 2020 and Bianco 2020

Figure 3 - Example Pathogen Vulnerability to UV (Z or K Value)

*Scientific *consensus for z-values is determined after many independent studies. Many of these are still ongoing. The range reported above references the likely D90 dose of 37 J/m2 as found by Heßling and a 2020 study by Bianco, et al.(3)*

UV dosing for most airborne pathogens

For air disinfection, a great deal of UV efficacy data exists for tuberculosis (TB), still the single greatest infectious disease killer of adults globally under non-pandemic conditions. Because the mycobacteria that cause TB are intermediate in vulnerability to germicidal UV (see Z-values in Figure 3 above), designing systems to deliver dose levels effective against TB are highly likely to be effective against current and future pandemic influenza, coronavirus, and other viral pathogens.

Approaches to air disinfection

There are several approaches to applying germicidal UV for air disinfection to prevent person-to-person transmission. The most widely available approaches are upper-room GUV and enclosed system UV. Upper-room GUV disinfects air in the room where transmission is likely between occupants – not after it leaves the room – an important distinction.

Upper-room GUV air disinfection use is similar to the UV school measles experiment conducted 80 years ago when the technology was already well established and considered safe and effective. 254 nm lamps or newer germicidal LED solid state sources generate a zone of germicidal UV in the space above people's heads to prevent overexposure to eyes and skin. Air mixing by convection currents generated by occupants and other sources, or much more efficiently by ceiling fans, produces optimized circulation between the upper and lower room, assuring high levels of air disinfection in the occupied space.

In two controlled clinical trials done by separate investigators with similar methods in hospitals in Lima, Peru and Witbank, South Africa, upper-room germicidal UV with mixing fans was shown to be approximately 80% effective against TB transmission from human patients to highly susceptible guinea pigs.[4,5] The guinea pigs served as living air samplers – reporting not just the presence or absence of detectable pathogens, but actual infection – the principal end point of interest in testing infection control interventions. Unlike surface disinfectants, where 3 log reductions (99.9%) in culturable test microbes is expected, real world clinical air disinfection trials deal with ongoing generation of pathogens and such variables as imperfect air mixing, imperfect room conditions, and the potential for transmission outside the irradiated areas, or even between persons before the air can reach the upper room to be disinfected. The efficacy of upper-room germicidal UV to reduce airborne infection has been more rigorously studied under field conditions (including the Philadelphia measles-in-school UV study) and the reported protection (70-80%) is greater than many **other public health and engineering interventions**, such as immunization, ventilation, and personal respiratory protection.

Another approach to UV air disinfection is treating air with very intense UV light in the airside of the HVAC system. This assures that recirculated pathogens are not contributing to transmission and thus a safe and effective strategy for mitigating room-to-room spread, and a possible primary strategy against microbial bioterrorism – such as smallpox or anthrax spores. Within the HVAC system, there are no safety concerns or dose limitations as in-room applications. However, recirculation of airborne pathogens is not always a concern. Within rooms, dilution of infectious particles increases with the distance from the infectious source, and even more so as air enters the exhaust duct and mixes with outside air and air from other rooms. For virulent airborne infections where a single infectious droplet nuclei can cause infection (*i.e., M. tuberculosis*), dilution makes recirculated infection less likely, but still possible. For pathogens like SARS-Covid-2, there is currently little evidence of multi-room spread through building ventilation systems, probably because the infectious dose threshold is relatively high. If an infectious dose of 500 or 1000 infectious virons is needed to cause infection, that dose is more likely to be inhaled near the infectious source, but not as particles are diluted with distance from the source, and even less so after passing through the ventilation system. While UV or filters in the HVAC system are potentially effective strategies against recirculated virus, they do little to prevent transmission *within the room*. In fact, when high-resistance filters (ie, MERV 13 or higher) are used to reduce recirculated pathogens, the pressure load can result in reduced total flow rate, negatively impacting dilution within the room.

Safety of upper room germicidal UV

While germicidal UVC readily penetrates and inactivates pathogens in air through nucleic acid mutations, short wavelength UVC penetrates skin and eye cells (epithelium) poorly - compared to significant penetrating from dangerous long wavelength UVA and UVB in sunlight. Moreover, germicidal UV is confined to the upper room, above the heads of room occupants, thereby minimizing eye and skin exposure. Before germicidal UV systems are activated, they are checked with a sensitive UV photometer to be sure that eye and skin exposure is below well-established safety limits. Still, despite warnings and training, workers occasionally climb up on ladders to clean or paint and are accidently exposed to intensive UVC. At most, *accidental overexposure to UVC* can cause transient, painful eye inflammation or skin redness, but no serious short or long-term damage like skin cancer or cataracts. The outer skin and epithelium are normally replaced about every 48-hrs, so there is no risk of long-term effects on the cells that absorb most of what little UV is allowed in the lower room. For comparison, whereas a dose of only 3 - 6 mJ/cm2 of UVC is allowed in the lower room over an 8-hour period, a 2-hour outdoor exposure to peak summer sun delivers a 240 mJ/cm2 or greater dose of more dangerous, penetrating UVB in sunlight. When properly planned, installed, commissioned, and maintained, well-designed upper room UVC air disinfection fixtures and UV-fan systems are unlikely to cause any short or long-term health effects while reducing the risk of dangerous airborne pathogens.

Conclusion

In summary, germicidal UV is a long-established, evidence-based, safe and effective strategy for mitigating airborne transmission in rooms where person-to-person risk is greatest. All known pathogens are vulnerable to germicidal UV with variable susceptibility. Respiratory viruses suspended in air are especially vulnerable to UV, but even UV-resistant TB and fungal organisms are easily inactivated using UV. Upper-room GUV has an advantage over in-duct UV by mitigating person-to-person transmission within the room where high concentrations of pathogens increase risk. Advances in the UV industry, including UV-C LEDs and innovative fixture designs, ceiling fan and UV integration, and safe whole-room air and surface disinfection are revolutionizing the application widely to create healthier spaces.

Upper room UV air disinfection has a long track record of safety and efficacy based on room experiments and field studies against a wide range of known pathogens and airborne health threats. As GUV technology has a proven germicidal capacity, future research should focus on human transmission studies. While especially challenging, this work will prove beneficial in continuing to optimize GUV system design and further understanding the impact of GUV in reducing the airborne transmission pathways.

References:

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