UPPER ROOM ULTRAVIOLET (UV) AIR DISINFECTION: Where are we and where are we going?

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WHAT IS UPPER ROOM ULTRAVIOLET GERMICIDAL IRRADIATION (UVGI)?

Upper room UVGI employs fixtures placed at least 8 feet off the floor, which are designed to irradiate and sterilize a large volume of air above the occupants' heads while not exposing room occupants to UV. Room air disinfection depends on the upward movement of warmed, contaminat-ed air from the lower room, heated by occupants and other sources, displacing irradiated air from the upper room zone, thereby disinfecting lower room air. Room air mixing, carrying contaminated air into the irradiated upper zone, can be passive, depending on temperature differences, or augmented by slow paddle fans, ventilation registers, or other air moving devices, which will all improve the performance of the upper room UV/air-mixing system (see Figure 1).

Figure 1. Photo of hospital room with upper room UV.

WHY UPPER ROOM UV AIR DISINFECTION?

Some readers may wonder why anyone would choose to disinfect air in the space above people's heads, when they could be doing the same thing in ventilation ducts, the technology discussed in most of the articles in this special issue. Let me begin this review with a brief comparison of these two approaches to germicidal air treatment. Reasons favoring upper room UV systems include:

1. Most person-to-person transmission of airborne infections is likely to occur between people in the same room, not recirculated through the building's ventilation system, although the latter mechanism occurs. If one is in an examination room with a patient with infectious tuberculosis, or an airborne viral infection, there is little comfort knowing that the air will be disinfected only after it leaves the room. To lower the risk of infection within that room requires dilutional ventilation, but the protection achieved by ventilation has theoretical limits (Nardell et al. 1991). For extra protection, very large numbers of equivalent air changes are required, and upper room UV air disinfection offers the important advantage of disinfecting large volumes of air at one time. Upper room UVGI also prevents recirculation of infectious agents within buildings, especially if most of the rooms serviced by the ventilation system are treated with UV.

2. The efficacy of upper room UVGI depends on good room air mixing, but not on the number of air changes in the room. In contrast, even if UV in ducts kills every infectious organism, the dilutional air disinfection benefit in occupied rooms is still limited by the number of air changes in that room. In other words, the efficacy of UV in ducts is limited by the ventilation rate, whereas upper room UV is not, providing air disinfection in addition to the room ventilation.

3. In many places in the world and in settings where airborne infections are a problem, central ventilation systems may not exist. Homeless shelters are often converted older buildings and warehouses and often do not have central ventilation. In many developing countries, especially in warm climates, buildings without central ventilation are the norm.

There are also some advantages to UV air disinfection in ventilation ducts over upper room UVGI, as follows:
1. UV in the ductwork may be logistically easier to install. Instead of planning upper room installations in many occupied rooms, irradiation of only one or at most several return ducts is required.

2. UV in the ductwork is out of sight and poses no potential for overexposure of room occupants, although maintenance workers could be accidentally exposed. I will discuss the safety issue in great detail later on in this article, but for now let me just reassure the reader that neither upper room nor duct UV air disinfection poses great safety risks either for room occupants or for maintenance workers as long as well-designed equipment is installed according to manufacturer's instructions and room occupants are properly trained. Because in-duct UV is out of sight, enforcement of regular maintenance procedures is essential to ensure good performance. Regular maintenance is also needed for upper room UVGI systems, but because these lamps are visible, it is somewhat easier to keep their maintenance in mind.

3. A variation of UV in ventilation ducts is irradiating air in self-contained, fan-driven room air cleaning/disinfection devices. Again, there are no safety issues, real or perceived, as the UV is contained. Such units are intended to supplement the air disinfection produced by mechanical room ventilation or natural ventilation. Their benefit is limited by the number of equivalent room air changes added to whatever existed in the room. For large rooms, this can be limited because of noise and drafts to just a few added air changes, which may or may not be well-mixed.

4. In addition to reducing transmission of person-to-person infectious agents, UV in ventilation systems has been shown to reduce building-associated complaints often due to the growth of mold and other agents on cooling coils and in drip pans (Menzies et al. 2003). Upper room UVGI has no effect on these complaints.

HOW LONG HAS UPPER ROOM UVGI BEEN IN USE, AND WHY ISN'T IT BETTER KNOWN AND MORE WIDELY APPLIED?

The history of the use of UV to disinfect air of human pathogens is intimately intertwined with the history of airborne infection itself. A central figure in these histories was William Firth Wells, a sanitary engineer working at Harvard in the early 1930s, who established the foundations of our current understanding of airborne contagion and air disinfection (Wells 1955). Wells had invented an air centrifuge that allowed him to culture bacteria out of the air. He was commissioned by the Massachusetts Department of Public Health to investigate the possibility that workers in New England textile mills were becoming sick as a result of aerosols of stagnant, contaminated water used to keep down dust in the mills. Working with him at the time was a Harvard medical student, Richard L. Riley, who participated in the textile mill investigation, and wrote the seminal paper for Wells making the critical distinction between ordinary respiratory droplets, and droplet nuclei, the dried residua of larger droplets (Wells and Riley 1937).

Respiratory droplets are larger (> 5 μm diameter) than droplet nuclei (1 - 5 μm) and settle onto surfaces within a meter or so of their source. Respiratory droplets can spread infections when others make contact with contaminated surfaces and then inoculate vulnerable mucosal surfaces. Many bacteria (e.g., Staphylococcus, Pneumococcus, etc.) and many respiratory viruses (e.g., corona viruses, including SARS, RSV, and perhaps rhinoviruses) are spread primarily by ordinary respiratory droplets. Because close proximity is required, transmission by respiratory droplets is considered an extension of close personal contact spread. Relatively fewer infectious agents are spread primarily by the airborne route (e.g., tuberculosis, measles, anthrax). Contact with these infections can occur some distance from the infectious source because air currents can carry infectious droplet nuclei long distances, including recirculation through mechanical ventilation systems (see Table 1).

Table 1. Large Respiratory Droplets compared to Droplet Nuclei.

<table>
<thead>
<tr>
<th>Large Respiratory Droplets</th>
<th>Droplet Nuclei</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 3 μm in diameter</td>
<td>&lt; 3 μm in diameter</td>
</tr>
<tr>
<td>settle within 1 m of source</td>
<td>negligible settling tendency</td>
</tr>
<tr>
<td>may evaporate before impact to form droplet nuclei</td>
<td>follow air currents, distant infection possible</td>
</tr>
<tr>
<td>transferred by hand to mucosa</td>
<td>inhaled deep into lung</td>
</tr>
<tr>
<td>stopped by hand or simple mask</td>
<td>may pass through simple masks</td>
</tr>
<tr>
<td>transmission mode of most bacteria and viruses*</td>
<td>transmission mode of measles, TB, anthrax</td>
</tr>
</tbody>
</table>

*Legionella, flu, SARS, smallpox, and other organisms may transmit by large or small particles

Tuberculosis is almost exclusively airborne, and remains a disease of global importance, still among the greatest killers of adults in the world. It is airborne because the organism infects the alveolar macrophage deep in the lung, requiring particles in the 1 - 3 μm range, small enough to by-pass impaction on the upper respiratory tract defenses. If the upper respiratory mucosal were vulnerable to TB, spread by contact with larger particles might result in infection. Historically, as well as now, interest in upper room UV air disinfection has been driven by a need to control the spread of TB in congregate settings, such as hospitals, clinics, jails, prisons, and shelters for the homeless. My own interest in air disinfection was stimulated by outbreaks of TB in a Boston homeless shelter and an office building in the early
1980s, when this country experienced a resurgence of the disease (Nardell et al. 1986, 1991) (see Figure 2).

![Image](image.jpg)

**Figure 2.** Photo of beds in Boston shelter.

The office building had been the source of many air quality complaints, and CO₂ measurements before and after the outbreak indicated that the fresh air ventilation rate was low (approximately 15 cfm/person) resulting in CO₂ levels averaging 1000 ppm throughout the 2-story facility (Nardell et al. 1991). We used mathematical modeling to predict that a fresh air ventilation rate twice that observed (well above current standards for an office building) would still have resulted in approximately half the infections. The reason for this, the model indicated, was because the infectious source was generating an unusually large number of infectious particles. Each doubling in the ventilation rate reduces by half the expected number of infections. The result is an asymptotic curve in which each increment in ventilation produces a progressively smaller reduction in infection risk. We concluded that to approach complete protection would require much higher rates of ventilation than most mechanical ventilation systems can provide. Having UV air disinfection in the central ventilation system would have prevented the recirculation of TB though the office building, which we believe occurred, but it would not have increased effective ventilation rates to prevent most of the infections.

Upper room UVGI is not widely known and in use in part because it is extremely difficult to prove efficacy under field conditions - a limitation also true for ventilation, air filtration, and even for the use of personal respiratory protection. However, ventilation and air filtration have become established methods of removing a variety of airborne contaminants, some of which are easily measured, and it is assumed that they work as well for air disinfection, despite the quantitative limitations mentioned above.

There are other reasons why upper room UVGI is not widely known and in use today. About the time that Luckiesh published his detailed monograph on the use of germicidal irradiation, streptomycin, the first effective antibiotic against tuberculosis, was discovered (Luckiesh 1946). Other antibiotics followed, and it was assumed that TB would become a disease of the past. Similarly, with the widespread use of vaccines against common communicable viral infections, such as measles, the use of air disinfection seemed unnecessary. Finally, upper room UVGI straddles several disciplines and none has taken complete ownership of the technology. Germicidal fixtures, their design and installation, maintenance and safe use are all analogous to other lighting technologies, but lighting experts and architects are generally not familiar with this technology. Because upper room UVGI, like ventilation, disinfects air and is dependent on good room air mixing, is also squarely in the realm of engineers. The lack of clear application guidelines, concerns over liability, and an inability to readily measure the effects of upper room UV or its interaction with room ventilation has generally dampened the enthusiasm of many engineers for its use.

The situation is changing. Today, TB is again a global threat, especially drug-resistant strains, and viruses such as virulent influenza and SARS threaten public health in rich countries (Olsen et al. 2003). As if natural epidemics were not enough, the most effective bioterrorism threats are airborne, such as weaponized anthrax and smallpox. For these reasons there is renewed interest in the use of upper room germicidal UV.

**WHAT EVIDENCE SUPPORTS THE USE OF UPPER ROOM UVGI?**

Despite the paucity of good field trials demonstrating efficacy, there is strong evidence that upper room UVGI works. The best evidence has been produced by a series of room experiments, using surrogate test bacteria, including mycobacteria, to predict the effectiveness of upper room UVGI. Riley and Middlebrook carried out a room study in Baltimore in the 1970s which demonstrated that a single 30 W UVGI fixture added the air disinfecting equivalent of approximately 10 room air changes to an unventilated room where viable vaccine strain attenuated bovine TB organisms (BCG) had been aerosolized (Riley et al. 1976). The only source of room air mixing on the winter day of the experiment was a single radiator and air infiltration from leaky windows. Using more rapidly growing ordinary bacteria, Riley, Permutt, and colleagues did a detailed analysis of room air mixing and the impact of mechanical mixing and temperature differentials between the upper and lower room (Riley et al. 1971a,b, Riley and Permutt 1971). More recently Ko et al. (2000), and Miller and colleagues (Nicas and Miller 1999; Miller and Macher 2000) have published room studies using BCG or other test organisms. Although there are many technical differences among the studies, a consistent finding has been the addition of at least 10 equivalent air changes, and in some experiments, as many as 16 air changes. The most recent study results are contained in a final report to NIOSH, the funding agency, by Miller et al. (2002) in Colorado.
While field trials of upper room germicidal UV have proven difficult, two experimental wards, one in Lima, Peru, and another in Witbank, South Africa, plan to test the efficacy of the technology under real world conditions, using colonies of guinea pigs as quantitative air samplers. Unlike the test chamber experiments mentioned above, where bacteria were artificially aerosolized and quantified by mechanical air sampling, the aerosol source in these hospital studies will be human subjects with infectious TB. Guinea pig air sampling is needed because the concentration of infectious droplet nuclei in the air is low compared to the large number of ambient competing airborne bacteria and fungal spores which grow faster in culture than Mycobacterium tuberculosis and soon overgrow culture plates. Guinea pigs, like humans, generally ignore airborne ambient microorganisms but are exquisitely susceptible to TB, becoming infected when a single droplet nucleus lands and sets up an infectious focus in the lung periphery. In the late 1950s, Riley et al. (1962) pioneered this experimental method to prove that TB is airborne, and further demonstrated that patients varied greatly in infectiousness and became rapidly non-infectious on effective therapy. The goals of the experiments planned in Peru and South Africa are to further define the effectiveness of current upper room UVGI fixtures under a variety of conditions found in high-prevalence countries.

WHAT IS KNOWN ABOUT THE SAFETY OF UPPER ROOM UVGI?

Concerns about the safety of upper room UV are generally not well-founded. Although germicidal (254 nm UVC) UV readily penetrates and damages the nucleic acid of microorganisms, this same reactivity prevents it from penetrating the outer, dead layer of skin to reach the top, viable layer of skin cells to cause serious damage, or to penetrate the eye's cornea to cause cataracts (Bruls 1984). Because the cornea is unprotected, transient eye irritation is the limiting factor for exposure to germicidal UV. In contrast, sun burning, skin cancer, and cataracts are all well known complications of exposure to longer wavelength UV-B, the damaging UV in sunlight and in certain other hazardous UV sources, but these are not associated with germicidal UV at the exposure levels realistically possible from upper room UVGI fixtures. The threshold limit UV dose for 254 nm UV is 6.0 mJ/cm² for an 8 h exposure. By comparison, just 2 h of sunbathing at peak intensity results in a UV dose of as much as a 240 mJ/cm² exposure of more damaging UVB (Sterenborg 1988). Germicidal UV can cause eye or skin irritation after direct, high-intensity exposure. Such exposures can occur when a maintenance worker climbs into the upper room zone, for example, to paint the walls or clean the UV fixtures, without first turning off the lamps. A symptom-free period of several hours, the eye irritation (photokeratoconjunctivitis) can be painful, but there is no permanent damage to the cornea. The damaged corneal layer of cells sloughs off and is replaced by a new corneal layer in a few days.

Current, well-louvered fixtures for upper room air UVGI generally produce a highly collimated beam designed to deliver high intensity UVGI to the upper room zone while at the same time producing UV flux in the lower room that is safe for room occupants (ACGIH 2002). Although the human eye can tolerate UV dose of 6.0 mJ/cm² 254 nm UV over an 8 h period, shielding by head structures, intended to prevent overexposure outdoors to sunlight, and movement of occupants within rooms, effectively limits exposure from upper room UV to just a small fraction of what would occur if exposure were direct and continuous. In a recent investigation where subjects wore small personal UV meters in rooms with high-intensity, upper room UVGI, cumulative 8 h doses measured on the chest were just a fraction of the 8 h threshold limit value (TLV); no more than 37%.

WHERE CAN ONE LEARN MORE ABOUT THE APPLICATION OF UPPER ROOM UVGI?

Guidelines on the application of upper room UVGI are few, and none are entirely satisfactory. A two-part article in the engineering literature may be the most comprehensive document, but it relies on a UV dose formula employing the nominal input wattage of UV fixtures per area of floor space (First et al. 1999a,b). A much better approach would employ the actual UV output and take into account room air mixing as well as room volume, but such guidelines do not yet exist.

WHERE IS UPPER ROOM UVGI GOING?

The future of upper room UVGI is promising, even if progress has been slow during the first 70 years or so. As long as humans occupy buildings together, they will spread airborne pathogens to one another. The availability of a relatively inexpensive technology that can quickly kill or inactivate almost any infectious agent without harming room occupants is almost too good to be true. Concerns about a future lethal influenza pandemic, about new pathogens such as SARS, and about bioterrorism agents may fuel use and development of this relatively old technology into the 21st Century. Better installation guidelines are needed for current fixtures. Better safety guidelines are needed to reassure manufacturers, regulators, and consumers that current installation practices are, if anything, too protective of room occupants at the expense of germicidal efficacy. Better fixtures are needed that are less intrusive on room décor and are more efficient, producing higher irradiance levels in the upper room while fully protecting room occupants. Better UV-reflective coatings, thinner, more powerful UV lamps that can be focused using reflectors, not inefficient louvers, and better ways to predict both UV safety and germicidal efficacy are all achievable technological goals for the near future. Soon, I can safely predict, upper room UVGI will be widely
deployed, familiar to engineers and architects, and considered as safe and effective as heating and air conditioning.

REFERENCES

ACGIH 2002. TLVs and BEIs. In Proc. American Conference of Governmental Industrial Hygienists, Cincinnati, OH.


