The History of Ultraviolet Germicidal Irradiation for Air Disinfection

SYNOPSIS

Public health concerns such as multi- and extensive drug-resistant tuberculosis, bioterrorism, pandemic influenza, and severe acute respiratory syndrome have intensified efforts to prevent transmission of infections that are completely or partially airborne using environmental controls. One such control, ultraviolet germicidal irradiation (UVGI), has received renewed interest after decades of underutilization and neglect. With renewed interest, however, come renewed questions, especially regarding efficacy and safety. There is a long history of investigations concluding that, if used properly, UVGI can be safe and highly effective in disinfecting the air, thereby preventing transmission of a variety of airborne infections. Despite this long history, many infection control professionals are not familiar with the history of UVGI and how it has, and has not, been used safely and effectively. This article reviews that history of UVGI for air disinfection, starting with its biological basis, moving to its application in the real world, and ending with its current status.

Ultraviolet germicidal irradiation (UVGI) is an established means of disinfection and can be used to prevent the spread of certain infectious diseases. UVGI has been used to treat various infections, including tuberculosis, influenza, and hepatitis, among others.

UVGI has been shown to be effective in inactivating bacteria, viruses, and fungi. It works by damaging the DNA of microorganisms, rendering them unable to reproduce and thus preventing the spread of infection.

UVGI is used in healthcare settings, hospitals, and other environments to control and prevent the spread of infections. It is a safe and effective method compared to traditional disinfection methods such as chemical disinfection.

UVGI is also used in food processing facilities to control bacterial growth, ensuring food safety. It is an environmentally friendly method of disinfection, as it does not produce harmful byproducts.

UVGI is a cost-effective method of disinfection, as it is a one-time investment that can be used repeatedly with minimal maintenance costs.

UVGI has been shown to be highly effective in preventing the spread of infections. It has been widely adopted in healthcare settings and has been shown to be effective in preventing outbreaks of infectious diseases.

UVGI has been successfully used in various environments, including hospitals, schools, and public facilities, demonstrating its effectiveness in controlling the spread of infections.

UVGI is a promising method of disinfection in the prevention of infectious diseases, offering a safe, effective, and cost-effective alternative to traditional disinfection methods.
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Figure 1. Overview of selected key events in the history of UVGI air disinfection

1877 - 1905

- 1877: Discovered and patented the discovery of ultraviolet light to prevent microbial growth. It is later shown that the ability of light to inactivate microorganisms is dependent on the dose (intensity x time) and wavelength of radiation and the sensitivity of the specific type of microorganism.
- 1930: Gates introduces the first analytical bactericidal action spectrum of peak effectiveness at 254 nm, very near the 254 nm output of low-pressure Hg germicidal lamps.
- 1933: While presenting the concept of airborne infection via "droplet nuclei", a sporadic death due to tuberculosis was noted.
- 1935: Wells and Faraday demonstrate the ability of UVGI to efficiently activate airborne microorganisms and prove the concept of infection via the airborne route.
- 1937: Wells et al. use uvc germicidal UVGI to prevent the outbreak of measles in suburban Philadelphia public schools, where infection occurred outside the school.
- 1945-1950: Several studies are not able to reproduce Wells et al's success in using UVGI to prevent the spread of measles in schools, contributing to the development of the smallpox vaccine, and the abandonment of UVGI for air disinfection. These failures have since been attributed to infections occurring outside the isolated schools.
- 1954-1962: Riley exposes guinea pigs to air originating from an occupied TB ward and proves that TB is spread via the airborne route. A group of guinea pigs exposed to air via a UVGI-irradated duct were not infected, while a group receiving air via a non-irradated duct were infected.
- 1965-1972: Riley and colleagues conduct mixed room studies evaluating the use of uvc germicidal UVGI to reduce the concentration of aerosolized test organisms in the lower room. They also show that air mixing between the upper and lower room is impermeable for effective disinfection and confirm that UVGI is less effective at high humidity. The upper room UVGI is shown to be highly effective in disinfecting the lower room, quantitatively demonstrating the potential of upper room UVGI to reduce TB infection.
- 1985-1992: After decades of decline, there is an unexpected rise in TB in the United States, leading to a renewed interest in UVGI for air disinfection.
- 1990s to present: New in-depth efforts are undertaken to determine the potential of using UVGI by passing sunlight through an infrared-absorbing water filter before it reached a bacterial sample. Wound illumination of these results between 1892 and 1894, demonstrating differences in sensitivity to ultraviolet radiation by different types of bacteria. In 1899, Koch demonstrated the lethal effect of sunlight on tubercle bacilli, prompting the modern use of UVGI to combat TB. In 1914, they observed the effect of sunlight on microorganisms. Between 1904 and 1905, they observed the effect of sunlight on microorganisms. between 1904 and 1905, they observed the effect of sunlight on microorganisms. between 1904 and 1905, they observed the effect of sunlight on microorganisms. between 1904 and 1905, they observed the effect of sunlight on microorganisms. between 1904 and 1905, they observed the effect of sunlight on microorganisms. between 1904 and 1905, they observed the effect of sunlight on microorganisms.

UVGI (UV-C) irradiation

nm: nanometer
UVB (290-315 nm): UVA (315-400 nm), visible (400-700 nm), infrared (700-1000 nm).

In 1885, du Toit reported differences in sensitivity to ultraviolet radiation by different types of bacteria. This finding pointed to another key factor that influences UVGI performance—microbial sensitivity. Different microbes have different sensitivities to UVGI and require varying doses of radiation for the same fraction of inactivation. Many studies would attempt to quantify the sensitivity of numerous types of microorganisms. In 1899, Koch demonstrated the lethal effect of sunlight on tubercle bacilli, prompting the modern use of UVGI to combat TB. In 1914, they observed the effect of sunlight on microorganisms. They observed that the lethal effects of longer wavelength radiation were amplified at increased irradiances. Bucher determined contributions from infrared radiation on the genicidal action of sunlight was found to be the UVGI, followed by UVB, UVA, and visible radiation, respectively, with the dose required for cell death increasing by orders of magnitude in the visible region. In 1914, Henri and Henri were the first to show the stimulation of UVGI by cell death, and by 1944, Hollander and Oliphant claimed, "It is quite possible that the high
sensitivity of many agents at about [250 nm] is based on the important function denatured nucleic acid plays in biological activities. Bruckner and Berendes6 exposed frozen solutions of thymine to UVC radiation in 1960, resulting in the formation of thymine dimers. Shortly thereafter, the production of dimers from adjacent pyrimidines was demonstrated after exposure to UV radiation, accounting for "a large part of the effects of ultraviolet radiation on biological systems." The biological foundation of UVGI had been laid. For a more extensive review on the history of the biological effects of UV radiation on microorganisms, see Hirschler62 and Cossad63.

The distinction should be made between the biological effect and the penetration depth of UV radiation. A key concept in UVGI safety. UVGI wavelengths are the most biologically active radiation and, ironically, much less dangerous to humans. This is because UVG radiation is absorbed by the outer dead layer of human skin, while UVA and UVB radiation penetrate deeper.64 While attention to UVGI safety is important, because overexposure to 284 nm radiation can readily cause erythema ("sunburn") to the skin and photokeratitis ("welder's flash") to the eyes, the long-term health risks are considered to be negligible compared with common solar UV exposure.

### THE EFFICACY AND APPLICATION OF UVGI AIR DISINFECTION

The beginning (1950s to 1960s): Wells, droplet nuclei, and the prevention of measles

William F. Wells pioneered both the concept of airborne infection by droplet nuclei and the use of UVGI to disinfect the air. In 1933, Wells presented the idea that inactivated droplets containing infectious organisms are expelled into the air and quickly dried by evaporation after an infectious person coughs or sneezes, expanding upon an early droplet theory put forth by Filipp. These evaporated droplets, or droplet nuclei, remain in the air for extended periods of time, and people can breathe them in. The idea of infection via droplet nuclei had been sparked by investigations into respiratory infections associated with dust-laden water sprays used in New England textile mills.

While the ability of UV radiation to inactivate microorganisms was known, previous studies had exposed microorganisms to solid media or in liquids, not in the air. In 1955, using aerosolized B. subtilis 254 nm radiation, and carefully controlled conditions, Wells went on to demonstrate that airborne infectious organisms could effectively kill in a short period of time.65 The use of UVGI not only inactivated the infectious organisms in the air, but proved the very concept that infections can be spread via the airborne route. Sharp was the first to confirm these results and document an example of air route disinfection, forewarning the use of UVGI in induct-UVG systems.66 These initial investigations would prove the framework and impetus for infection control by the irradiation of air.

Immediately pursuing the potential of UVGI, Hart employed direct, high-intensity UVGI for the disinfection of hospital operating room air at the Duke University Hospital in 1936, after traditional methods had failed.67 The setup was designed to irradiate the entire room, with special emphasis on highly irradiating the volume around the surgical site and instrument/supply tables. Hart later reported the reduction in the postoperative wound infection rate in clean cases from 11.62% without the use of UVGI to 0.24% with the use of UVGI.68 Following Hart’s lead, colleagues from Duke and other hospitals installed UVGI in their operating rooms and reported success.69

Following initial successes in the operating room, the application of UVGI in hospitals was soon extended to inanimate walls by implementing various configurations of cubic-like UVGI “light curtains” designed to prevent respiratory cross-infections. As in the operating room, high-intensity, direct UVGI was used, assuming that human exposure would be transient in passing through. In 1936, Wells and colleagues designed such UVGI barriers for Charles McKhann at the Infants’ and Children’s Hospital in Boston. In 1941, Del Mundo and McKhann reported a difference in the infection rate of 12.5% in a control ward and 2.7% in a ward with UVGI barriers.70 Parallel studies evaluating UVGI barriers reported success similar to that in Boston, including both the reduction of respiratory cross-infections and the reduction of cross-contamination spread of aerosolized test organisms.71

Modifying the original experimental design, other studies of cross-infection in infant wards employed upper-room UVGI instead of direct curtains. As discussed previously, upper-room UVGI confuses the germicidal radiation to the entire room area above people’s heads, and effective air disinfection in the lower room then depends on good vertical air movement between the upper and lower room. Robertson et al. reported nearly one-half the number of infections using only upper-room UVGI in rooms where natural ventilation was impeded; no additional effect from UVGI was found in rooms where doors and windows were left open.72 Several other investigations produced further positive results using upper-room UVGI to prevent cross-infections.

Between 1957 and 1941, Wells successfully used upper-room UVGI to prevent the epidemic spread of measles among children in suburban Philadelphia day schools, where infection outside of school was unlikely—a classic experiment that has been difficult to reproduce. During this study, 55.5% of susceptibles in unirradiated schools were infected, while only 13.3% of susceptibles in irradiated schools were infected (excluding secondary infections from siblings), even with the irradiated schools having a greater percentage of susceptibles.73 These results were supported upon investigation of measles attack rates in other nearby unirradiated schools.74

In 1948, the Council on Medical Therapy accepted UVGI for disinfecting purposes. From 1941 to 1948, Lurie exposed two sets of rabbits to air originating from rabbits infected with TB. With sufficient germicidal intensity, none of the rabbits receiving irradiated air developed TB, while the majority of the rabbits receiving non-irradiated air did.75 In the 1950s, studies undertaken to evaluate the ability of upper-room UVGI (the floor was later irradiated also) to prevent respiratory infections in the intermittent aggregations at naval training stations. These studies produced modest success, limited by lensehade-decal experimental designs.76

Early investigations by Whaley,77 Wells,78 and others79 evaluated the effect of physical and environmental factors on UVGI efficacy, including humidity and air circulation—two important factors in the performance of UVGI. Microbes were found to be significantly more resistant to UVGI at higher humidity. Luckily, the humidity of most buildings is kept well below average levels to provide occupant comfort. Also, as discussed previously, good air circulation is requisite for effective upper-room UVGI. Infected lower-room air must circulate through the irradiated upper room, where inactivation depends on the received dose (the...
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UV intensity of radiation in the upper room multiplied by how long the air mixture remains in the irradiated zone. Air circulation is also an important factor in inducting UVGI, which requires maximal room air circulation through the duct and is dependent on the velocity of airflow through the duct.

Throughout the 1940s, extensive work by Lockeridge and colleagues provided further evidence for the efficacy of UVGI, while also detailing early designs and guidelines for UVGI air disinfection systems and applications of UVGI. This work represented a high water mark in the technical knowledge and expertise of UVGI. The effectiveness of UVGI to disinfect exhaust air in infectious disease laboratories was also demonstrated, including the first use inside an air conditioner.

In 1955, Wells published the authoritative Air Contamina
gion and Air Hygiene, a detailed "landmark monograph" on air hygiene by Edward Nadel. Six years later, Riley followed with his Ambient Infection: Transmission and Control. These two works may be consulted for greater detail in the early studies using UVGI and all other aspects of airborne infection.

Continued progress (1950s to 1970s)

Riley, TB ward, and model rooms

Beginning in the 1950s as a Harvard medical student working in Wells' lab, Richard L. Riley became a disciple of and collaborator with Wells and his work on airborne infection and UVGI. In fact, Wells shared credit with Riley for the droplet nuclei concept. Riley and colleagues conducted two-year experiments in a Veterans Hospital TB ward during the 1950s and early 1960s. In a preliminary study, patients with tuberculosis were isolated in a separate ward and assigned to a UVGI and a control group. No patients in the control group developed active TB, while those in the UVGI group had a significantly lower rate of reinfection.

During these early years, UVGI was used to treat TB, and the results were encouraging. However, the technology was still in its infancy, and more research was needed to fully understand its efficacy.

Additional studies (1970s and beyond)

Riley and colleagues continued to study the effectiveness of UVGI in controlling TB. They found that UVGI could significantly reduce the incidence of TB in hospitals and that it was a cost-effective intervention.

In conclusion, UVGI has proven to be an effective method of controlling airborne infections, particularly TB, in healthcare settings. Further research is necessary to fully understand its mechanisms of action and to optimize its use in different environments.

Disinflammation, resurgence, and the current state of UVGI air disinfection

Despite the early successes in demonstrating the effectiveness of UVGI, the technology was largely abandoned and forgotten in the years following Wells' promulgating work. There are several reasons why this occurred. The inability to reproduce the success of Wells in preventing the spread of measles, along with other failures, engendered broad disillusionment with UVGI. Around the same time, antibiotics were developed to treat TB, and there was hope that common viral illnesses could be controlled by immunization. Additionally, there was concern regarding the health effects from UVGI exposure. As a result, UVGI was largely abandoned as a method for air disinfection.

It is now known, however, that UVGI can be effective. UVGI is most effective in preventing infections that are spread primarily by droplet nuclei, not by direct contact or large respiratory droplets, although some surface decontamination likely occurs. The location(s) where UVGI is most effective may also be the primary location(s) of disease transmission (i.e., there cannot be a high risk of acquiring the same infection outside the location where UVGI is used). From these studies, the risk of previous UVGI failures can be deduced. The failure to prevent the spread of measles in schools can be explained by infections occurring outside the classroom (i.e., an outbreak from a primary source that is not contained).

Conclusion

In summary, UVGI has proven to be an effective method of controlling airborne infections, particularly TB, in healthcare settings. Further research is necessary to fully understand its mechanisms of action and to optimize its use in different environments.

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Figure 3. Disappearance rate of Bacillus Calmette-Guérin in a model room without upper-room UVGI and with a 17-watt upper-room UVGI lamp

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Following this guideline, similar air disinfection rates would be achieved.

UVDiff: 2 ACH/hour (12/27/14)
UV17W: 12 ACH/hour (12/27/14)

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UVGI – ultraviolet germicidal irradiation
UV – ultraviolet
ACH – air changes
W – Watt
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Since then, ongoing efforts toward meeting these new challenges have included aerosol chamber and model room studies, evaluating various environmental and physical factors on UVC efficacy (e.g., airflow mixing and ventilation, humidity, microbial sensitivity, fixture irradiance and configuration, and photoactivating wavelength), mathematical modeling and predicting of UVC fixture irradiance and room and duct disinfection/infection rates, including the use of computational fluid dynamics and applying UVC in real-world studies. Other efforts have been directed toward establishing the maintenance requirement for UVC fixtures, developing methods of accurate UVC measurement, and evaluating the safety of UVC installations, including the development of more modern “concave” lamps. In 2003, the CIE published a technical report on UVC air disinfection, summarizing the present state of knowledge. At press time, a CIE committee was preparing a report on the risk of photocarcinogenesis from UVC lamps, including a comparison of the relative risk compared with typical UV-B and UV-A exposures from outdoor sunlight. Additional research has continued to evaluate the use of UVC in the operating room to reduce nosocomial infections.

The Tuberculosis Ultraviolet Light Study (TUSLS), the first real-world study on the use of UVC to prevent TB, was conducted from 1997 to 2004. TUSLS was a double-blind, placebo-controlled trial that evaluated the use of upper-room UVC at 14 homeless shelters in six U.S. cities. The results from TUSLS were inconclusive due to insufficient numbers of documented TB skin test conversions (i.e., the rate of TB in the control group had already been checked); however, much practical experience and other data were gained from the study.

Preliminary guidelines have also been published, and, in 2006, the Centers for Disease Control and Prevention (CDC) expanded on its previous recommendation that UVC be used as a supplement for TB infection control in healthcare settings. In 2009, building upon initial guidelines and evaluating the influx of new research, CDC produced the first comprehensive guidance document for using upper-room UVC to control TB in healthcare settings.

In 2009, Escambe and colleagues published the first clinical trial using upper-room UVC to prevent TB transmission. Similar to Riley’s classic studies in the 1950s, this study ventilated air from a continually occupied HIV+TB ward in Lima, Peru, to guinea pig colonies housed in adjacent rooms for 55 consecutive days. On alternating UVA and UVC days, one group of guinea pigs breathed air from the TB ward with upper-room UVC and a mixing fan turned on, and a separate control group of guinea pigs breathed air filtered in the TB ward with upper-room UVC turned off. Further, air was drawn from the lower room without deliberately pasting it through the UV field, simulating air breathing by occupants. Results showed a 58.9% infection rate in the control group and a reduced rate of 9.9% in the group with UVC. TB disease was subsequently confirmed in 8.6% of the control group compared with 3.6% of the group with UVC (Figure 4). It should also be noted that the mean RH during the study was about 77%, determined by previous studies to be above the maximum level for optimal UVC efficacy.

At press time, Nardell and colleagues were completing a clinical trial using upper-room UVC to prevent TB transmission similar to that of Escambe et al. (Personal communication, Edward Nardell, Harvard School of Public Health, October 2008). Also at the time of publication, Noakes and colleagues planned to develop a design tool and guidance documents to assist architects and engineers in designing effective and safe UVC installations in real-world hospital environments (Personal communication, Catherine Noakes, Pathogen Control Engineering Research Group, School of Civil Engineering, University of Leeds, March 2009). Additionally, an inter-disciplinary computer-assisted design lighting project promises to help engineers and architects design UVC installations in a variety of settings (Personal communication, Edward Nardell, Harvard School of Public Health, October 2008). Together, these efforts will contribute even more valuable information, experience, and guidance for the use of upper-room UVC to prevent airborne infection.

**FUTURE DIRECTIONS**

Research on UVC air disinfection continues today. Although it is clear that UVC can be effective in test chambers, engineering specifications for a given room application remain elusive and are currently based more on common sense and historical practice than on actual evidence. However, that evidence is accumulating, along with data on maintenance and safety in a wide variety of applications. It is now clearly understood, for example, that occupants matter and position within rooms greatly reduce the possibility of harmful overexposures to UV radiation in lower rooms. In practice, if upper-room UVC systems are installed properly, UV radiation threshold limit values are rarely, if ever, approached, even using eye-level target values above those previously applied that assumed continuous exposure.

UVGI fixture designs are also evolving, becoming more efficient while remaining safe, but innovative designs are needed to further improve efficiency while keeping manufacturing costs low. Interest and investment by major lighting fixture companies is badly needed to stimulate further development; however, the cost of applying upper-room UVC is an important factor—but not in resource-rich countries, but in poor settings where UVC is most critically needed to reduce transmission of TB, pandemic influenza, and other major airborne infectious threats. In these resource-limited settings, local manufacturers are needed to keep costs down. Finally, experts in the real-world application of UVC are also needed, both in resource-rich and resource-limited settings. Once engineering specifications are better defined, however, interest from designers for early-stage architectural, and lighting industries should follow.

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**REFERENCES**

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The use of ultraviolet light in air disinfection and air purification

Barbara J. Morgan, PhD

Abstract

Ultraviolet (UV) germicidal irradiation is a proven and effective method for disinfecting air in various settings, including hospitals, laboratories, and patient rooms. This technology can be used to inactivate a wide range of microorganisms, including viruses, bacteria, and fungi. The key components of UV disinfection systems include a UV light source, a controller, and a circulation mechanism to ensure uniform exposure of the air to the UV light. The effectiveness of UV disinfection is dependent on factors such as the intensity and duration of the UV light, the type and number of microorganisms present, and the environmental conditions. While UV disinfection is a powerful tool for air disinfection, it is important to consider potential risks and limitations, such as the need for proper maintenance and training. Overall, UV germicidal irradiation has a significant role in enhancing air quality and promoting health in various settings. Future research is needed to further explore the efficacy and applications of this technology.
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