Controlling Tuberculosis Transmission with Ultraviolet Irradiation

The air in buildings often contains potentially health-threatening bacteria and viruses, particularly for people who have impaired immune systems. Tuberculosis is an infectious disease that can be contracted by breathing air containing the tuberculosis bacterium. To reduce the risk of transmission of disease, the air can be disinfected in three ways: dilution, filtration, and purification by ultraviolet germicidal irradiation (UVGI). In addition to controlling tuberculosis, these approaches to disinfection are applicable for controlling other microbial disorders such as influenza, measles, and aerosolized bioterror agents.[1] This publication answers common questions about tuberculosis and shows how to control its transmission using UVGI. This publication is intended for engineers, architects, and the general public.

What is tuberculosis?

Tuberculosis is an infectious disease caused by the bacterium *Mycobacterium tuberculosis*. It most frequently attacks the lungs (pulmonary tuberculosis), but it can also infect other parts of the body.

What are the symptoms of tuberculosis?

Persons who have tuberculosis disease tend to show one or more of the following symptoms: a cough that will not go away, persistent tiredness, weight loss, fever, coughing up blood, and night sweats.

Who gets tuberculosis?

Anyone can be infected by *Mycobacterium tuberculosis*. However, being infected does not necessarily lead to tuberculosis disease because, in many cases, the immune system counteracts the bacterium and makes it inactive. Those most likely to become *infected* with tuberculosis are individuals who are in close contact with persons who have untreated, active tuberculosis. Those most likely to become *ill* with tuberculosis following infection are persons who have a weakened immune system, such as the very young, the very old, or people with HIV/AIDS.

How common is tuberculosis?

Worldwide, tuberculosis is the leading cause of adult deaths from a single infectious agent, with a fatality rate of about 23%.[2] In many parts of the world tuberculosis is still prevalent. In the United States, rates of tuberculosis were decreasing until the mid-1980s, then became resurgent during 1985-1991, but now are once again quite well-controlled. Current tuberculosis case rates in the United States are due to increased numbers of immigrants from parts of the world where tuberculosis is more common, a deterioration in public health controls, an increase in the number of persons with weakened immune systems, and the development of drug-resistant strains of the bacterium.[3]

How is tuberculosis spread?

Tuberculosis is spread when a person who has tuberculosis disease coughs or sneezes, thereby releasing the bacteria into the air in the form of an aerosol. Persons inhaling these bacteria may become infected.

Where is one most likely to be infected with tuberculosis?

Tuberculosis infection is most likely to occur during prolonged exposure to others who have tuberculosis disease, particularly when the exposure occurs in crowded conditions.[4,5] Recent outbreaks of tuberculosis have been reported in homeless shelters,[6] prisons,[7] commercial aircraft,[8] healthcare clinics, and schools.[9]

Are drugs available for treating tuberculosis?

Pharmaceutical treatment is available, but some strains of *Mycobacterium tuberculosis* are drug-resistant, so the drugs do not work in all cases. As a general principle, it is better to prevent infection from occurring rather than try to cure a disease after it has been contracted.

What technological methods can be used to reduce the risk of infection, and how do they work?

Three technological methods can be used to reduce the risk of airborne transmission: *dilution*, *filtration*, and *purification*.

Dilution reduces the concentration of infectious agents in a space by increasing the amount of outside air brought into the occupied portion of that space. Dilution does not destroy the bacteria, but rather reduces the probability of transmission by spreading the bacteria over a larger volume of air. An appropriate level of dilution is achieved by ensuring six air changes per hour in the space. One air change per hour means that the volume of fresh air supplied to the space in 1 hour is the same as the volume of the space. At six air changes per hour, the air in the space is replaced with fresh air every 10 minutes. The fresh air required for dilution can be provided by natural or mechanical means. Where natural ventilation is used, additional operating costs may be incurred by the heating or cooling necessary to ensure thermal comfort. Where air-conditioning or mechanical ventilation systems are used, dilution requires additional operating costs because of the larger volume of fresh air that must be treated and moved.

Filtration reduces the concentration of infectious agents in a space by passing the air through a high-efficiency particulate air (HEPA) filter that traps bacteria and viruses (and other particles), thereby removing them from circulation. Like dilution, HEPA filtration can impose additional operating costs from the increased fan power required to push air through the filter. Few tuberculosis bacteria survive for more than 48 hours on the filter,[10] and those that do are difficult to remove, so there is minimal risk of re-releasing the bacteria into the air when changing the filter. HEPA filtration can be used within the ductwork of an air conditioning or mechanical ventilation system, or within a freestanding unit in the occupied space.

Purifying the air through UVGI destroys the infectious agents in the air because exposure to ultraviolet (UV) radiation damages the deoxyribonucleic acid (DNA) of bacteria and viruses, including that of *Mycobacterium tuberculosis*. This DNA damage stops the infectious agent from replicating. Air cleansing using UVGI requires that persons in the treated space be shielded from excessive exposure to the UV radiation. This can be done by placing the UV source in the ductwork of a ventilation system, in a freestanding disinfecting system, or in an open location within a room. When installing UVGI in an open location, to prevent undue human exposure to the UV radiation, it is important to ensure that the UV radiation is restricted to the portion of the room that is above standing head height. The UVGI technology has long been used in laboratories and healthcare facilities, but it is also applicable for use in spaces where people congregate.

These three approaches can be used separately or in combination. The Centers for Disease Control and Prevention (CDC) has recommended that UVGI be used as a supplement to dilution in high-risk settings.[11]

What evidence indicates that these methods are effective?

Dilution, HEPA filtration, and UVGI have all been shown to be effective in reducing the concentration of tuberculosis bacteria in laboratory situations. At the time of this publication, no controlled field studies have been conducted to demonstrate the viability of dilution and HEPA filtration. A multi-city, multi-year study of effectiveness of air purification through upper room UVGI, called the Tuberculosis Ultraviolet Shelter Study (TUSS), is underway.[12] TUSS seeks to evaluate the effectiveness of upper room UVGI in homeless shelters as a representative environment of all congregate spaces.

What is the relative effectiveness of dilution, filtration, and UVGI purification?

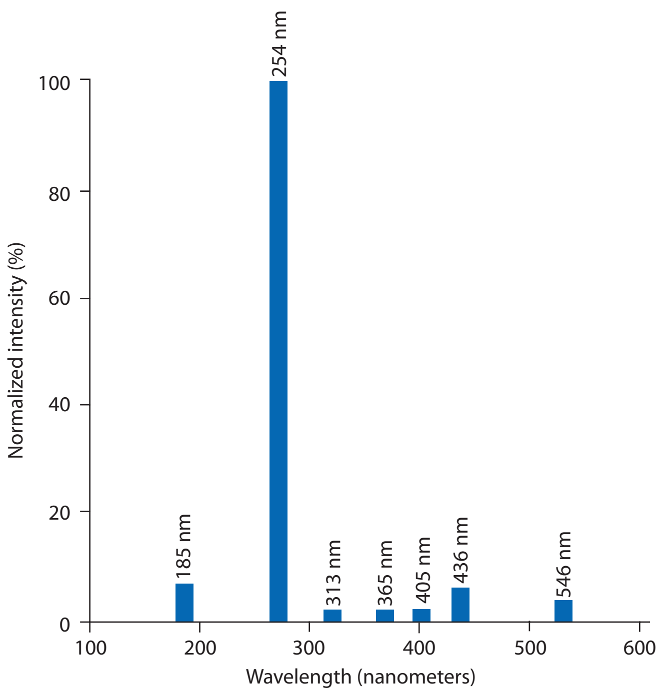
For air cleansing, the relative effectiveness of dilution, HEPA filtration, and upper room UVGI can be measured in two ways. One is on the basis of equivalent air changes per hour; i.e., the number of air changes per hour that would be required to reduce the concentration of tuberculosis bacteria by the same amount as achieved by filtering or upper room UVGI. Using this method of comparison, for dilution at 6 air changes per hour, HEPA filtering provides the level of air cleansing equivalent to 12 air changes per hour. UVGI can provide the level of air cleansing equivalent to 10 to 35 air changes per hour, a range that varies with factors that include UV intensity, time of exposure, and relative humidity.[13]

Another way to compare dilution, HEPA filtering, and upper room UVGI is by their cost effectiveness, expressed in terms of the number of dollars per case of tuberculosis infection prevented per year. One study estimates that for a high-risk setting (i.e. a hospital waiting room) the cost to avoid a tuberculosis infection was $133 for UVGI, $420 for HEPA filtration and $1708 for additional ventilation. Thus UVGI was the most cost effective of these three technologies.[14]

How is air purification achieved using upper room UVGI?

Upper room UVGI is achieved by using a UV lamp in a specially designed fixture that directs the UV radiation to the upper room area. The UV lamp used for UVGI is a low-pressure mercury discharge lamp. This lamp has a strong emission line at 254 nanometers (see Figure 1), a wavelength that causes DNA damage to bacteria and viruses. The lamp also emits some visible short wavelengths that appear as blue light. UVGI lamps are based on conventional fluorescent lamp technology except they have a special glass to *emit* UV and have no phosphor coating to produce visible light. Like conventional fluorescent lamps, UVGI lamps are available in linear and compact forms, both of which require ballasts to operate.

Figure 1. Spectral power distribution of the low-pressure mercury discharge



The fixtures used for upper room UVGI are designed to shield the lamp from direct view of persons in the occupied space and to emit the UV radiation in a wide, flat, slightly inclined distribution such as that shown in Figure 2. This is usually accomplished by placing the UV source inside an aluminum or stainless steel box and passing the UV rays through a series of wide horizontal louvers (see Figure 3). UVGI fixtures are available in forms suitable for wall and corner mounting and for suspension from the ceiling. The amount of UV radiation emitted from the fixture is low relative to the amount emitted by the UVGI lamp because of the absorbing effect of the louvers in the fixture.[15]

What other factors should be considered?

Two other factors need to be considered if an upper room UVGI installation is to be effective and safe. One is the pattern of air movement needed to bring the bacteria or viruses into the upper room. The other is the extent to which persons in the occupied space (the lower room) are exposed to the UV radiation. These two factors are discussed below.

Figure 2. Distribution of UV radiation from a typical wall-mounted UVGI fixture

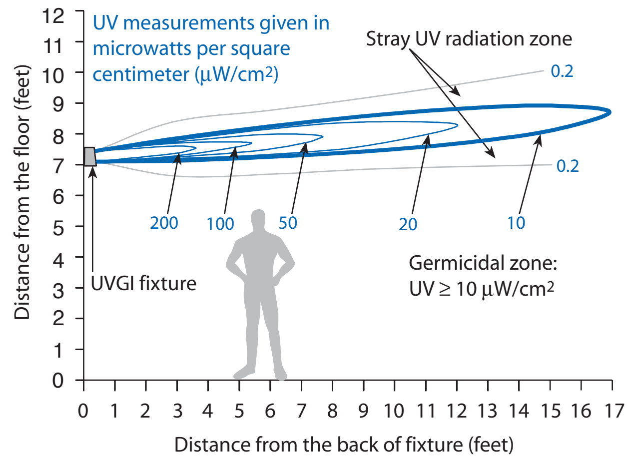
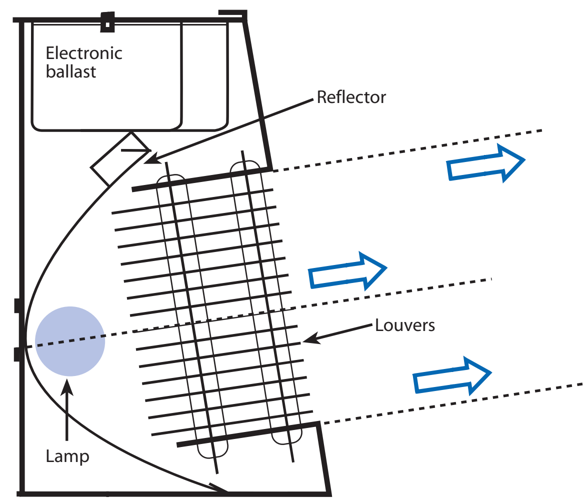


Figure 3. Cross-section through a wall-mounted UVGI fixture (adapted from Atlantic Ultraviolet Corporation)



What airflow patterns are required for upper room UVGI to be effective?

For upper room UVGI to be effective, the aerosolized infectious particles must be moved from the lower part of the room, where they are produced by a person coughing or sneezing, to the germicidal zone in the upper room. Practical considerations prohibit the ideal of UVGI cleansing of all infectious particles in one pass when they move through the upper room UVGI zone. The primary consideration is the need to limit the intensity of upper room irradiance in order to avoid excessive exposure of humans to UVGI in the occupied part of the room. However, complete inactivation of bacteria and viruses can occur through a cumulative effect of UVGI exposure over time as infectious particles are carried repeatedly through the irradiated upper room. Each pass into the UVGI zone will inactivate a fraction of the infectious particles. This cleansed air further dilutes the concentration of particles in the lower part of the room. Another consideration is how rapidly microorganisms proceed through the UVGI zone. Too much ventilation limits the time the infectious particles are exposed to the UVGI.

To what extent should exposure to UVGI be limited?

The distribution of UV radiation needs to be carefully controlled to limit human exposure. Excessive exposure to UV radiation at 254 nanometers can cause temporary reddening of human skin akin to sunburn, and inflammation of the conjunctiva of the eye, both resolving within 24 to 48 hours.[16] The American Conference of Governmental Industrial Hygienists[16] recommends that where people work a normal 8-hour day, at the irradiance at 254 nanometers should be less than or equal to 0.2 microwatts per square centimeter. This limit can be met by using fixtures that carefully control the distribution of the UV radiation, mounting the fixtures so that the direct UV radiation is confined to the upper room, and taking care to use materials and finishes in the upper room that absorb rather than reflect UV radiation at 254 nanometers.

How much UV radiation is necessary to stop transmission?

The amount of UV radiation required to kill or inactivate a bacterium or virus depends on the wavelength of the radiation, the duration of exposure, and the susceptibility of the bacterium or virus at the wavelength of the radiation. This susceptibility is measured as the reciprocal of the radiant dose required to kill or inactivate 90% of the infectious particles present before exposure to the UV radiation. The dose is the product of the UV irradiance and the duration of exposure. These two components are interchangeable over a wide range. Either a high irradiance for a short time or a low irradiance for a long time is equally effective. In practice, the effectiveness of a UVGI installation is determined by the following factors:

- The UV lamp used, because that determines the wavelength of the radiation
- The fixture in which the lamp is housed, because that determines how much of the radiation discharged from the UV lamp is actually emitted from the fixture and how it is distributed
- The distance of airborne infectious agents from the fixture, because that determines the irradiance level
- The airflow pattern, because that determines how long the bacteria and viruses are exposed to the UV radiation
- The humidity of the atmosphere, because water makes the infectious agent less susceptible to damage from UV radiation. Higher relative humidity makes it less likely that an aqueous aerosol will dry out. For UVGI to be most effective it is recommended that relative humidity of the air be below 75%.[17]

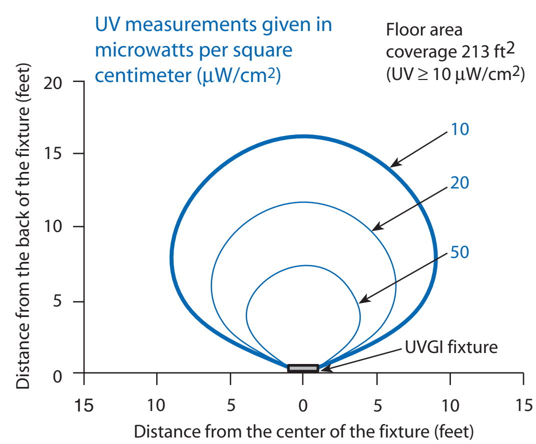
What advice exists for those wishing to use UVGI?

Guidelines on the use of UVGI have been published in several different forms. The CDC gives general advice on the prevention and control of tuberculosis among the homeless and in healthcare centers.[11] Such guidelines offer little advice to the designer of UVGI systems.

The designer needs to know whether the room is suitable for upper room UVGI, how many fixtures to use, and where they should be located. The suitability of a room for upper room UVGI is determined by the ceiling height and the UV reflectance of the surfaces in the upper room. Upper room UVGI should not be used in rooms with ceiling heights less than 8 feet.[18,19] All upper room surfaces likely to be UV irradiated should have a reflectance at 254 nanometers of less than 5%.[20*]

To determine the appropriate number of fixtures, a simple guideline is that 30 watts of UV lamp power are required for each 200 square feet of floor area.[19] As for location, manufacturers of UVGI equipment provide information on the area over which their equipment can be expected to damage tuberculosis bacteria (see Figure 4). Such information can be used to determine the number and positioning of the equipment necessary to cover the entire upper room effectively by overlaying the coverage area of the individual fixtures on the floor plan of the space to be treated.

Figure 4. Example of the coverage area information provided by a UVGI equipment manufacturer



* A low UV reflectivity finish must be used on upper surfaces such as the ceiling to ensure that UV radiation levels in the occupied space of the room do not exceed occupational eye and skin safety standards.[16]

A paper by First et al.[19] provides several design examples of upper room UVGI installations in a medical examination room, a homeless shelter, a drop-in center lavatory, a corridor, a stairwell, and a hospital isolation room.

A more comprehensive index for guiding the designer is under development as part of the TUSS project.[21] The TUSS project defines a UVGI Effectiveness Index (I) by the following relationship:

$$I = \frac{1}{\frac{1}{I_i} + \frac{1}{I_m}}$$

where I_i is the irradiation index, which is independent of mixing, and I_m is the mixing index, which is independent of the amount of UVGI. The irradiation index and mixing index are defined, respectively, by the following two equations:

$$I_i = \frac{zWL}{V\lambda} \qquad\qquad I_m = \frac{c\bar{S}}{2H\lambda}$$

where

- z is the microbe's UV susceptibility (m^2/J)
- W is the UV power output of the fixture (W)
- L is the mean path length of UV rays (m)
- V is the room volume (m^3)
- λ is the outdoor air exchange rate (s^{-1})
- c is an empirical constant
- $\bar{S}$ is the mean vertical airspeed (m/s)
- H is the room height (m)

The parameters in these equations are known constants, or can be measured onsite, or are part of the normal heating and ventilating design process. Preliminary measurements in a model room have shown a good correlation between the UVGI Effectiveness Index and the concentration of bacteria.[21]

What does an upper room UVGI installation look like?

Figure 5 shows an upper room UVGI installation in the main room of St. Agnes Shelter for the Homeless, New York City. The ceiling height is 12 feet. Eleven UVGI fixtures, of the type shown in Figure 6, are mounted on the wall, approximately 8 feet above the floor. Figure 7 (shown on page 6) suggests the UV radiation distribution from this fixture in terms of the blue pattern visible on the walls.

Figure 5. Main room of the St. Agnes Shelter for the Homeless

Figure 6. Wall-mounted UVGI fixture used in the St. Agnes Shelter for the Homeless (Atlantic Ultraviolet Corporation *Hygeaire* ™ model LIND24-EVO)

What does an upper room UVGI installation cost?

The cost of an upper room UVGI installation can be considered in two parts: the cost to purchase and install the fixtures and lamps, and the cost to operate them. For the upper room UVGI installation in the St. Agnes Shelter for the Homeless, the installation cost was approximately $4.60 per square foot. Operation costs include electricity and lamp replacement. The annual cost of electricity per fixture is $28, assuming a power demand of 31.4 watts per fixture, an operating schedule of 24 hours per day, and an electricity cost of $0.10 per kilowatt-hour. The lamps are replaced annually at a material cost of $43 per lamp.

What is the future of upper room UVGI?

Upper room UVGI is likely to become a common feature of buildings. Upper room UVGI is an effective method for cleansing the air of many types of viruses and bacteria, including some of those suggested as weapons for bioterrorism. The technology is well-developed. It can be easily retrofitted in many buildings. It has been shown to be effective in the laboratory and is currently undergoing an extensive test of its effectiveness for preventing the spread of tuberculosis in representative environments. Estimates of its cost effectiveness for this purpose support the use of upper room UVGI rather than the alternatives of dilution and filtration. Taken together, these facts support the value of using upper room UVGI where airborne infectious diseases are a concern.

Figure 7. A wall-mounted UVGI fixture used in the St. Agnes Shelter for the Homeless (the distribution of ultraviolet radiation from the fixture is indicated by the pattern of blue light on the nearby walls)

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Upper room ultraviolet germicidal irradiation at St. Agnes Shelter for the Homeless

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