Health Facilities Scotland

NHS National Services Scotland

Research Report
Use of Light Based Technologies for the Decontamination of Air

Background:

It has been suggested that light-based air decontamination technology can be utilised to help prevent the growing number of nosocomial infections. To help inform Estates and Facilities Managers it was identified that there is a need to draw together information on these technologies.

Research Question/Title of work:

Investigation of light-based air decontamination technologies which have the potential to help decontaminate air and surfaces.

Summary

Nosocomial infections i.e. those which occur as a result of treatment in a healthcare facility, which remain a major concern in healthcare facilities, can be reduced in frequency through surface or air disinfection. This report looks at the spread of infection in hospitals through air, and examines different technologies used for its decontamination, describing a number of well-known and less well-known technologies. Conclusions on use derived from a literature review are put forward, and case studies identifying lessons learned for each technology are also presented

Abstract

Healthcare Associated Infections (HAIs) are acquired in hospitals, care homes, GP surgeries or dental practices. Germs causing these infections, such as bacteria, fungi or viruses, can be picked up from healthcare workers; other infected patients, the environment or by way of airborne spread. These infections pose a significant burden to healthcare facilities, and have been a priority for government agencies and the NHS, indicating a need for effective air and surface decontamination processes.

The aim of this report is to provide insight into light-based decontamination technologies for surfaces and air. The report focuses on Ultra Violet Germicidal Irradiation (UVGI), describing how the technology works, the history of its use and how the ambient environment can impact its performance. Case studies and journal articles assessing its use are also described. Less well-known light-based technologies such as High Intensity Narrow Spectrum-Environmental Decontamination Systems (HINS) are also explored, as well as more traditional non light-based methods such as dilution and filtration. Lastly, conclusions are provided on the suitability for use of each of the technologies presented.

Method:

The information contained within this report has been compiled through a number of methods, namely:

- Interviews with suppliers, researchers and design consultants.
- A review of published case studies on the technology.
- Review of published scientific literature.

Background

Need for Technology – Airborne Contamination

Light-based air decontamination technology can be utilised to help prevent the growing number of nosocomial infections in hospitals that are caused by airborne pathogens, or surfaces contaminated with bacteria and viruses. Nosocomial infections are a significant problem throughout the world and are increasing in number (Alvarado, 2000), with approximately 1 in 10 hospital patients acquiring a nosocomial infection (Breathnach, 2005). Nosocomial infection rates are as high as 40% in some parts of Asia, and although the infection rate in U.K. hospitals is not yet at this level, this issue still proves to be a significant problem within the U.K. At any time, over 1.4 million patients worldwide will have infectious complications acquired through the hospital environment (Tikhomirov, 1987), acquired most commonly through contaminated surfaces, equipment, hand hygiene and airborne pathogens.

The control of pathogens that cause disease is something that hospitals have to deal with everyday. Disease-causing pathogens can be categorised into three main groups being viruses, bacteria and fungi, and are classified according to their size since it directly impacts on filtration efficiency (Burroughs, 1997). Viruses are the smallest microbes and span a range of about 0.02 to 0.22 μm. They include many highly infectious pathogens (Fraenkel-Conrat, 1985) such as the Severe Acute Respiratory Syndrome (SARS) virus, influenza virus, and enterovirus. These pathogenic viruses are formed indoors and are rarely found in the outdoor environment where they do not survive well (Morey et al., 1990).

The next smallest pathogens are bacteria which cause of many different types of disease and follow many infectious pathways (Kowalski, 2006). Bacteria spans a size range of about 0.2 to 5.0 μm, which renders some of them highly filterable and others highly penetrating due to their size (Kowalski et al., 1999) such as Streptococcus pneumoniae, Streptococcus pyogenes and Bordetella pertussis. Lastly, fungal spores originate from the environment and are 2 to 10 μm in size, which makes them very susceptible to filtration such as Histoplasma capsulatum, Aspergillus, and Cryptococcus neoformans.

The outdoor environment contains fungal spores, pollen, and environmental bacteria, and although high efficiency filters can remove these pathogens, when filtering indoor air and attempting to remove viruses, another solution must be used. Indoor environments such as those found in healthcare facilities contain the ideal climate for microorganisms to survive, with the most frequently isolated microorganisms being Staphylococcus epidermis, S. haemolyticus, Enterococcus spp., Enterobacter, Pseudomonas spp., Micrococcus, Corynebacteria, and Streptococcus faecalis (Kowalski, 2007). Most airborne nosocomial infections are transmitted directly or indirectly through air and may cause respiratory (primarily pneumonia) and surgical-site infections. Those transmitted by the airborne route, especially fungal infections such as Aspergillosis, are a major source of morbidity and mortality in immuno-compromised patients (Arnow et al., 1991). The levels of airborne microbes are not routinely checked in hospitals, however a variety of studies have indicated that the air in hospital areas rarely, if ever, is sterile (Kowalski, 2007). For instance, in a 1993 study of airborne microbial contamination in the Operating Room and Intensive Care Unit of a surgery clinic, bacterial concentrations of 150 to 250 cfu per cubic meter were measured (Holcatova, 1993 as cited in (Kowalski, 2007).

Kowalski (2007) states that if the transmission of infection in healthcare facilities is predominated by direct contact, as many experts suggest, then surface-disinfection technologies should have a major impact on reducing infection rates. However, Kowalski (2007) also states that more than a third of all nosocomial infections may at some point involve airborne transmission and therefore a combination of surface and air disinfection methods should produce optimum results.

Technologies for Decontamination

Many technologies are available for improving the aerobiological quality of our indoor environments. Established methods include: dilution ventilation, filtration, ultra violet germicidal irradiation (UVGI), air disinfection, pressurisation control and dehumidification, while less well-known methods are photocatalytic oxidation (PCO), and atmospheric disinfection using hydroxyl and antimicrobials. New technologies such as pulsed light; ozone, ionisation, plasma and HINS (High Intensity Narrow Spectrum) light are also mentioned in the literature (Maclean et al., 2008).

UVGI

UVGI utilises the short wavelength of UV that is harmful to forms of life at the micro-organic level. By effectively destroying the nucleic acids in organisms so that their DNA is disrupted by the UV radiation (Bolashikov & Melikov, 2008), UVGI removes their reproductive capabilities and destroys the organisms. As a result, using a UVGI device in certain environments, such as in circulating air or water systems, creates a deadly effect on existing microorganisms such as pathogens, viruses and moulds.

History of UVGI

Kowalski (2000) states that since 1909, when the first UVGI system was successfully implemented for disinfecting the municipal water system in Marseilles, France, the disinfection of water using UVGI has been a common and reliable practice. Use of UVGI to decontaminate medical equipment is also reliable, however the disinfection of air streams using UVGI has a history of varying success.

UVGI and Air Decontamination

Martin et al. (2008) list the following historical events leading to the uptake of UVGI:

- 1920s -The first laboratory studies on UVGI in the air showed such promise that the elimination of airborne disease seemed possible.
- 1936 - Hart used UVGI to sterilise air in a surgical operating room.
- 1937 - the first application of UVGI for a school ventilation system dramatically reduced the incidence of measles.
- 1941 – 1942 showed a significant reduction in infection among Philadelphia school children in classrooms where UVGI systems were installed, compared to control classrooms without UVGI.

In the same paper, it is stated that later experiments by Riley and O'Grady (1961) resulted in the elimination of tuberculosis (TB) bacilli from hospital ward exhaust air. However, after this success, Martin et al. (2008) state that a large number of similarly designed devices

were tested with a mixed result of successes and failures, such as the 1954 study in which UVGI failed to reduce disease in London schools.

The success of some early experiments provided hope that UVGI could be useful in preventing the spread of disease, however successful outcomes were countered by showing that UVGI had little or no effect. This mixed experience is reflected in various guidelines that decline to sanction the use of UVGI as a primary system. Although limited data is available to determine the causes of earlier design failures, the apparent cloning of UVGI systems without regard to operating conditions probably doomed many installations from the start (Kowalski and Bahnfleth, 2006).

How UVGI Works

Ultraviolet light is electromagnetic radiation containing wavelengths shorter than visible light. At certain wavelengths, UV is mutagenic to bacteria, viruses and other microorganisms. UV light can be separated into various ranges, with short range UV (UVC), at or near 265 nm, considered germicidal due to its resonance with microbes' molecular structures. Low-pressure mercury lamps, which project electromagnetic radiation, have a wavelength of 253.7 nm, which is extremely close to the optimum wavelength stated above. UV works at this wavelength by breaking the molecular bonds within microorganisms' DNA, producing thymine dimmers and thereby destroying and rendering the microorganisms harmless or prohibiting their growth and reproduction. The process by which they are destroyed is similar to the UV effect of longer wavelengths (UVB) on humans, such as sunburn or sun glare, which is limited to the skin and eyes (Penn State University, 2009).

The ultraviolet component of sunlight is the main reason microbes die in the outdoor air. The die-off rate varies from one pathogen to another, but can be anywhere from a few seconds to a few minutes for a 90-99% kill rate of viruses or contagious bacteria (Kowalski, 2007). A UVGI system typically uses a much higher concentration of ultraviolet energy than is found in sunlight, making this system particularly lethal for most pathogens (Kowalski, 2007), however spores, and some environmental bacteria, are resistant and can survive much longer exposures (Riesenman & Nicholson, 1999). The UVGI system is designed to expose environments such as water tanks, sealed rooms and forced air systems to germicidal electromagnetic radiation, which at the correct wavelength, irradiates pathogens in the environment.

Areas of use for UVGI

As discussed in the background section, there are many viruses contained in the airstream and there is potential for diseases such as TB to be airborne. Therefore, in a hospital setting, UVGI would mainly be used in ventilation systems for supply to general wards and outpatient departments, where UV light could be incorporated to destroy any viruses in the re-circulated airstream. Other areas that require a high degree of air filtration are burns units, since Revathi et al. (1998) state that infection is a direct or indirect cause of 75% of deaths in burn patients, and Sengupta et al. (2001) state that nosocomial infections remain the leading cause of morbidity and death in burn patients. At present, antibiotics are used against burn infections, however if all pathogens could be removed from the surfaces and the air, infection frequency and severity may be markedly reduced. Despite the significant advances made in the last 40 years in the treatment of burn patients, infections continue to

represent a serious complication of burn injuries and remain a challenge for medical staff (Malandri et al., 1999).

Many studies have also been carried out on infection in operating theatres (Miner et al., 2005; Chow, 2003; Howorth, 1985). Clinical trials conducted in Britain, Europe, and the United States have confirmed that between 80 and 90% of bacterial contaminants found in the wound after surgery come from colony forming units (cfu) present in the air of the operating theatre (Howorth, 1985). White et al. (1982) established that laminar flow in an operating theatre results in a 97-fold reduction in bacteria in the air and a 35-fold reduction in bacteria washed out after surgery. SHTM 03-01 states that an Ultra-clean ventilation system (UCV) dilutes the air to provide a large volume of clean filtered air to the zone in which an operation is performed and where sterile items are exposed. In this case, air is discharged above the operating zone and while not truly laminar, its downward displacement purges the clean zone of contaminants and particles generated by the activities within it, as shown below in Figure 1.

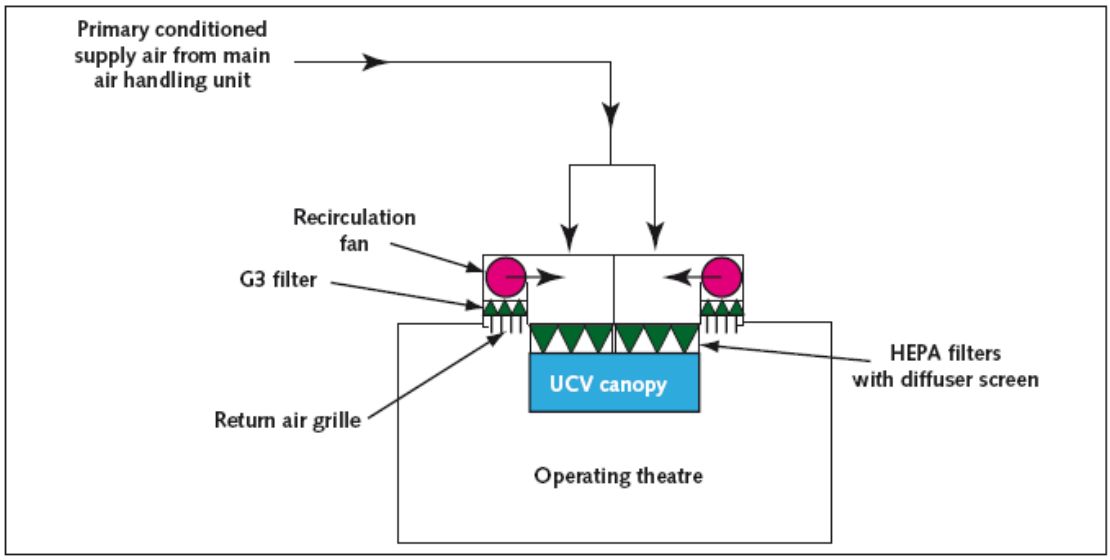

Figure 1: UCV theatre with modular system

A UV system has the potential to be incorporated into this design to decontaminate the re-circulated air; a contact time and dwell time would have to be established for these conditions to assess if this is a feasible option.

UVGI and Air decontamination

Design information about the effects of UVGI on airborne pathogens lacks the detail necessary to guarantee predictable performance (Kowalski et al., 2000). This is due to the varying conditions in which the UVGI lights are used and the need for each individual system to be calculated and tested once it is installed. Some UVGI lights can produce ozone which is harmful to humans, however this only occurs with lights that operate at wavelengths below 254 nm. Kowalski (2006) subdivides UVGI air disinfection systems into 3 separate categories, namely in-duct air disinfection, recirculation units and upper air disinfection units. Kowalski (2000) describes the categories as follows:

Induct

"Systems are commonly located in air handling unit downstream of mixing box. They can also be placed in return air duct to deal with recirculation of contagious pathogens. However they are rarely placed in outside air supply duct, as spores are resistant to UV light and are usually removed by filtration. Many characteristics of the air stream can impact on the efficacy of the system. Increases in relative humidity tend to increase pathogens resistance to UV exposure. Temperature has a negligible impact on microbial susceptibility however it can greatly impact on the power output of the UVGI lamp if it exceeds the design values. Air velocity operating system at levels above the design value will reduce the UV output due to the cooling effect of air on the lamp". (Kowalski, 2000, UVGI Design Basics, Page 101)

Kowalski (2000) further states that in hospital ventilation systems, the supply air to the rooms is from fresh outside air, which is tempered and filtered before being delivered to the space required. Since there are some forms of bacteria and spores present, SHTM-03 states that grade G4 filters are required for general supply. As discussed in the background section of the report, there are no viruses present in outside air, and therefore, a UV system would not be required in this instance. However, a UV light could still disinfect the filters and cooling coils, and this is discussed in the section on surface decontamination.

Upper room air disinfection

"Upper Room UV systems, sometimes called Upper Air systems, create a germicidal zone of UV rays that are confined to the upper portion of a room, known as the UV zone or stratum. Air that enters into this field is disinfected, along with any exposed surfaces. UV exposure levels in the lower room are maintained below the American Conference of Governmental Industrial Hygienists (ACGIH) 8-hour exposure limit of 30 J/m2 (broadband UV) or 60 J/m2 (254 nm). Upper Room systems operate continuously in occupied areas and if properly designed and installed are safe". (Kowalski, 2009, Ultraviolet Germicidal Irradiation Handbook, chapter 9, page 211)

The UK has also recently produced the document on Artificial Optical Radiation (2006/25/EC) on 27 April 2010, with an exposure limit for workers of 180-400 J/m2 for an 8 hour working day.

The upper air UVGI systems operate on the principal that warm air rises and is disinfected at a high level before cooling and descending. This may not be the case in all situations, however, due to ventilation systems and other external factors, and therefore the movement of air must first be established to ensure all internal air has sufficient contact with the UV light to allow for disinfection.

Air recirculation

Recirculation of extracted air is usually adopted in order to save energy, since it is expensive to expel air which energy has been used to heat or cool (Beggs ND). A UV filter would be beneficial in a recirculation system, since viruses contained in indoor air can be re-circulated around the hospital. Currently, SHTM-03 Part A, paragraphs 2.36 and 2.37 (pending publication), discusses recirculation systems and states that, there are few opportunities for the application of recirculation air systems within a healthcare environment. They are however normally used for HEPA filtered clean room applications

where the extract air is significantly cleaner than the outside supply. Recirculation is also routinely used in the canopy section of Ultra Clean Operating theatre ventilation systems.

Where the designer is considering the installation of a recirculation air system, due account must be taken of minimum fresh air supply volume required by the Building Regulations (currently 20%).

At present, most operating theatre canopy designs use HEPA filters, which do not filter out viruses. As operating theatres are thoroughly cleaned after every operation, there should be no viruses present, however they can still enter theatres via the surgeons clothes/skin or the patients gown/skin, which presents a problem as any virus in the air will be circulated through the system and will not be eradicated by the HEPA filter. If UV filtration was integral to the design of these canopies, all viruses could be eradicated, and if re-circulated air could be utilised in a hospital ventilation design for general ward areas, the energy costs for heat recovery would be greatly reduced. However, as stated in SHTM-03 a minimum of 10 litres per second per person of fresh air would still be required to eliminate odours in the air since UV filters cannot do this.

"Ventilation Systems that re-circulate room air where the UV filter is placed in the return duct or mixing air plenum deliver multiple doses to airborne microorganisms. Effect is partially dependant on air change rate; the result is an effective increase in removal rate in comparison with a single pass system. Room recirculation units and upper air systems can be used to augment induct systems or where induct installation is not feasible". (Kowalski, UVGI Design Basics, 2000, Page 107)

Factors to be considered when operating UVGI Systems

Kowalski (2000) reviewed current industry practices and indicated that, at the time, information on the design of UVGI systems was lacking the detail necessary for engineers to ensure its performance. However, in actual applications, many factors can alter the effectiveness of UVGI. Through studies in several hospitals and schools, some properly designed, and well-maintained UVGI installations have proven highly effective, and in laboratory tests, extremely high rates of mortality have been achieved under idealised conditions.

Pre-filtration

Prior to being subjected to UV light, the incoming air must be filtered as certain microorganisms have the ability to withstand UV light during exposure. UVGI destroys small microbes, such as viruses, that may be difficult to filter out, while filtration easily removes spores, which tend to be resistant to UVGI (Kowalski & Bahnfleth, 2000). By combining these two technologies, large particles that may protect microorganisms from the UV light will also be removed to enable more effective decontamination (USEPA, Guide to air Cleaners in the Home, 2008).

Airflow

If the air moving past the lamp is not the correct temperature the lamp may function above or below its optimum operating point, which will reduce its output. Lamps in the return air of building ventilation systems are likely to be slightly cooled below their optimum temperature, while lamps downstream of a cooling coil could be considerably cooled due to

a combination of airflow and low temperature. Lamps designed for operation at low temperatures however, should be resistant to these airflow effects.

The length of time the organisms in the air are exposed to the UV light is also significant, and the exposure time has to be calculated to ensure passing air has sufficient contact with the light. The airspeed must remain below the level calculated, however several passes will increase effectiveness if needed (VanOsdell & Foarde, Defining the effectiveness of UV lamps installed in circulating air ductwork, Page 21).

Temperature

Air temperature does not affect a microorganism's susceptibility to UVGI. However, if providing air at a low temperature with a high velocity can have an effect on the lamp temperature, this in turn can cause significant variation in lamp output, and ultimately the UV dose*. "Depending on the lamp used, the UV output for in-duct systems can vary by more than 60% across a range of temperature and velocity conditions typical of HVAC system operation, particularly in VAV systems where both can change simultaneously. Modern UVC lamps are designed to reduce the output variation experienced by lamps designed to operate at room temperatures and still-air conditions when they are used for in-duct applications. The impact of air temperature and velocity should be considered in the design of in-duct systems to ensure that desired performance is maintained. Where possible, lamps should be outwith the airstream". (Martin et al., 2008, Page 34)*

Relative humidity

The literature regarding the effects of humidity on UVGI does not present a completely consistent picture (Kowalski and Bahnfleth,2000; Scheir & Fencl, 1998; Martin et al., 2009). Water molecules are known to absorb UV light, so increased humidity should reduce the transmittance of UVGI and the effect should be proportional to absolute humidity (mass of water per volume of dry air), rather than relative humidity. Within the normal ranges of temperature and humidity in ventilation systems, the effect would be expected to be modest because water comprises only a small and generally unchanging fraction of the total gas. As noted by Kowalski and Bahnfleth (2000), studies on this matter are contradictory and incomplete. Scheir and Fencl (1998) state that humidity is an attenuator to UVGI energy, however more recently a paper by Martin et al., (2009) indicates that relative humidity (RH) has no significant impact on the performance of UV lamps, and its effect on the susceptibility of microorganisms (k-value) is not well understood. Attempts to correlate susceptibility of microorganisms to RH have yielded inconsistent results but it appears to be organism-specific. The relationship between RH and k-values seems complex, but most research has reported effects only when RH values increased above 70%. CIBSE Guide B (2005) states that the risk of condensation and microbiological growth will be reduced where room humidity is below approximately 70% saturation. It is therefore recommended that UVGI systems are operated below 60% RH, which is consistent with CIBSE Guide B (2005), which states that 40% to 70% humidity is acceptable for providing comfort and acceptable indoor air quality, and minimising indoor microbial contamination.

Reflectivity

In-duct systems benefit from increasing UVC reflectivity within the ductwork. Reflection can be an economical way to increase UVGI intensity because reflected energy adds to direct energy in determining UV dose, however while a surface may reflect visible light, it may not reflect UVC energy. For instance, polished brass reflects most visible light, but less than 10% of UVC, while galvanised duct material has a UVC reflectivity of around 55%. Aluminium and other reflective materials may however, be used to line ducts to improve effective irradiation levels.

System designers and manufacturers can provide information on improving reflectivity for UVGI in-duct applications. Although reflectivity is desirable for in-duct systems, it could be a safety concern for upper-air systems. Properly designed upper-air fixtures virtually eliminate UV reflections from ceilings or opposing walls located more than 10 ft (3m) from the outward opening of the fixture, yet, there may be times when fixtures must be mounted in suboptimal positions. Reflections from walls and ceilings can be minimised with low UV-reflectance paint or wall coverings while maintaining adequate irradiation in the upper air and limiting UV exposure to people in the room (Kowalski 2000).

Distance from pathogens

One of the more confusing aspects of comparing the effectiveness of different UV lights is that manufacturers report different dosages, and therefore, different kills (VanOsdell et al., 2002). Due to these variations, each lamp each should be tested on an individual basis to determine its effectiveness.

Lamp Power

"Germicidal UV is delivered by a mercury-vapor lamp that emits UV at the germicidal wavelength 254nm. Many germicidal UV bulbs use special transformers to ensure even electrical flow to the bulbs so the correct wavelength is maintained. Since germicidal UV has a narrow bandwidth, power fluctuations will render intended irradiating environments ineffective". (Kowalski, 2000)

UV Degradation

Inorganic materials like metal and glass are not affected by normal exposure to UVC energy. However, organic materials such as synthetic filter media, gaskets, rubber, motor windings, electrical insulation, internal duct insulation, and plastic piping, that are within 6 ft (1.8m) of in-duct lamps can rapidly degrade and should therefore be shielded with UV-resistant materials. Failure to do so can lead to damage of system components resulting in reduced performance and/or safety concerns. Degradation of system components however, is usually not a concern with upper-air systems (Kowalski, 2000).

Building materials can degrade if wall or ceiling paint is cracked or peeling, and books, paper, and other items stored in the upper-portion of a room may suffer from discoloration and deterioration. Plants being wilted by upper-air UVGI systems have also been reported. While not desirable, these problems can be prevented easily by proper maintenance and by moving susceptible items to outside the irradiated zone (Kowalski, 2000).

UVGI and Surface Decontamination

Although not in the scope of this work it is clear that the intrusion of airborne fungi and environmental bacteria can cause contamination of carpets and furniture (Kowalski, 2007). Contamination may also come from visitors and can cause accumulation of microbes on the surfaces within the healthcare environment. A novel application of UVGI is the use of systems to decontaminate surfaces, including floors, carpets, and equipment in unoccupied areas. These systems can be portable or mounted on walls or ceilings and can be installed to irradiate an entire room while it is unoccupied. Safety systems, such as motion detectors, must be in place to prevent this UV light coming into contact with humans and shutting down the system whenever someone enters the room. This application can also be used inside the air-handling unit (AHU) to disinfect and clean the cooling coils and filters, during which UV filters are placed upstream and downstream of them if possible. Low levels of irradiance are required as the UV exposure is continuous.

Surface decontamination prevents microbial growth that leads to contamination of the airstream. Menzies et al. (2003) assessed whether cooling coils within ventilation systems of office buildings reduced microbiological contamination, and as a result occupants' work-related symptoms, and it was found that UVGI resulted in a 99% reduction in microbial and endotoxin concentrations on irradiated surfaces within the ventilation systems. Menzie et al. (2003) also state that with the UVGI system on, there were fewer related mucosal, respiratory, and overall symptoms.

Conclusions and recommendations

General

VanOsdell (2002) concludes that UVGI system designers should make reasonable and responsible performance estimates for most in-duct applications however, the common lack of test results that provide lamp output at use temperature and airflow makes independent verification of a vendor's UVGI system design difficult. VanOsdell (2002) recommends that designers:

- apply safety factors to their designs, particularly as they depart from operating modes for which they have performance data and field experience;
- know the actual lamp output at the most challenging operating condition in the duct;
- avoid relying solely on design equations to determine the performance of their systems. Actual testing with the contaminants of interest is highly recommended;
- designer should be extremely cautious regarding claims about UVGI systems' high levels of inactivation of pathogenic bio aerosols.

Taking the literature findings into account, the following section summarises the ways in which UVGI systems might be utilised, and the resulting recommendations:

Recommendations and conclusions for Ventilation Design

UVGI is effective at removing pathogens from the air but is not effective at removing fungal spores (Knudson, 1986). This system must therefore be combined with an initial filter to eradicate the spores from the outside air and a UV filter to eradicate the pathogens created from internal air. The overall supply still must contain 10 l/s/pp of fresh air, possibly complimented with re-circulated air if this air has been proven to eradicate viruses.

The use of an initial particle filter followed by a UV filter could also be used in theatres to reduce the chance of infection to the patient from operating theatre staff or a previous patient. It would not replace HEPA or ULPA filters, but would rather compliment them to decontaminate the air further, and more effectively reduce infection. A UVGI filter would be particularly useful in burns units as the risk of infection is very high and accounts for 70% of deaths in these wards.

Another factor to consider is the energy consumption aspect involved, as at present the two heat recovery systems that are permitted in hospital ventilation design is either a cross flow plate heat exchanger or a run around coil, which is the most inefficient way to recover heat from a ventilation system. If all extracted air was treated however, and pathogens were removed, the risk of cross contamination would be negligible and more efficient methods of heat recovery could then be adopted. In addition, if a UVGI filter was utilised and proven to work effectively, a cross plate heat exchanger or thermal wheel could be used for heat recovery, which would greatly reduce energy consumption. Furthermore, in some sections of a hospital there may also be more fresh air entering a room than is required, in which case, re-circulated air could be utilised using a mixing box, which again would reduce energy consumption. However, as many manufacturers develop lights with varying outputs, the equations in the literature should only be used as a guide and rather, specific calculations from each manufacturer should be used to design a UVGI Lamp. After

development, an independent tester must establish if the lamp is decontaminating the area effectively.

Recommendations and conclusions for Upper Air Disinfection

This design kills particles coming into contact with UV rays at a high level, and although the harmful rays are directed towards the ceiling and not the occupants, some people may be exposed to rays through reflection. These levels must be measured once the lamp is installed in the room to ensure the rays are transmitted at a safe level. To establish how well this system eradicates pathogens, computational fluid dynamics (CFD) analysis must be carried this will give some indication of whether or not all air will pass the UV light, and it will have sufficient time to kill the pathogens. Some mechanical movement of the air may be required to ensure all air passes through the UV light as some pathogens may be shielded by larger particles such as dust,. This design can also be used at a low level to decontaminate any pathogens at floor level.

Recommendations and conclusions for Surface decontamination

UV surface decontamination should only be carried out in an unoccupied room. Safety features, such as movement sensors or automatic switches, must be incorporated into the design to prevent people from being accidentally exposed to the UV light. All areas to be disinfected must be in direct sight of the UV light and the exposure time for each must be calculated, as distance from the source will determine the disinfection rate. The system must then be tested after installation to ensure the surfaces are disinfected properly.

UV Case Studies

NHSScotland studies on efficiency of UV

No current studies on the effect of UV on the decontamination of air are being carried out within NHSScotland.

Other studies on efficiency of UV

1. Article details:

Paper by B.M. Andersen, H. Bånrud, E. Bøe, O. Bjordal and F. Drangsholt, Entitled Comparison of UVC light and chemicals for disinfection of surfaces in hospital isolation units, *Infect Control Hosp Epidemiol* 27 (2006), pp. 729–735.

Objective

The objective of this paper was to determine the bactericidal effect on surfaces of ceiling- and wall-mounted UVC light (wavelength, 254 nm), in isolation units, compared with standard hospital environmental cleaning and chemical disinfection procedures during the final disinfection after patients are treated for infections.

Method

This study was completed by collecting microbial samples obtained from surfaces in isolation units (patient room, anteroom, and bathroom) before and after irradiation with UVC, chloramine disinfection, and standard hospital environmental cleaning. Samples were tested using standard contact plates. The experiment was carried out in four identical, negative air-pressure isolation units (patient room, anteroom, and bathroom) with a defined number of ceiling and wall-mounted UVC light units. The UVC distribution was monitored in one isolation unit after irradiation for approximately 40 minutes, corresponding to doses ranging from 160 J/m^2 in a shadowed area to 19,230 J/m^2 at the most highly exposed site (which is high enough to inactivate most bacterial organisms, including spores).

Results

The study showed UVC disinfection significantly reduced the number of bacteria on surfaces directly or indirectly exposed to UVC to a very low number, as did 5% chloramine disinfection alone ($P < .001$ for both). Completely shadowed areas in the isolation unit (e.g. the bed rail, lockers, and mattresses) still required disinfection by chemicals.

Conclusion

The results showed that disinfection with UVC light may significantly reduce environmental bacterial contamination and thereby protect the next patient housed in an isolation room. UVC disinfection cannot be used alone but is a good addition to chemical disinfection.

2. Article details

Menzies D, Popa J, Hanley JA, Rand T, and Milton DK. (2003), Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and well-being: double-blind multiple crossover trials. Lancet, Volume 362, Issue 9398, Pages 1785-1791.

Background

Workers in modern office buildings frequently have unexplained work-related symptoms or combinations of symptoms. Menzies et al. (2003) assessed whether ultraviolet germicidal irradiation (UVGI) of drip pans and cooling coils within ventilation systems of office buildings would reduce microbial contamination, and thus occupants' work-related symptoms.

Method

Menzies et al (2003) undertook a double blind, multiple crossover trial of 771 participants. In office buildings in Montreal, Canada, three cycles were conducted where UVGI was turned off for 12 weeks, and then on for 4 weeks. Primary outcomes of self-reported work-related symptoms, and secondary outcomes of endotoxin and viable microbial concentrations in air and on surfaces, and other environmental covariates were measured six times.

Results

Menzies et al (2003) found that the operation of UVGI resulted in a reduction of microbial and endotoxin concentrations on all surfaces exposed to UVGI within the ventilation systems and found no adverse effects from any of the 711 participants. The use of UVGI also resulted in fewer work related respiratory and mucosal symptoms, the greatest reduction was within workers with an atopic history and never-smokers. With UVGI on, there was also a large reduction in never-smokers having work-related respiratory and musculoskeletal symptoms.

Conclusion

Installation of UGVI in most North American offices could resolve work-related symptoms in about 4 million employees, caused by microbial contamination of heating, ventilation, and air-conditioning systems. The cost of UVGI installation could in the long run prove cost-effective compared with the yearly losses from absence because of building-related illness.

3. Steril-aire study

Worrilow KC. (2008). IVF Laboratories and UVC Ionising Radiation. IAQ Applications; (4-6)

A newly released study provides compelling evidence of the effectiveness of Steril-Aire UVC devices for indoor air quality and infection control. The seven and a half-year study, conducted in the In Vitro Fertilisation Clean-room Laboratory of the Lehigh Valley Hospital and Health Network, found that the use of germicidal ultraviolet C or UVC lights installed in the HVAC system helped to improve clinical pregnancy rates (CPR). Clinical pregnancy rates increased by an average of 18.2% following 10 of the 13 change-outs of the Steril-

Aire UVC Emitters™ used in the HVAC system. By contrast, there were no statistically significant differences associated with the replacement of the particulate or gas phase filters over the same time period.

4. Medixair study

Nielsen PB (2007) Clean Air Project, 8th Congress of the International Federation of Infection Control Budapest, Hungary. October 2007.

Medixair have produced a high-energy ultraviolet air steriliser that is an air purification device that re-circulates air after exposure to UV light. This system is extremely quiet in operation, economical to operate, portable, easy to install and maintain and has full safety certification. Medixair is designed to run continuously in the immediate proximity of both patients and healthcare staff. The system uses four, 25W low pressure mercury UV lamps that emit germicidal radiation at a peak wavelength at 253.7nm. By arranging the lamps in a close coupled geometric pattern and employing a slow and controlled airspeed, it is possible to produce exceptionally high energy levels which, in turn, generate significant logarithmic levels of pathogen kill. The product has an internal fan that processes 25m^3 of air per hour. One machine thus produces an ideal level of protection for a single bedded side room. In open wards, the use of multiple machines on a one per bed basis enables treatment of much larger spaces. The machine is designed to be either floor mounted on a wheeled stand or attached permanently to the wall. Mounted on a floor stand the product is 90cm tall and occupies a 20cm x 20cm footprint.

Use of acoustic damping reduces and maintains the machine noise emission to <33dB whilst special filter material within the UVC tube envelopes eliminates the side band UV responsible for creation of ozone.

Northwick Park Hospital, a 900 bed acute Hospital in North London, allocated two identical rooms in a general medical ward. One had a Medixair (UVC) air sterilisation unit installed; the other did not. For a period of three months each room had 7 identified surfaces swabbed and cultured three times per week. Each room was clean as per normal procedures and staff worked within both rooms as required.

Results

The result of this research was that the test room fitted with the Medixair device was found to have MRSA traces on just nine occasions as opposed to 23 in the ‘Control’ room. This reduction of two thirds had a dramatic effect on the patients in the room. During the whole period of the trial at no time was MRSA found to have colonised a patient in the trial room whereas in the control room on 11 occasions out of 23 the patient was found to be colonised by MRSA on the skin and one developed a surface wound MRSA infection.

Conclusion

The controlled clinical trial and continuing surveillance evidence from Northwick Park Hospital demonstrates that when correctly engineered and applied, the contribution of UV technology is significant.

Other Light-Based Technologies

HINS-EDS (High Intensity Narrow Spectrum-Environmental Decontamination System)

HINS-EDS is a low illuminance lighting system, normally positioned at ceiling level, which provides continuous disinfection of the air and all exposed surfaces in wards and other clinical areas. The system is designed for treatment of the environment rather than patient treatment, although it is claimed to be a patient-safe technology. HINS-EDS was developed to eradicate pathogens, a cause of healthcare-associated infections (HAIs).

Maclean et al., (2008) states that the exposure of skin and eyes to HINS light is comparable to that of fluorescent light exposure under well-lit room conditions. Maclean et al., (2008) has also put forward that the system provides continuous disinfection and is active against MRSA and other nosocomial pathogens, treating air and all visible surfaces. Moreover they state that the system operates like a normal room light, has little or no operational requirements and requires no training for the user. HINS-light uses a narrow band of blue light from the visible spectrum to inactivate bacteria and uses a wavelength that is bactericidal but safe for human exposure. Photosensitive bacterial molecules absorb the wavelengths, which produces reactive oxygen species within the bacteria, resulting in inactivation.

Case Study

HINS-light technology was developed within Robertson Trust Laboratory for Electronic Sterilisation Technologies (ROLEST) at the University of Strathclyde, ROLEST are currently conducting investigations into the bactericidal effects of visible light on methicillin-sensitive and methicillin-resistant Staphylococcus aureus (MRSA), and have consequently identified that the optimal wavelength to inactivate it is 405 ±5 nm. They have subsequently designed a violet-blue light that operates within this bandwidth (HINS-EDS) and can be used within wards as the current data available indicates that this light is harmless to patients and staff.

Performance evaluations of the HINS-EDS are currently underway within hospital isolation rooms and other clinical areas. Each evaluation involves monitoring of environmental bioburden levels over a 1-2 week period, with samples being taken before, during and after HINS-light treatment.

Results

Early results have demonstrated that HINS-EDS is effective in reducing the environmental bioburden. The figures below demonstrate some of the latest results:

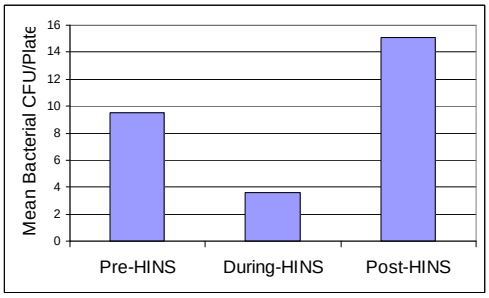

Figure 1. Bio-burden reduction during HINS light exposure

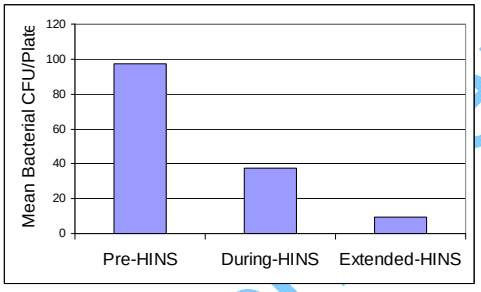

Figure 2. Reduction of Bio-burden after extended HINS light exposure

Initial conclusions

- Results in this example show reductions in environmental bacterial contamination levels in the treated isolation room.
- HINS-light EDS permitted continuous disinfection and is complementary to standard infection control methods.

Other Non-Light Based Technologies

Dilution and Filtration

Filtration can be an effective means of controlling air quality of incoming air. For the general area of a hospital, SHTM 03-01: Heating and Ventilation Systems, states that a grade G3 filter is suitable. The SHTM 03-01: Heating and Ventilation Systems also states that given that almost all viable particles originate from the occupants of a space and not from the incoming air, dilution is the more important factor aerobiologically. More critical areas require a grade F7 filter. For ultra clean systems HEPA filters can be used that can remove particles down to a size of 0.3 μm with at least 99.97 percent efficiency. An ULPA filter can further filter down to 0.1 μm with 99.999 percent efficiency. As some viruses have a smaller diameter than this, down to 0,02 μm, another solution must be found for targeting these pathogens. In typical healthcare applications and as stated in SHTM 03-01 (Heating and Ventilation Systems), there are three categories of filter used in health care:

- General ventilation filters graded G1 to G4;
- Fine filters graded F5 to F9;
- HEPA filters graded H10 to H14;

When only using filters to provide clean air the most effective method is, as stated above, by dilution, using the incoming air with a high air change rate. This would remove any pathogens from the outside to ensure the air entering the room is free of all contaminants. The internal air may contain pathogens and viruses from the internal occupation of the area, and to dilute the contaminated air, it shall have to be extracted and replaced with fresh incoming air. To ensure the flow rate would sufficiently remove pathogens in the air CFD analysis could be carried out on each area to prove how the air would flow in each room.

Initial conclusions

- Dilution is effective at expelling viruses and pathogens from the area through the extract system.
- The incoming air is filtered using various grades of filter depending on how critical the area is. The filters specified in the HTM-01 and SHTM 2025 remove most of the environmental contaminants from outside air to produce high quality indoor air.

Carbon Filtration

Another form of filtration is carbon filtration, which is the use of activated carbon impregnated with various compounds to enhance the absorption of gases and vapours. These filters are mainly used to control odours and volatile organic compounds (VOCs), HTM-01 state that active carbon filters should be used if the air intake is drawing in traffic fumes.

The intake air must be established prior to any design being proposed, as this will determine if, and how much carbon filtration is required. After the Outdoor Air Quality has been categorised, the European Standard EN 13779 clearly specifies the filter class that is required to achieve preferred Indoor Air Quality, as seen in the tables below. The filter classes are specified in accordance with EN 779:2002.

Classification of Outdoor Air Quality

Description of air quality	Concentration levels*					Category of outdoor air
	CO_2 (ppm)	CO (mg/m³)	NO_2 (µg/m³)	SO_2 (µg/m³)	PM_{10} (µg/m³)	
Rural areas with no significant sources	350	< 1	5 – 35	< 5	< 20	ODA 1
Smaller towns	400	1 – 3	15 – 40	5 – 15	10 – 30	ODA 2/3
City centres	450	2 – 6	30 – 80	10 – 50	20 – 50	ODA 4/5

The above table is from EN 13779

Classification of Indoor Air Quality

Category	Description	CO_2 -level above level of outdoor air (ppm) Typical range	Rate of outdoor air (m³/h/person) Typical range, non-smoking area
IDA 1	High IAQ	≤ 400	>54
IDA 2	Medium IAQ	400 – 600	36 – 54
IDA 3	Moderate IAQ	600 –1000	22 – 36
IDA 4	Low IAQ	> 1000	< 22

The above table is from EN 13779

Filter recommendations

	Outdoor Air Quality	IAQ Indoor Air Quality			
		IDA 1 (High)	IDA 2 (Medium)	IDA 3 (Moderate)	IDA 4 (Low)
Pollution level ↓	ODA 1	F9	F8	F7	F6
	ODA 2	F7 / F9	F6 / F8	F6 / F7	G4 / F6
	ODA 3	F7 / F9	F8	F7	F6
	ODA 4	F7 / F9	F6 / F8	F6 / F7	G4 / F6
	ODA 5	F6 / GF / F9	F6 / GF / F9	F6 / F7	G4 / F6

The above table is from EN 13779

Many of the Volatile Organic Compounds (VOCs) found in polluted air can be eradicated through the use of carbon filters. For even higher filtration, impregnated carbon absorbers are used to remove low molecular weight compounds like ammonia, hydrogen sulphide, and formaldehyde (Underhill, 2001). The level of filtration and type of filtration will vary for each location but levels inside the building must adhere to the levels stated above.

Initial conclusions

- Carbon filters can be utilised when the air being supplied has a high level of pollution, as is the case with car fumes.
- There are many types of activated carbon filters that can be tailored to remove specific contaminants from the incoming air.
- These filters initially require other filters to ensure the carbon filter is not blocked by larger particles from the outside air.

Photocatalytic oxidation

Photocatalytic oxidation (PCO) is a technology that disinfects surfaces and air. It has the unique ability to eradicate microorganisms and volatile organic compounds produced by microbes [(microbial volatile organic compounds (MVOCs)]. The oxidation process requires a surface coated with Titanium dioxide (TiO2) to react with UV light to form hydroxyl radicals (OH) and superoxide ions (O2-) that oxidize volatile organic compounds (VOCs) and many chemical pollutants. As a by-product of this reaction, carbon dioxide is created, and as shown in the graphs above, IAQ is dependant on the amount of carbon dioxide in the air. The UK statutory limit for adult working day exposure is 5000 ppm and as can be seen in the table above, low IAQ is anything above 1000 ppm. A designer should aim for indoor levels to be below 400 ppm.

At slightly elevated temperatures, approximately 6% of the incoming carbon is converted to carbon monoxide (CO), which is very toxic to humans. The UK statutory limit for adult working day exposure is 30 ppm for carbon monoxide. In addition, hydroxyl radicals are harmful to humans, however they usually exist for no longer than a second before becoming involved in an air-cleansing chemical reaction (Lash, 2003).

Although photocatalytic oxidation has many benefits over the other air and surface disinfection methods mentioned, since it eradicates many microorganisms and volatile organic compounds, it would need to be proved safe and adhere to UK and European standards for indoor air quality before being used for decontamination.

Initial conclusions

- This form of air and surface disinfection provides a unique property in that it eradicates microorganisms and microbial volatile organic compounds.
- This technology can be used to disinfect surfaces that are subject to UV light and have a surface coated with Titanium dioxide.
- There are still some unanswered questions regarding the safety of this technology , and these must be addressed before implementation in a hospital environment.

Ionisation

Ionisation occurs when a particle is given a positive or negative charge leaving a temporary charge imbalance. These atoms then join together and form cluster ions. The typical lifetime of a naturally generated small ion in clean air is about 100 to 1000 seconds (Daniels, 2002). The formation of these ions depends on the level of contaminants and the humidity of the air, and once formed, the ionised particles react with airborne gasses and particulates, and have the potential to reduce the concentration of bio aerosols (Phillips et al, 1964). Although ionisation can be achieved by negatively or positively charging atoms, negative ionisation is more common, may have additional health benefits. Generally, the more negative ions a person is exposed to, the better and more uplifted he feels (Nikken Research Institute, 2006).

The two most common ways to use an ioniser for disinfecting the air are a stand-alone system placed in a room, or a system inserted into the air-handling unit. The stand-alone system will produce a strong local electric field and any gas molecules coming into contact

with this will acquire the same charge as the electric field. Ionisers placed in the air-handling unit work on a similar principle, in that they are placed downstream or upstream of the filters, ensuring that all of the supplied air must pass through the ionised field. Many ionisation air cleaners generate ozone, which is a documented health hazard and lung irritant.

Initial conclusions

- Ionisation can reduce the concentration of bio aerosols in the air.
- Ionisation has a positive effect on mood.
- The system can be used as a stand-alone system in each room or to negatively charge particles in an AHU.
- Some ionisers may be dangerous to humans as they create ozone.

Ozone

Another type of machine sold as an air disinfectant is an ozone generator. Ozone is a pollutant and SEPA states that levels of outdoor air should not be above 50 ppb for an eight hour period more than 10 times in a year. There is not sufficient UK data on the use and effects of this technology, however the EPA has published documents discouraging the use of ozone generators as air cleaners due to ozone being harmful to humans. The EPA also states that the same chemical properties that allow high concentrations of ozone to react with organic material outside the body, give it the ability to react with similar organic material that makes up the body, and potentially cause harmful health consequences. When inhaled, ozone can damage the lungs; even relatively low amounts can cause chest pain, coughing, shortness of breath, and, throat irritation. Ozone may also worsen chronic respiratory diseases such as asthma and compromise the ability of the body to fight respiratory infections.

Initial Conclusions

From the available literature on this method of decontamination, it would not be recommended to use this technology as an air disinfectant since it is harmful to humans and the benefits of its use do not outweigh the hazards that it presents.

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