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The Use of Engineering Controls to Disinfect *Mycobacterium tuberculosis* and Airborne Pathogens in Hospital Buildings

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Abstract

Nosocomial infections are a major problem in many hospital buildings, with approximately 10% of patients acquiring such an infection during a hospital stay. Airborne transmission is one of the important routes for a number of nosocomial pathogens. To combat this problem there are a number of engineering control strategies, such as the use of ultraviolet germicidal irradiation and advanced ventilation techniques, which can be used. This paper outlines the 'state of the art' in air disinfection, and reviews recent research work in this field.

Introduction

Nosocomial infection (i.e. infection originating in hospital) is a major problem in many health care facilities. Despite general improvements in health care arising from medical advances, it has been shown that the incidence of nosocomial infection has remained unchanged over the past 20 years and that approximately 1 in 10 patients acquire an infection during a hospital stay [1]. These infections are associated with significant morbidity and may prolong the hospital stay for many patients. Some infections, such as nosocomial pneumonia are of particular concern because the ratio case:fatality may be substantial. As well as the misery caused by such infections, the economic impact of nosocomial infection on health care systems should not be understated. A US study estimated that the total annual cost of nosocomial infection was $4 billion (1985 dollar rate), with 8 million lost bed days. It was estimated that 20,000 deaths were directly, and 60,000 deaths partly attributable to these infections [2]. A smaller DHSS study estimated that in acute care hospitals in England 950,000 lost bed days and financial costs of £111 million (1986 rates) were associated with nosocomial infection [3]. Given these statistics, it is not surprising that health care authorities around the world are very concerned about nosocomial infection and are continuously seeking innovative methods to control the problem. Unfortunately, many of the micro-organisms responsible for nosocomial infections found in hospital buildings are difficult to eradicate and are drug-resistant. Notable examples are methicillin-resistant *Staphylococcus aureus* (MRSA), glycopeptide-resistant enterococci and multiply antibiotic-resistant *Mycobacterium tuberculosis* (MDR-TB), all of which may be found in hospitals in the UK and the USA.

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Airborne transmission is an important route for a number of nosocomial pathogens. Indeed, it has been calculated that the airborne route of transmission accounts for 10% of all sporadic cases of nosocomial infection. Although physicians and microbiologists have a good understanding of the micro-organisms involved and the natural history of the infections which they cause, their understanding of the physical science involved in airborne transmission is more limited. Indeed, the physics associated with the airborne transmission of pathogens falls within the remit of the building services engineer (or more precisely the ventilation engineer), and it is this discipline which offers some potential solutions to the problem of nosocomial infection. It has been demonstrated that through the use of engineering measures including increased mechanical ventilation rates, high-efficiency particulate air (HEPA) filters, and ultraviolet germicidal irradiation (UVGI) lamps, it is possible to control airborne pathogen levels in hospital buildings. However, the knowledge base on air disinfection techniques is relatively small, and little expertise exists on the application of air disinfection control measures to health care facilities. Consequently, there is a need to raise the general awareness of the available engineering control measures, and to carry out research into the optimisation of these measures in health care facilities.

Nosocomial Infection

Many nosocomial infections of bacterial, fungal or viral aetiology are transmitted via an airborne route. For example, pulmonary aspergillosis results from the inhalation of spores of *Aspergillus* spp. These spores are widespread in the outdoor environment, where they colonise soil, leaves and living plants. They often enter hospital buildings through mechanical ventilation ducts which have inadequate filter protection. Also, outbreaks of pulmonary aspergillosis are often associated with construction work which may liberate very large numbers of spores into the air. Immuno-compromised patients are particularly vulnerable to infection from *Aspergillus* spp. Morbidity and mortality in immuno-compromised individuals is significant, especially in bone marrow transplant recipients in whom case:fatality ratios of 85% are typical [4]. The problem is not only confined to hospital buildings; a recent study in the USA found that 'the second most common fungal infection requiring hospitalisation is aspergillosis' [5, 6].

Although infection with MRSA is generally associate with person-to-person contact, MRSA respiratory tra colonisation or infection results in airborne dispersal this bacterium prompting infection control measur which include isolation of the patient [7]. Recently, t emergence of strains of MRSA resistant to the antibiot vancomycin, often the only therapeutic option in t management of MRSA sepsis, has been described. Cas of vancomycin-resistant *S. aureus* pneumonia have a ready been documented [8]. Several investigators ha attempted to quantify the costs incurred in controllir hospital outbreaks of MRSA. Cox et al. [9], for exampl calculated that the cost of the control measures adopte following an outbreak at a district general hospital in 19 was £403,000.

In contrast to the gram-positive bacteria (which po sess a peptidoglycan-rich cell wall, conferring relati resistance to desiccation), an airborne route of transmi sion has not been considered important in the epidemic ogy of gram-negative infections in the hospital settin There is, however, accumulating evidence to suggest th the important gram-negative nosocomial pathogen, *A netobacter* spp., can be spread in this manner. Allen a Green [10] report an outbreak of *A. anitratus* that i volved two hospitals, in which 10 cases of pneumonia a 2 each of meningitis and septicaemia were associated wi the outbreak strain. In addition to bacterial infection, should not be forgotten that nosocomial viral infectio may also be spread via the air. Although respirato viruses are most obvious in this respect, it is now evide that the airborne route is a significant mode of spread outbreaks of acute viral gastroenteritis [11]. A 30-ml bol of vomit has been estimated to liberate 30,000,000 vi particles into the environment and, as air currents m cause these particles to be widely distributed in some h pital areas, it is not surprising that attack rates in sor viral infections are very high [12].

Of particular concern to health authorities world-wi is the threat posed to hospital patients and health ca workers by *M. tuberculosis* (MTB). Tuberculosis (TB) widespread in many developing countries, and partly d to increased international travel is on the increase many developed countries. The emergence of MDR-T in both the UK and the USA is of particular concern. number of recent outbreaks of MDR-TB have be recorded [13–15], in which mortality rates of up to 9 have occurred. These outbreaks have focused attention hospital authorities on the airborne transmission MDR-TB in hospital buildings.

TB in Health Care Facilities

Primary pulmonary TB is caused by inhalation of droplet nuclei, carrying MTB, of less than 5 μm diameter. These droplet nuclei are so small that they bypass the innate host defence mechanisms of the respiratory tract and are deposited in the alveoli in the lungs. Individuals who become infected with MTB have an approximate 10% lifetime risk of developing post-primary infection [16]. Post-primary infection most commonly affects the lungs, but infection of other sites such as the genito-urinary tract and bones and joints is well documented.

The world-wide occurrence of TB is very high, and in many parts of the world has reached epidemic proportions. Approximately one third of the world's population is thought to be infected with MTB, with the result that in 1996 it was estimated that there were 8.8 million new cases of TB and 3 million deaths [17]. In 1993 the World Health Organisation declared the disease a global emergency [18], and in their 1996 report estimated that 30 million people would die as a result of TB infection in the following decade [19].

TB acts synergistically with the human immunodeficiency virus (HIV), being responsible for the death of approximately a third of all patients suffering from the acquired immunodeficiency syndrome (AIDS) in Africa. Most TB cases occur in the developing world, but there has been a significant increase in TB within the developed world. Between 1985 and 1991 there was an increase of 18% in the occurrence of TB in the USA [16]. The reasons for this increase are multifactorial and include continued migration of individuals from endemic areas, socio-economic changes in urban areas leading to increased numbers of homeless persons, growth in at-risk groups, such as HIV-infected individuals and redirection of health care resources away from TB control programmes.

The emergence of new MDR-TB is of particular concern. These strains have arisen, at least in part, because of poor patient compliance with drug regimes. It has been estimated that of the 300 million people who are likely to become infected with TB in the next 10 years, 50 million will be infected with MDR-MTB [20]. Case:fatality ratios of up to 93% have been recorded with MDR-TB [21]. Another disturbing development is the recent emergence of a new virulent strain of MTB with increased transmissibility and whose growth characteristics in an in vivo model greatly exceed those of other clinical isolates of MTB [22].

Classically, TB is considered to be a disease of the poor, which spreads in crowded areas and confined buildings, typically among those who have inadequate access to medical treatment. Transmission of TB occurs in situations where infected persons come into close contact with others, such as in overcrowded housing, prisons or shelters for the homeless. Recently, however, several outbreaks in UK hospital buildings have highlighted the ever-present potential for transmission in the nosocomial setting [13, 15]. The measures required to control the spread of MDR-TB in hospitals represent a significant financial burden. It has been estimated that in the UK, the treatment of 1 MDR-TB patient costs between £100,000 and £200,000 [Davies P., private commun., 1998]. In the USA, a recent increase in MDR-TB transmission in health care facilities has alarmed the healthcare authorities. Given that the median time to death from presentation is 4 weeks in HIV-infected individuals [20] and that, using standard microbiological techniques, it may take up to 12 weeks before an MDR-TB strain is identified and antimicrobial susceptibilities determined, this concern is understandable. In a study of eight US hospitals undertaken by the Centers for Disease Control and Prevention (CDCP) in the USA, it was found that between 1989 and 1992, more than 100 health care workers had skin test conversions following exposure to patients with TB, and that at least 17 developed MDR-TB [23]. In New York City, which has experienced the largest increase in TB cases in the USA, it appears that hospital transmission has played a major role in the resurgence of the disease, with almost two-thirds of MDR-TB cases being linked to four hospitals [24]. Outbreaks of MDR-TB have also been reported in UK hospitals [13, 15]. As a direct result of the increase in TB transmission in hospitals, the CDCP in 1994 revised their TB infection control guidelines [23] and emphasised the requirement for the increased use of engineering-related techniques to control the risk of infection. In the UK the Department of Health is currently reviewing its TB infection control guidelines [Leese J., private commun., 1998], although these are as yet unpublished.

Although much concern has focused upon MDR-TB, it should be noted that nosocomial transmission of *Mycobacterium* spp., is also increasing. This is highlighted by a recent report of an outbreak of a strain of *Mycobacterium bovis* resistant to 11 antituberculous drugs, in which 19 patients died [25].

Infection Mechanisms

In a discussion of airborne routes of transmission of hospital infection, it is important to distinguish between transmission by respiratory droplets and by droplet nuclei. Respiratory droplets are generated by patients during coughing and sneezing and may also be produced during therapeutic manoeuvres, such as endotracheal suctioning or diagnostic procedures including sputum induction or bronchoscopy. Droplets then impact upon the conjunctivae or oronasal mucosae of susceptible patients or health care personnel, resulting in infection in susceptible individuals. Examples of infection spread in this manner include respiratory infections associated with *Mycoplasma pneumoniae* and *Bordetella pertussis* and systemic infection caused by *Neisseria meningitidis.* As these droplets are greater than 5 μm in size they do not remain suspended in the air or travel over long distances, and so, close contact between the index case and a susceptible contact is necessary for transmission to occur.

In contrast, droplet nuclei, which are produced by evaporation of droplets and which are typically 1–5 μm in size, settle slowly and remain suspended in air for long periods until they are removed by either ventilation or filtration. Furthermore, these particles can, depending on ventilation-associated factors, be distributed widely throughout the hospital environment. Examples of infections transmitted in this manner include pulmonary TB and varicella-zoster virus infection. It is also important to consider that dust particles carrying pathogenic microorganisms may also be distributed throughout the hospital environment in a similar fashion. With budgetary constraints in hospitals negatively impacting on frequency and thoroughness of hospital cleaning, the significance of this mode of transmission for nosocomial infection rates is likely to increase.

The Role of Ventilation

Airborne microbial pathogens travel on aerosol particles which are carried along by convection currents. Therefore it is important when considering nosocomial infection, to understand the air movement patterns which occur within hospital buildings. The important role that ventilation plays in the spread of nosocomial infection is illustrated by the following TB case studies.

Case Study 1 [26]. A patient in hospital in the USA had a hip abscess which was treated by irrigation of the wound with a high-pressure water jet. Unfortunately, unknown to the medical staff, the abscess contained large numbers tubercle bacilli, which were aerosolised by the water jet. was not until secondary cases of TB occurred that a dia nosis of TB in the index case was considered. Investig tions later revealed that the treatment room was und positive pressure and, that over a 3-day period, 58 oth post-operative patients in rooms off a common corrid had been exposed to MTB. It was subsequently found th the highest cross-contamination rates occurred in t rooms nearest the infection source, ranging from 67 across the hallway from the source, to 1% in roor approximately 50 m from the source. It was conclud that contaminated aerosol particles had entered a corrid adjacent to the treatment room due to the positive pre sure of the room. They had then travelled down the cor dor due to prevailing convection currents, infecting p tients in the side rooms off the corridor. The risk of cro infection was however reduced along the corridor, b cause the aerosol diluted as it passed along the corridor

Case Study 2 [26]. This case concerns an AIDS trea ment clinic in Florida, where widespread cross-infecti to the staff occurred from patients with unsuspected T Investigations revealed that the building had a centralis mechanical ventilation system which was recirculati contaminated air so that it was widely distribut throughout the clinic.

Case Study 3 [15]. A patient with MDR-TB was adm ted to a major teaching hospital in London and placed i ward side-room, adjacent to a ward in which HIV-po tive patients were based. Unfortunately, the side-roc was positively pressurised relative to the adjacent wa and 7 HIV-positive patients contracted MDR-TB. Tl ultimately resulted in the deaths of the index patient a 2 of the contact patients.

These case studies demonstrate the influential role th hospital ventilation systems may play in the transmissi of airborne pathogens. They also illustrate the need ensure that isolation and treatment rooms are not ma tained at a positive pressure. Case study 1 highlights t potential problem posed by corridors in hospital bui ings. Corridors are the hospital's 'arteries', and act as cc duits for both patients and staff. Unfortunately, in doi so they also act as transport routes for nosocomial inf tion, either by allowing infected persons to travel arou the hospital, or by funnelling the airborne pathogens convection currents [26].

Engineering Controls

There are three basic engineering control measures which may be employed to reduce the risk of transmission of MTB and other airborne nosocomial pathogens in health care facilities:

(1) the use of mechanical ventilation techniques to dilute or remove pathogenic micro-organisms present in room air;

(2) the use of HEPA filters, which are 99.9% efficient for particles ≥ 0.3 μm in diameter, which may be either mounted in ductwork systems or within room spaces, to prevent ingress of airborne pathogens, and

(3) the use of UVGI lamps which emit short-wave ultraviolet (UV, 253.7 nm) radiation in the UV-C range and which may be either mounted in ductwork systems or within room spaces to disinfect airborne pathogens.

Both the CDCP guidelines on TB control in the USA [23] and the NHS Health Technical Memorandum 2025 on hospital ventilation in the UK [27] concentrate on the use of improved ventilation techniques and the use of HEPA filters as the primary means of TB control in health care facilities. The use of HEPA filters is also strongly recommended in certain applications. By comparison, UVGI is treated with caution and few recommendations are made, primarily because of the lack of fundamental research that exists relating to disinfection rates and the practical application of UVGI [28].

Neither improved ventilation techniques nor the use of HEPA filters are always effective at controlling airborne pathogens. In addition, they can be expensive to install, difficult to retrofit to existing installations, and can result in greatly increased running costs [26, 28]. Conversely, through the use of UVGI lamps it is possible to provide a similar degree of pathogen disinfection in hospital buildings as that achieved by high ventilation rates, but at a fraction of the capital and operating costs [28].

Ventilation Strategies

The primary engineering control strategy adopted in hospitals for isolation rooms is to employ a mechanical ventilation system to produce a negatively pressurised space, from which airborne pathogens are unable to escape. Although the CDCP in the USA recommend a minimum negative pressure of 0.25 Pa for isolation rooms [29, 30], Streifel and Marshall [29] recommend a higher value of 2.5 Pa as an ideal. These negative pressures can be achieved by supplying less air to an isolation room than is extracted. This can be achieved by a supply to extract volume differential of between 10 and 20% [30–32]. It should be noted that in many countries, including the UK, the location of a negatively pressurised isolation room directly adjacent to a corridor directly contravenes the fire regulations. In such situations it is recommended that a positively pressurised ante-room be placed between the corridor and the isolation room [33].

In isolation rooms, high ventilation rates should be used in conjunction with negative pressurisation, to dilute the contaminated air. Table 1 shows data produced by the CDCP for contaminant removal times for a variety of air change rates [29, 32]. It should be noted that these data assume that perfect mixing of the air occurs within the room space, which in practice is impossible to achieve.

It can be seen from table 1 that the time taken to achieve 99% contaminant removal at a ventilation rate of

Table 1. Time required for the removal of contaminants from a room for a variety of air change rates [28, 29]

Air changes per hour (ach)	Minutes required[1] for a removal efficiency of		
	90%	99%	99.9%
1	138	276	414
2	69	138	207
3	46	92	138
4	35	69	104
5	28	55	83
6	23	46	69
7	20	39	59
8	17	35	52
9	15	31	46
10	14	28	41
11	13	25	38
12	12	23	35
13	11	21	32
14	10	20	30
15	9	18	28
16	9	17	26
17	8	16	24
18	8	15	23
19	7	15	22
20	7	14	21
25	6	11	17
30	5	9	14
35	4	8	12
40	3	7	10
45	3	6	9
50	3	6	8

[1] The times stated assume perfect mixing of the air within the space.

6 room air changes per hour (ach) is 46 min, whereas at 12 ach this time period reduces to 23 min and for 25 ach it is only 11 min. However, at 50 ach the removal time is still 6 min, which suggests that there is relatively little benefit to be derived from ultra-high ventilation rates. The CDCP guidelines recommend a minimum of 6 ach for existing isolation wards, of which at least 2 ach should be of fresh outside air and a minimum of 12 ach for new installations [23]. Whilst the use of such high mechanical ventilation rates in isolation wards should produce clinical benefits, there are large capital and running cost penalties associated with this strategy [23, 29]. In addition, the spatial restrictions in many older hospital buildings make it impossible to achieve these ventilation rates in practice. Consequently, it is often impractical to flush out the airborne pathogens simply by using mechanical ventilation, as this results in the installation of a disproportionately large mechanical ventilation system [26].

In isolation rooms, where health care workers are particularly vulnerable to airborne nosocomial infection, it is important to produce airflow patterns which reduce the risk of infection. Clean air should therefore be introduced into the room space, so that it passes over the health care worker before the infectious patient. The CDCP recommend that airflows should *ideally* be laminar, with supply diffusers located in a wall opposite to the patient, and the exhaust located in a wall near the patient. Alternatively a ceiling supply can be used with the exhaust located at low level in the walls [34]. In reality, however, laminar flow is impossible to achieve due to spatial restrictions. Consequently, vortexes are created which cause airborne pathogens to recirculate within the room space [32].

Whilst negatively pressurised rooms and high ventilation rates offer some protection against nosocomial infection, a total reliance on well-ventilated isolation wards ignores some important issues:

(1) If the ventilation air successfully flushes out the airborne pathogens from isolation and treatment rooms, then the exhaust air from the facility becomes contaminated, and is a potential health hazard to anyone either near the exhaust outlet, or maintaining the ventilation system. This poses problems in both recirculation and full fresh air systems alike.

(2) While isolation wards in hospitals may be protected by the use of specialised mechanical ventilation, communal areas such as waiting rooms, emergency rooms and general wards are not.

The issue of contaminated extract air is covered by the CDCP guidelines, which permit the re-circulation of air, provided the extracted air is disinfected by using a HEPA filter located in the return air duct. The diagnosis of pul monary TB often involves taking samples of sputum anc other respiratory tract specimens. This is a particularly hazardous process since large amounts of potentially infectious droplet nuclei are produced. The solution to this problem is to install purpose-built sputum samplin booths which are well ventilated and negatively pressu rised. Because the exhaust air is contaminated, it i important to install HEPA filters in the exhaust duct from such booths so that the pathogens are not transmit ted elsewhere.

The issue of the vulnerability of patients in waitin rooms, emergency rooms and general wards to nosocom ial infection is one of considerable importance, since witl conventional microbiological techniques the time to diag nosis of pulmonary tuberculosis in sputum smear-nega tive patients is relatively long. Consequently, an infec tious patient may infect many other patients and healtl care workers before a diagnosis is made, and the patien can be isolated. Indeed, there is evidence to suggest tha the greatest risk to health care workers of TB infectio does not occur in isolation wards, but in waiting rooms corridors, and general wards, where TB patients may a yet be undiagnosed [28, 29, 35]. These areas are not venti lated to the same standard as used in isolation rooms an so are less protected. Other pathogen control strategies ar required for these areas.

HEPA Filtration

HEPA filters are able to trap droplet nuclei and there fore can be used to remove MTB and other airborn pathogens. They are often placed in the supply air duct work to isolation rooms and other specialist treatmer areas, where they disinfect the air supply to the roor space, albeit at an increased capital and energy cost com pared with conventional bag filters. Although the use c HEPA filters in supply air ducts ensures the supply c clean air to room spaces, they are probably better utilise in exhaust and return air ducts, where airborne pathogen are likely to be recirculated through the mechanical vent lation system, or exhausted to atmosphere.

As with other types of filter, the effectiveness of HEP filters depends on correct installation and regular mainte nance. The CDCP guidelines, therefore, recommend tha the effectiveness of HEPA filters should be evaluate using the American Society of Heating Refrigeration an Air Conditioning Engineers (ASHRAE) dioctyl phthalat penetration test: This test should be undertaken when th

filter is installed, when it is changed, and at regular 6-month intervals [33].

In most situations, airborne nosocomial infections are more likely to occur due to cross-contamination within a room space rather than via the ventilation ducts, with the result that HEPA filters placed in ventilation ducts provide only limited protection. In order to combat this problem, HEPA filters may be placed in stand alone units within a room space to entrap the airborne pathogens [16]. These stand alone units employ small fans to draw the air through the HEPA filter and are usually placed at a high level within the room space. The fans recycle the room air through the HEPA filters so that the airborne pathogens are removed.

Room-mounted HEPA filter units have proved relatively effective. Recent work by Miller-Leiden et al. [16] has shown that, compared with a base condition of 2 ach, the use of room-mounted HEPA filters can achieve reductions in room droplet nuclei concentrations ranging from 30 to 90%. This study indicated that room-mounted HEPA filters have the potential to significantly reduce the risk of nosocomial infection if correctly utilised. There are, however, some drawbacks associated with HEPA filters. They are vulnerable to adverse room air currents and to the short-circuiting of airflow in the vicinity of the unit. Although such devices appear to achieve an initial rapid decrease in pathogen concentrations, the disinfection rate falls off as concentration levels reduce, and more and more air needs to be entrained in order to achieve low levels of contamination. In addition, as the HEPA filters become dirty, so the fan discharge rate falls, so that the quantity of air cleaned by the device will fall dramatically.

UV Disinfection

The lethal effect of UV-C radiation on bacteria has been known for approximately 100 years. The activation spectrum peaks in the range 260–270 nm and is similar to the absorption spectrum of nucleic acids, thus deoxyribonucleic acid is the main target. Conventional low- and medium-pressure mercury discharge UV lamps have a strong spectral emission at 253.7 nm, close to the peak of the action spectrum, and can be used as an effective bactericidal agent. UV light at this wavelength is absorbed by nucleic acids with the formation of pyrimidine dimers, resulting in damage to the DNA of the micro-organism which is lethal. However, a number of factors, such as humidity, temperature and air cleanliness affect the efficiency of action of UV light and the influence of these factors has, to date, not been researched in depth. Under conditions of high relative humidity for example, cells my be sublethally damaged. It is therefore of key importance to understand the mechanisms which impair UV irradiation, because micro-organisms possess DNA repair systems which may permit recovery from sub-lethal UV-induced damage.

Although UVGI was pioneered in the 1930s and 1940s, it is in many ways the least well understood of the three approaches to air disinfection [28, 36]. Very little work has been done on the practical application of UVGI in hospital buildings. Therefore the knowledge base that exists on UVGI and its application is relatively small. Consequently, the CDCP and the Department of Health in the UK are cautious about recommending its use as a primary engineering control measure and system designers have few guidelines on which to make decisions.

The most influential research work on UVGI was by Riley et al. [31] of Johns Hopkins University, USA, from the 1950s to the 1970s, when the relative susceptibility of various mycobacteria, including MTB, to UVGI was demonstrated. Riley et al. [31] reported that two experiments (in particular) conclusively demonstrated the potential of UVGI to kill MTB:

(1) The first experiment was undertaken in the 1950s over a 4-year period in a hospital in Baltimore, USA [37]. During the initial 2-year period of this study, Riley et al. [37] placed guinea pigs in an exposure chamber located in the exhaust air duct from a TB ward. During the second 2-year period, the exhaust air duct was split equally and two exposure chambers were created into which guinea pigs were placed. A UVGI lamp was placed in the duct to one chamber, while the other was left untreated. The results of the study were conclusive. After 2 years none of the guinea pigs in the UVGI protected chamber developed TB, while those in the unprotected chamber died at the same rate as those in the original chamber over the initial 2-year period.

(2) The second experiment involved installation of a shielded 17-watt UV lamp (i.e. an uplighter fitting) suspended 600 mm from the ceiling of a sealed test room having a background ventilation rate of 2 ach, and a floor area of 200 ft^2 (18.6 m^2) [28, 31]. Bacillus Calmette-Guérin, which is equally susceptible to UV-C radiation as MTB [31], was nebulised and introduced into the test room. The results of the experiment revealed a dramatic reduction in the colony-forming units over a short period of time, due to the action of the UVGI lamp. Riley et al. [31] estimated that the results achieved by the 17-watt fit-

ting were equivalent to that achieved by an increased ventilation rate of 10 ach.

Despite the impressive results obtained by Riley et al. [31, 37], interest in UVGI waned because of the use of improved drug therapies and relatively little new work has been published since the 1970s on the UV disinfection of air. Indeed, the work which does exist has tended to focus on the medical and microbiological aspects of UV disinfection and not on its practical in situ application. Indeed, although over 20 years old, the work by Riley et al. [31, 37] remains the only basis for the CDCP's current UV dosing guidelines (for the USA) of one 17-watt upper room suspended fixture, or one 30-watt wall fixture for each 200 ft^2 (18.6 m^2) of floor area [28, 34, 38]. Consequently, there is a need for more research into the quantification and classification of UVGI fittings, in order to establish reliable guidelines for use by system designers.

One factor which has contributed to the demise of research into UVGI has been fear over the safety of UV-C radiation. While UV-C is lethal to bacteria, it does not possess the penetrating capabilities of UV-A or UV-B, and is, therefore, much safer for humans. Consequently, the CDCP give the maximum 8-hour limit for UV-C as 0.2 $\mu W \cdot cm^{-2}$ [38, 39], whereas for UV-B the limit is only 0.1 $\mu W \cdot cm^{-2}$ [26]. However, Nardell [26] commenting on the CDCP's requirements believes that they are over-cautious, stating: 'The exposure limit for 254 nm UV of 0.2 $\mu W \cdot cm^{-2}$ during an 8-hour period incorporates a margin of safety and also assumes continuous eye exposure ('stare time') at the maximum UV intensity measured by a meter aimed at the fixture, ... For more than 50 years UVGI has been used safely in hospitals, clinics, jails, and shelters ... without injuries more serious than an occasional transient eye irritation from accidental direct exposure.'

In the past, the designers of UV installations have had to consider the amount of radiation received by individuals in the vicinity of UV lamps and incorporate safety measures. Often automatic sensors are used in rooms to ensure that UV lamps are only operational when rooms are empty. Recently, however, some researchers and manufacturers have developed room-mounted shielded UV devices, which prevent any injury to room occupants [40, 41]. Fittings of this type generally use parallel fins to act as a 'cutoff' so that room occupants are prevented from seeing the UVGI lamp. Unfortunately, the use of these fins significantly reduces the UVGI output of the fitting, leading to a reduced overall efficiency [42].

UVGI lamps can be installed in ventilation ductwork systems to disinfect supply and exhaust systems in a similar fashion to HEPA filters. Unfortunately, little is known about how UV lamps should be applied in order to achieve optimum performance. The CDCP, for example, discourage the use of UV lamps as a substitute for the use of HEPA filter in ductwork systems, but offer no firm guidelines [33, 34]. Other commentators are similarly vague on this issue [32, 35]. Indeed, UV lamp manufacturers, including Philips plc., admit that key information is not available. For example, with regard to the sizing of UV lamps for installation in ductwork systems, a Philips technical document on UV disinfection states: 'In the calculation ... it should be emphasised that it results only in a rough estimation; we did not incorporate the possible effects of humidity and temperature on the killing rate. Philips is not a specialist in that field, we always advise to contact qualified authorities to evaluate the bacteriological aspects' [43]. It can be concluded, therefore, that relatively little is known concerning the action of UVGI on many nosocomial pathogens, or on the effective practical application of UV devices in hospital buildings.

The Potential for UVGI

Recently, in the USA, there has been renewed interest in the work of Riley et al. [31, 37], and a number of researchers, notably First and Nardell of Harvard University, have initiated new programmes of research into the use of UVGI. This research has been prompted by the increased occurrence of TB in hospitals within the US, and the realisation that the existing engineering control have serious deficiencies. Therefore, current researchers and practitioners in the USA have been forced to look to the past for guidance. The following account published in 1996 is typical: '... at the Milwaukee County Hospital in the 1960s to 1970s ... We relied solely on UVGI to protect personnel of a 40-bed TB ward in a building of 1920s vintage with no mechanical ventilation. Re-testing of a medical and nursing students after they had spent 6 weeks tours on the TB ward revealed no PPD conversions [skin test]. In newer parts of the hospital, which had neither UVGI nor known TB patients, there always were several PPD conversions each year, presumably from patients with unrecognized TB' [44].

This account clearly illustrates the potential role of UVGI and corroborates the findings of Riley et al. [31, 37]. It also identifies the major advantage of using UVGI to disinfect nosocomial pathogens, which is that effective air disinfection can be achieved without the use of expensive mechanical ventilation systems; also the major disadvantage of an over-reliance on mechanical ventilatio-

namely that negative pressure ventilation systems cannot cover those areas of a hospital such as corridors and waiting rooms where undiagnosed TB patients may be located. It is in these unprotected areas where UVGI offers the greatest potential. UVGI is much less costly than the installation of expensive mechanical ventilation systems. It is also much more flexible, and can be installed without extensive alteration to the fabric of buildings.

In addition to hospital buildings, there are a number of other applications which might benefit from the use of UVGI. One such application, which is in need of further investigation, is the use of UVGI to control pathogens in commercial aircraft. There have been a number of well-documented cases in which passengers on aircraft have contracted TB during flights [17, 45]. This is an issue of concern which, as yet, has not been fully addressed. However, it may be that UVGI has the potential to improve passenger safety.

New Research on UVGI

A survey of publications indicates that there is a paucity of active research programmes into UVGI, although there are a few initiatives which have recently started. For example in the USA, scientists from the Massachusetts Department of Public Health and Harvard University are collaborating in a study to investigate UV air disinfection [Nardell EA, First M: Private commun., 1999]. Also, the Electricity Power Research Institute (EPRI) is working with various US bodies in a coalition to limit the spread of TB; they are currently running a large study to investigate the effectiveness of upper room UVGI fittings which have been installed in a number of homeless shelters in the USA. In Britain, a recent initiative, 'TB focus', has been launched, with a view to promoting research into TB control. Also, work supported by the National Health Service has recently commenced at the University of Leeds, which is intended to explore the in situ application of UVGI in hospital buildings.

Although there is currently an increase in research activity into the use of UVGI, this still leaves a paucity of information about the physical parameters which influence UV disinfection rates. It has been established by the authors that little validated data exist on microbial kill rates under various airflow conditions and that the crude calculations in current use do not take into account many of the pertinent parameters, such as: air temperature, air relative humidity, cleanliness of air, air velocity, distance of the pathogen from the UV source, reflectance of duct and room surfaces, and photo-reactivation of micro-organisms.

Another issue which affects critically the operation of room mounted UV devices is the extent to which air mixing occurs between the upper and lower levels within room spaces [38, 39]. Most of the work on this subject assumes that complete mixing of the air occurs. In reality, however, this is unlikely to occur. Consequently, there is need for further investigation of room air mixing within a clinical setting.

Because of the lack of valid fundamental data, it is difficult to determine the optimum solution for any particular current or future UVGI application. Consequently, there is a need for research work in this field in order to enlarge the fundamental knowledge base, with a view to producing design and operating guidelines for hospital buildings.

Computer Modelling

In recent years designers of HVAC systems have found computational fluid dynamics (CFD) programs to be valuable modelling tools. The flexibility afforded by CFD analysis enables system designers to assess quickly the impact of various fan, duct or building configurations. CFD is also of potential benefit when analysing air disinfection systems in hospital buildings. However, some questions should first be asked concerning the ability of CFD packages to predict what is required. Current CFD tools have become so useful because their simulation of airflow is accurately described by the models they encompass. However, when contaminants, pollutants or pathogens are introduced into air a number of submodels must be considered which govern their behaviour and durability. These submodels simulate the motion of particles, varying in size from 0.01 to 10 μm, in the air stream. Commonly, these submodels are not used (if indeed they are available) when modelling airflow using standard CFD packages. Consequently, users of standard CFD packages may obtain misleading results.

In order to determine the effectiveness of any UVGI air disinfection system it is necessary to determine the length of time and cumulative dose of irradiation experienced by a microbial particle. It is possible to determine the length of time spent by a particle within a UV field by using a CFD package. Calculated UV field intensities should allow for the effect of reflecting surfaces. Pure radiation field intensities can be readily calculated for any fixed geometry, although the computational costs associ-

ated with this are usually quite high and most CFD packages therefore 'import' this data from an external source. Field intensities are also affected if the air is highly contaminated (e.g. by dust) due to shadowing of particles, or if humidity of the air is high.

The length of time that a microbial particle is within a UV field is determined by the velocity at which it travels along its path. The path taken is governed by many factors, each of changing importance depending on local conditions. Primary motion is along streamlines, moving in tandem with the air molecules. On changes in air direction, even in laminar flow, larger particles will move off the streamline depending on the magnitude of their inertial force, which can be characterised using a combination of the particle Reynolds number and Stokes' law. Secondary effects on the dynamics are: Brownian motion in a random direction; gravitation, which imparts a settling out effect in the downward direction; electrical forces which move individual particles toward the opposite charge; photophoresis in which opaque particles move away from a radiation source and transparent particles move toward it and the effect of particles colliding with surfaces or each other and adhering. The majority of models that take these factors into account assume particles to be spherical and inert. However, the particles of concern in UVGI systems are probably neither and may even change in dimension, on exposure to UV irradiation, due to evaporation.

Although most CFD programs on the market today do not take into account all the factors listed above, when predicting particle motion in air, effective use can be made of them regarding larger scale motion (i.e. general room to room ventilation). However, when considering in detail the airflow around individual UVGI fittings it may be necessary to allow for these factors as they may have an important impact on the overall air disinfection pr cess. Work is continuing in this direction at the Univers ty of Leeds, where small-scale, high-detail models of inc vidual particles within UV fields are being develop [46]. These models also investigate effects of evaporati on particle dynamics.

Conclusions

The incidence of nosocomial infection world-wide i major and increasing problem. Although medical a vances can be used to combat nosocomial infection, t problem is essentially a public health one, which impin on the use of building services in hospital buildings. Sir airborne transmission is an important route for a la number of nosocomial pathogens, it is possible to cont these pathogens through the correct application of en neering controls.

Advanced ventilation techniques and the use of HE filters offer some protection against nosocomial pat gens although their effectiveness is limited and there cost penalties associated with these strategies. UV lamps, however, appear to offer the greatest potential improved air disinfection. The use of UV disinfectior hospital buildings should produce both the clinical be fits and reduce capital and operating costs. Further search is therefore needed into the optimisation of UV lamps in health care facilities. This research will be of b efit to all those associated with health care facilities. H pital designers, managers and clinicians will benefit fr clear guidelines on UVGI disinfection, and patients, itors and health care workers will benefit from a safer c ical environment.

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