THE OPTIMISATION OF UVGI AIR DISINFECTION IN A UK HOSPITAL BUILDING

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ABSTRACT

A number of studies have shown that approximately 1 in 10 hospital in-patients will acquire a nosocomial infection (NI) [1]. These infections are associated with significant mortality rates, and have a large economic impact on health care systems. A Department of Health (DoH) 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 NI [3]. Through the use of ultraviolet germicidal irradiation (UVGI) lamps it is possible to achieve a high degree of pathogen disinfection. This paper presents a theoretical model for optimising the use of UVGI lamps in ventilation ducts. The paper also outlines a research project investigating the air disinfection effectiveness of UVGI in a Leeds teaching hospital.

INTRODUCTION

Nosocomial infection (NI) (i.e. infection originating in hospital) is a major problem in many health care facilities. A number of studies have shown that approximately 1 in 10 hospital in-patients acquire a NI [1] . These infections have a considerable economic impact on health care systems [2 & 3]. A US study estimated that the total annual cost of NI 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 DoH 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 NI [3]. Health care authorities around the world are therefore very concerned about NI, and are continuously seeking innovative methods to control the problem. Unfortunately, many of the micro-organisms responsible for NI are drug resistant and are therefore difficult to eradicate. Notable examples are: methicillin resistant *Staphylococcus aureus* (MRSA) and multiple antibiotic resistant *Mycobacterium tuberculosis* (MDR TB), both of which are found in hospitals in the UK and the USA.

Of particular concern to health authorities world-wide, is the threat posed to hospital patients and health care workers by *Mycobacterium tuberculosis* (MTB); especially the multi-drug resistant (MDR) strains of MTB. Tuberculosis (TB) is widespread in many developing countries, and is on the increase in many developed countries. A number of recent outbreaks of MDR TB in UK hospital buildings have been recorded [4 & 5] , in which mortality rates of 93% have occurred. 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 one MDR TB patient costs between £100,000 to £200,000 [6] . Given the high mortality rates and the high economic costs, it is not surprising that these outbreaks have focused attention of hospital authorities on the airborne transmission of MDR TB in hospital buildings.

Ultraviolet germicidal irradiation: It has been calculated that the airborne transmission of nosocomial pathogens accounts for 10% of all sporadic cases of NI. It is however, possible

effectively to disinfect air by using ultraviolet germicidal irradiation (UVGI) lamps which emit short-wave ultraviolet (UV) radiation at a frequency of 253.7 nm. Indeed, by using UVGI lamps it is possible to provide a similar degree of pathogen disinfection in hospital buildings to that achieved by high ventilation rates, but at a fraction of the capital and operating costs [7].

Work carried out by Riley et al. [8] in the USA, over a period from the 1950's to the 1970's, clearly demonstrates the susceptibility of various mycobacteria, including MTB, to UVGI. However, despite some impressive results obtained by Riley, interest in the use of UVGI waned because at that time improved drug therapies appeared to provide the solution, and since then relatively little work has been published on the UV disinfection of air.

Objectives: In 1998 a multi-disciplinary team from the University of Leeds initiated a 18 month pilot study of the practical application of UVGI at the Leeds General Infirmary (LGI). The objectives of this study were:

- To investigate the in-situ air disinfection capabilities of duct mounted medium pressure UV lamps in hospital mechanical ventilation systems.
- To establish the optimum location for UV lamps in a hospital mechanical ventilation system.
- To develop a room mounted shielded UV disinfection device for use in a clinical environment.
- To establish the optimum location for the shielded UV device in a clinical setting.

In addition to the experimental work, theoretical work has been undertaken in order to develop computer based models which would simulate and analyse the UV irradiation of airborne pathogens.

METHODOLOGY

At the time of writing the pilot study is in its infancy and relatively little experimental work has been completed. However a substantial amount of theoretical work has been undertaken. Consequently, this paper describes the methodology used currently to implement the experimental work, and presents the results obtained from the theoretical work that has been completed to date.

The pilot study comprises two experimental stages and complementary theoretical work. The methodology of the experimental work is as follows:

Stage 1: The Stage 1 experimental study investigates the effectiveness of medium pressure UV lamps placed in a ducted mechanical ventilation system in a hospital building. In the study, a pair of adjacent children's wards at the LGI were selected for investigation. These wards share a common air handling unit (AHU) which ventilates the wards through separate supply and return air ducts, fed from a common pair of rising ducts, as shown in Figure 1. This ductwork system was selected because it is accessible, and because the two wards are identical and are served by a common AHU. This is of particular importance because it enables one ward to act as a 'control' while the air supply to the other can be treated with UVGI.

During the study, microbiological samples were taken regularly, using an automatic air

sampler, at points 1 to 8 in the system (see figure 1). These samples were then analysed to determine the total viable count (TVC). In addition, the numbers of and types of Gram-positive bacteria, Gram-negative bacteria, and fungi were characterised. Once the background microbial environment had been established for both wards, a medium pressure UVGI lamp was located at point A in the supply air duct to ward 51, and microbial samples were taken at points 1 to 8, in order to establish the impact of the UV lamp on the system and the study ward. After the system had settled down, the UV lamp was removed from point A in the system and installed at point B in the return air duct. Once again microbial samples were collected at the various points in the system, in order to assess the impact of the UV lamp in the new position. Finally, the process was repeated with the UV lamp located at point C in the system.

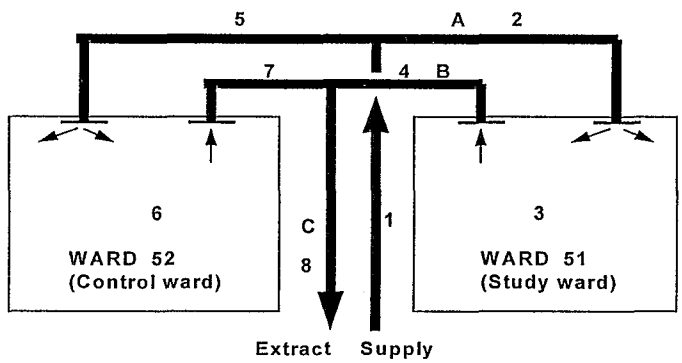

Figure 1 Schematic diagram of ductwork to the hospital wards

Stage 2: The Stage 2 experimental study investigates the effectiveness of shielded UV devices placed within a ward space. Stage 2 will not commence until the completion of Stage 1. The work will involve locating a number of shielded UV devices at high level in one of the children's wards. These devices will be designed at the University of Leeds and will comprise a number of UV lamp tubes located in a shielded housing containing a small fan. As in the Stage 1 work, the background microbial environment of both children's wards will be sampled before and after the insertion of the UV devices, in order to determine the impact of the devices. It is anticipated that the whole process will then be repeated a number of times until consistent reliable data is obtained.

Theoretical work: In order to support the experimental work, a computer based model was developed which simulated the UV germicidal irradiation of airborne pathogenic particles. This model simulates the direct irradiation dose received by a spherical airborne particle passing over a UV lamp mounted horizontally across a ventilation duct. (It should be noted that the model simulates only the direct irradiation dose received by the particle, and does not consider reflections from the duct walls.)

The irradiation dose, Q *(J),* received by an airborne particle can be represented by the expression:

$$Q = A \times E \times t \qquad (1)$$

where; A = Face area presented to the irradiation source (m^2)
E = UV irradiance (W/m^2)
t = Duration of exposure to irradiation (s)

and the *effective dose* H_{eff} (J/m^2) is given by:

$$H_{eff} = E \times t \tag{2}$$

With reference to Figure 2, the irradiance experienced by a spherical particle at a distance (h) from the UV lamp can be expressed as;

$$E = \frac{I_o(\sin\alpha_1 + \sin\alpha_1)}{(l_1 + l_2)h} \tag{3}$$

where:

I_o	=	Radiant intensity from lamp (W)
h	=	Perpendicular distance of particle from UV source (m)
l_1 & l_2	=	Partial UV lamp lengths (see Figure 2) (m)
α_1 & α_2	=	Aspect angles (see Figure 2)

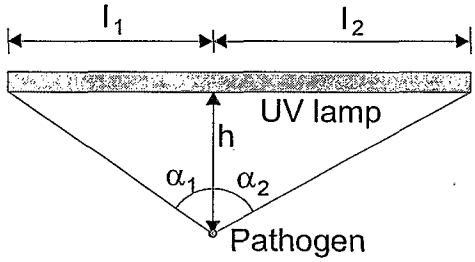

Figure 2: Plan view showing position of showing particle relative to UV lamp

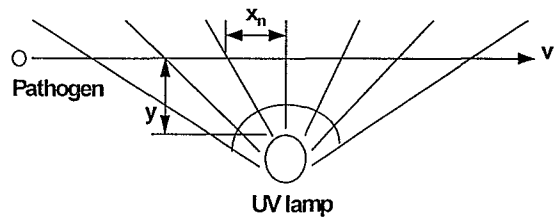

Figure 3: Cross-section view the movement of particle through UV field

To calculate the amount of irradiance experienced by a particle as it moves through the UV field requires the relative position of the particle and the lamp at any point in time and space to be known. Equation 3 gives the expression for the dose at this point. As the particle moves the irradiation dose changes as the distance from the source changes. To calculate the total dose E must be integrated with respect to time. In the model it is assumed that the particle moves in a horizontal path at a constant velocity through the UV field. To integrate E with respect to time, the field was divided into a number of equal segments, the time spent by the particle is given for the nth segment by equation 4.

$$t_n = \frac{(y\tan(\theta_{n-1} + \theta_n) - x_n)}{v} \tag{4}$$

where:

t_n	=	Period of time spent in segment n (s)
y	=	Off-set distance of particle path above/below lamp (m)
x_n	=	Length of particle path in segment n (m)
θ_{n-1} & θ_n	=	Segment boundary angles (^{o})
v	=	Velocity of particle (m/s)

Multiplying the time, t_n, by the mean irradiation dose for the sector and by the face area of the particle, gives the total dose received by the particle in that sector. The value for each sector may be summed to give an expression for the dose received by the particle as it moves through the whole field:

$$Q = \frac{\pi d^2}{4} \sum \left[t_n \left(\frac{I_o (\sin \alpha_{1n} + \sin \alpha_{2n})}{(I_1 + I_2) h_n} \right) \right] \quad (5)$$

where: d = Diameter of particle (m)
h_n = Average distance of particle from UV source in segment (m)
t_n = Time spent by particle in segment for time step (s)

so:

$$H_{eff} = \sum \left[t_n \left(\frac{I_o (\sin \alpha_{1n} + \sin \alpha_{2n})}{(I_1 + I_2) h_n} \right) \right] \quad (6)$$

Finally, the percentage pathogen kill rate can be determined from the H_{eff} value by using equation (7) [9 & 10] :

$$\frac{N_t}{N} = e^{-kH_{eff}} \quad (7)$$

where: k = Rate constant for pathogen (m^2/J)
N_t = Number of pathogens at time t
N_o = Number of pathogens at t = 0 s

RESULTS

The computer model was used to analyse the impact of direct UVGI on two airborne pathogens: *Staphylococcus aureus* and *B. subtilis spores*. In both cases it was assumed that the pathogens were travelling at a constant speed down a 1000 × 1000 mm rectangular ventilation duct in which a 1000 mm long UVGI lamp had been inserted (see figure 4). It was assumed that the UV radiant intensity from the lamp was 80 W/m, and that the total UV flux emitted by the lamp was 503 W. The rate constants, k , for the *Staphylococcus aureus* and *B. subtilis spores*, were assumed to be 0.104 and 0.023 respectively [9].

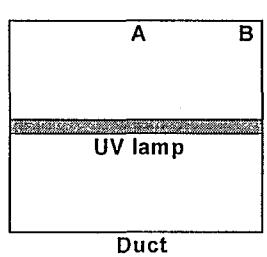

Figure 4 Location of paths A and B

Analysis was undertaken to predict the direct irradiation dose experienced by a pathogenic particle travelling in a straight line at the duct wall (i.e. the "worst case" scenario). It is assumed that if the pathogen was killed in this location, then other pathogens nearer the source would also be killed. Therefore, analysis was undertaken for pathogenic particles travelling at a range of velocities, at points A and B in the duct. The results of the analysis are presented in figures 5 and 6.

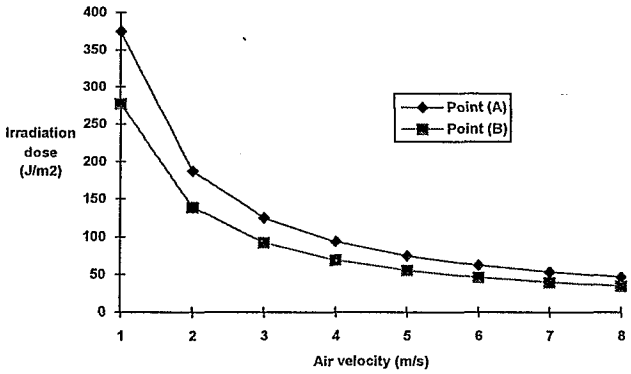

Figure 5: Irradiation doses received by pathogens at A and B (J/m^2)

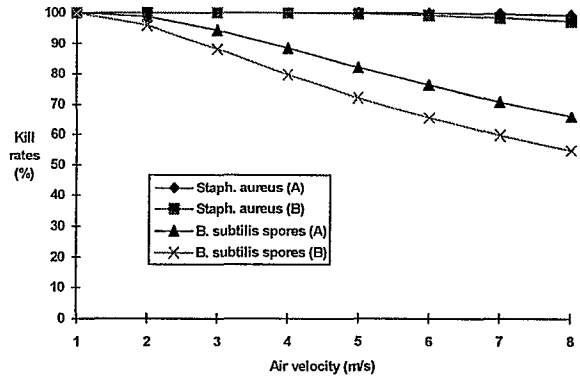

Figure 6: Pathogen kill rates at A and B (%)

DISCUSSION

It can be seen from the results presented in figures 5 and 6 that while the variation in air velocity has little impact on the disinfection of *Staphylococcus aureus*, it had a great impact on the *B. subtilis spores*. This is because *B. subtilis spores* are very 'hardy' and need a large UVGI dose for effective disinfection. Consequently, at air velocities in excess of approximately 2 m/s the effectiveness of the UV lamp against *B. subtilis spores* is greatly compromised.

It should be noted that the analysis was undertaken for a the worst case scenario (i.e. at point B). While some pathogens may indeed travel at point B in the duct, most will travel closer to the UV lamp and therefore will receive a considerably larger irradiation dose, as can be seen from the results for point A.

The theoretical analysis described in this paper illustrates the potential benefits to be gained from using a computer model to simulate the disinfection of pathogenic particle. It is anticipated that the model will be used to size and optimise the performance of the UV lamps used in the hospital based experimental work.

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