REVIEW

Some aspects of the airborne transmission of infection

Raymond P. Clark* and Mervyn L. de Calcina-Goff

The Society of Environmental Engineers, The Manor House, High Street, Buntingford, Hertfordshire SG9 9AB, UK

The relationship between the human body and the dissemination of potentially pathogenic particles and droplets is described. Airborne transmission of infection in operating theatres and a burns unit and the part played by the human microclimate and its interaction with ventilating air flows is discussed. The mechanisms by which different garment assemblies used for surgery can enhance particle dispersion are illustrated and the way that floor cleaning can increase the concentration of airborne organisms is described. The development of the successful use of ultra-clean air systems in orthopaedic implant surgery is reviewed. Relationships between contact and airborne transmission of disease are explored and ways by which containment strategies and metrics used in pharmaceutical and electronics manufacturing can be applied to the design and monitoring of healthcare areas is discussed. It is suggested that currently available techniques involving architectural, ventilation and operational aspects of healthcare provision, when properly applied, can markedly improve treatment outcomes that may otherwise be compromised by hospital-acquired infections involving both bacteria and viruses.

Keywords: airborne; transmission; infection

1. INTRODUCTION

Ways of reducing hospital-acquired infections have been studied for many years. Solutions for specific problems have often been devised by enthusiastic clinicians but implemented in a piecemeal way. In the 1970s, with the advent of antibiotic-resistant organisms and the development of orthopaedic implant surgery, there developed a need for a more systematic approach to contamination control that could produce better clinical outcomes by reducing hospital-acquired infections. For example, much effort was put into producing ultra-clean zones for implant surgery with considerable success and the techniques are now used worldwide. At the same time, the development of clean rooms for the production of microelectronic devices and pharmaceuticals provided techniques that could be transferred to the hospital.

Nowadays, the threat of infections is still of major significance in hospital environments and to the population generally. The prevalence of, for example, methicillin-resistant Staphylococcus aureus (MRSA), Clostridium difficile and TB infections where there is antibiotic resistance requires increasing effort in terms of physical containment and other engineering and management solutions to provide safe treatment facilities. Deaths from hospital-acquired infections are very significant in numbers and from the point of view of personal tragedy, and the cost of treatment for those who survive is extremely high.

Viral infections are now making world news and outbreaks of severe acute respiratory syndrome (SARS), H5N1 bird flu and H1N1 swine flu spread rapidly through communities and pose a great problem for the safe treatment of infected patients in hospital.

There are therefore continuing challenges to develop containment strategies in the built environment to reduce infection risks. This paper describes a number of interdisciplinary and related studies carried out over the last 30 years which, if properly combined and applied, in a modern context can provide a basis for comprehensive strategies that could reduce airborne infection risks in healthcare and other environments.

The topics in this paper are designed to follow a particular sequence showing how studies of the human microenvironment led on to practical contamination control work. First is the description of the human body and its physical and physiological interaction with the built environment. This is then

*Author for correspondence (ray@medi.demon.co.uk).

One contribution of 10 to a Theme Supplement 'Airborne transmission of disease in hospitals'.
specifically related to the hospital situation. Examples of the interaction between suitably clothed personnel in surgical operating rooms are described together with ways to quantify and visualize the effectiveness of such garments.

Next is a discussion about the environmental conditions that can be provided for surgery where the interactions of staff and building air systems can reduce the likelihood of airborne infection. This is followed by a description of the use of these methods in the design and operation of a sophisticated burns unit. Inter-relationships between airborne and contact transmission are considered and an example of the effects of floor surface cleaning on airborne contamination levels is given that can help in specifying safe cleaning regimes to take account of such effects. The next part of the paper develops quantitative approaches and describes how tracer methods can be used to measure containment levels in different situations (including the effects of staff moving around) and how such methods can be incorporated into national and international standards for patient treatment areas. Because of the increasing problems associated with virus transmission, this section also contains a description (not previously published) of the investigation of potential virus transfer during the last known outbreak of smallpox in 1978.

2. VISUALIZATION OF THE HUMAN MICROENVIRONMENT

The first systematic visualization and analysis of convective flow in the human microenvironment (the region a few centimetres from the skin surface) was carried out in the 1970s at the MRC in the UK (Lewis et al. 1969). A convective flow is established around the human body (clothed or nude) by virtue of the fact that the surface of the skin or clothing is warmer than the ambient air within the built environment. The temperature patterns on the skin are complex and determined by factors such as exercise, cutaneous perfusion under sympathetic neurological control, human morphology, environmental conditions, etc. (figure 1) (Clark et al. 1977a; Clark & Edholm 1985; Goff & Clark 1985; Jones et al. 1988).

Average skin temperature is frequently used in heat transfer calculations and is some 3°C (some 4°C below core temperature) in ambient temperatures of between 20 and 25°C. This leads to a temperature

Figure 1. (a) Thermal images showing the temperature map over the skin of two subjects at room temperature. Adjacent colours differ by 1°C, and there is a temperature difference between the warmest and coolest areas of more than 10°C. (b) Thermal images of a clothed subject showing a reduced temperature over the clothes at room temperature.
gradient of some 13°C between the skin and surroundings. The natural convective flow produced by this temperature difference was visualized over the whole body surface using the technique of Schlieren (Settles 2001) photography. This technique demonstrated graphically the thickness and speed of the flows produced (figure 2).

3. CONVECTIVE FLOW PARAMETERS

Subsequent measurements of the flow characteristics using a full-sized heated and breathing model of the human form and thermocouples and miniature hot wire anemometers together with calculations and estimates from Schlieren visualization produced the following figures for a nude standing subject at a room temperature of 20°C in still conditions (Clark 1973a, 1976; Cox & Clark 1973; Clark & Cox 1974a):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of air passing over the head</td>
<td>approximately 600 l min⁻¹</td>
</tr>
<tr>
<td>Maximum air velocity in the convective flow</td>
<td>0.25 m s⁻¹</td>
</tr>
<tr>
<td>Maximum thickness of the flow</td>
<td>0.15 - 0.20 m</td>
</tr>
<tr>
<td>Extent of the flow above the head</td>
<td>1 - 2 m</td>
</tr>
</tbody>
</table>

Such is the thickness of the convective flow that interactions between people can occur at body separations as great as 0.4–0.5 m.

Considerations of the temperature and refractive index gradients within the convective flow indicated that it was about twice as thick as that determined by the Schlieren visualization.

3.1. Postural variations

It was recognized that changes in posture produced different flow patterns and Schlieren photography has enabled the convective airstreams over the body in various postures to be visualized. Figure 3 illustrates diagrammatically the convective flow patterns for the lying, sitting and standing postures (Clark & Edholm 1985).

The above discussion is mainly related to humans in still conditions when natural convection predominates. This is rarely the case in practice. The human body is constantly in motion, and in ventilated/air-conditioned environments and out of doors, there is generally air movement to disturb the convective flow. In these cases, the body is subjected to forced convection.

One example of this is the environment within an infant incubator. Newly born babies require the protection of an incubator to provide warmth to grow but also to provide a ventilated and clean environment. Schlieren photography revealed that in some incubators the ventilating air flow was sufficient to completely disrupt the convective flows, which for a baby, are only some 0.04–0.05 m s⁻¹ (figure 4).

When the incubator air flows were re-configured so that they caused minimum disruption to the microclimate (Clark 1975; Clark et al. 1978) thermal imaging showed that there were fewer cold areas over the skin and the baby was more relaxed. Other factors such as the need to humidify while avoiding bacterial growth in water reservoirs and the prevention of airborne micro-organisms entering the canopy also need to be taken into account in the design.

When the body is in motion (walking or running) or is outside in a wind, the natural convective air flows are again modified. The disruption to the convective flow in the built environment when a person moves is very considerable and large volumes of air can be entrained to combine with the natural convective flows. Flows around the arms and legs are particularly complicated because of the ‘swinging’ or ‘pendulum’ motion of the limbs. This pendulum motion can dramatically increase heat loss by forced convection owing to the modified warm air streams (Clark et al. 1974). The unsteady wind outside also increases the forced convective heat loss. The modified nature of the airstreams in walking also causes a complex air flow that is further modified by the bellows actions of clothing as described below. The disruption can cause ventilating air flows to become less effective and compromise their ability to provide containment. This can be dramatically visualized using a theatrical fog machine or an industrial nitrogen fogger (as used to validate clean room ventilation systems) and have a subject walk through the fog cloud. In operating theatres where the maintenance of cleanliness around the operation site is paramount,
suitable procedures should be put in place to minimize the need for significant movements by the staff during surgery. Recently, studies on human wake patterns have been carried out by Edge et al. (2005).

4. THE ROLE OF THE CONVECTIVE FLOW IN PHYSIOLOGY AND PATHOLOGY

There are two important roles played by the human convective air flow. The first is that it contributes to physiological heat loss. This is some 30 per cent of the total body heat loss in still air or free convection conditions. In forced convection or when the body is in motion through the air, this proportion rises dramatically (Clark 1974a; Clark & Toy 1975a,b; Clark & Mullan 1976a; Clark et al. 1977b).

The second role is in the transport of particles that may be shed from the body or clothing or entrained from the surroundings. The convective flows can carry particles (with the density of water) upwards and at a size up to some 80 μm equivalent diameter. This means that practically all particles of biological or pathological interest can be moved by this convective flow (Clark & Cox 1973a).

Figure 3. Diagrammatic representation of the natural convective boundary layer flow generated over a subject in the standing, sitting and lying postures as visualized by the Schlieren technique. When lying, the flows are generally slower and thinner than when standing. Sitting produces flows that are intermediate between lying and standing.

Figure 4. Schlieren photographs of an infant nursed in an incubator. (a) The confused airflows over a neonate in a temperature-controlled incubator where the ventilating airflows are producing a forced convective situation thermally stressing the neonate. (b) Reduced ventilating air flows causing less disruption to the neonatal convective flow.
Of particular importance here are skin scales that are continually being shed from the body surface. Many of these carry micro-organisms that are termed commensals that ordinarily inhabit the skin surface and may be carried to the surroundings on these skin scales. Organisms from the respiratory tract can contaminate skin or clothing when they are dispersed through speaking, sneezing or coughing and afterwards they can become detached and entrained in the convective flow and also become important in handborne transmission.

As many as $10^6$–$10^7$ of these skin particles can be dispersed from the body in 24 h. They are detached from the body by movement and the rubbing actions of clothing. They can be sampled from air in occupied spaces and figure 5 shows two of the first scanning electron micrographs of skin scales on the surface before release and scales recovered from the air (Clark et al. 1970, 1971; Clark 1973b, 1974b; Clark & Shirley 1973; Clark & Cox 1974b).

The demonstration of the particle transport action of the human convective flow led to the realization of its potentially important role in cross infection. In consequence, considerable research was carried out into the part played by this flow in operating theatres and other hospital areas such as burns wards where patients are particularly susceptible to airborne cross infection.

Having established the convective flow as a link in the chain of general airborne infection, further research led to considering particular areas where the dissemination of potentially pathogenic particles needed to be controlled. In industrial clean rooms, skin scale and micro-organism shedding was seen as constituting a major problem in the contamination of products such as microelectronics and in pharmaceuticals where both skin particles and associated micro-organisms were potential contaminants. In hospital operating theatres, the convective flows could spread infection and pose a real threat to the outcome of surgery. Indeed, it is well accepted that the skin of staff and/or patients is the most significant source of infection for surgical procedures other than in abdominal surgery (Lidwell 1984).

As surgical operations became more advanced, the requirements for sterile conditions around the operation site became more rigorous. Progress in open heart and orthopaedic surgery (especially hip joint replacements) demanded great care from the operating team to guard against infection from airborne particles and droplets during the operation. Trends in immunosuppressive therapy and in open chest surgery required that these precautions be extended to vascular procedures and to intensive care and isolation units for the whole time that a patient would be at risk from airborne pathogens. Nowadays, with the prevalence of organisms such as MRSA and *C. difficile* and a range of viruses, the general hospital environment can be a reservoir for infection spread. The design and operational strategies for these facilities need to take this into account.

5. EFFECTS OF SURGICAL GARMENTS ON DISPERSAL OF ORGANISMS

The continual shedding of skin scales and micro-organisms and their dispersal from the microenvironment was considered in the design of clothing for use in the operating theatre. A basic set of surgical garments consists of a cotton surgical gown worn over a pair of cotton trousers and a vest, a pair of plastic boots (or other footwear), a hat and surgical mask completes the clothing assembly.

With body movement, the bellows or pumping actions of these garments together with the abrasive effect of the fabrics on the skin surface could detach and disperse skin scales which could subsequently become entrained in the boundary layer flow (Clark & Cox 1973a; Clark 1974a). This was shown dramatically using the Schlieren technique to visualize the air streams produced by this pumping action and is illustrated diagrammatically in figure 6.

6. GARMENTS COMPATIBLE WITH COMFORT AND REDUCED BACTERIAL DISPERSAL

Bethune et al. (1965) investigated the dispersal of *Staphylococcus aureus* from the body surface. They showed that this was mainly from the perineal region and that plastic underpants could reduce this dispersal. There was also interest at that time in using disposable

![Figure 5. (a) Scanning electron micrograph of skin scales nearly ready to be detached from the skin surface. (b) Scanning electron micrograph of skin scales sampled from the air.](http://rsif.royalsocietypublishing.org/Downloaded from)
plastic or paper garments for use in ultra-clean areas to reduce infection spread. Using the methods of Bethune et al., studies were carried out on the whole body dispersal of organisms from subjects wearing different garment assemblies (Clark & Mullan 1976b). The following garment assemblies were used in the study: open-weave cotton two-piece suit, cotton gown worn over the cotton suit, disposable plastic apron worn over the cotton suit and disposable spun bonded polyethylene two-piece suit worn in place of the cotton suit.

As well as evaluating the dispersal from these garment assemblies, assessments were made of their overall comfort and acceptability and representative results are shown in figure 7.

Although plastic two-piece suits allowed less dispersal of micro-organisms, disadvantages from aesthetic and comfort standpoints outweighed this and they were considered unacceptable for long-period use in intensive care or burns wards, although they were more acceptable in operating rooms.

Whyte et al. (1978) suggested that, although ordinary theatre clothing does reduce bacterial dispersal to some degree, any significant reduction requires occlusive clothing to be used; however, as indicated above, this may have adverse comfort consequences. Many of these comfort issues can be avoided by the use of mechanically ventilated clothing systems (Howorth 1984) that can give a reduction in dispersal at least 10-fold in comparison with traditional garments (Whyte et al. 1976). Studies of ergonomic and comfort aspects of ventilated operating room clothing confirmed the comfort superiority compared with traditional clothing (Ross & Clark 1988).

7. VISUALIZATION OF AIR FLOW THROUGH FACE MASKS

Early stroboscopic photography revealed the violence of a sneeze and the attenuation afforded by a mask (figure 8). Schlieren photography was used visualize the air flow modification produced by masks that are worn for surgery (figure 9). Some masks allow filtered warm, moist air to escape from the respiratory tract at a slower speed than normal and the expelled air can join with the convective air flows and be deflected upwards. Some masks have larger pore sizes and the expelled air comes through the fabric as many high-speed jets and appears to travel further from the skin than with the softer mask. The filtering efficiency of the masks will determine whether organisms in the expired flow penetrate the mask material and enter
the convective flow. Schlieren visualization appears to be a useful tool in the evaluation of masks suitable for surgery. More recently, very fine Schlieren images have been produced and analysed to give numerical values for the speed and extent of expired air (Tang & Settles 2008).

8. ENVIRONMENTAL CONDITIONS SUITABLE FOR SURGERY

Cleaner environmental conditions, leading to reduced probabilities for cross infection, can be achieved by a reduction of dispersal and by consideration of the above clothing factors. This needs to be combined with improved discipline and procedures and by the removal of dispersed organisms in as efficient manner as possible by suitable ventilation systems. It is considered that all of these elements need be in play at the same time for sustained improvements to be made.

Conventional turbulent ventilation systems have limited potential to reduce the level of airborne contamination and so ultra-clean unidirectional flow systems incorporating high-efficiency filters were developed (Clark 1977). These unidirectional ultra-clean air systems cause air to move through the working area in specific directions only and the air does not return to the working area except after passing through high-efficiency filters (HEPA). The air flows can be vertical or horizontal and can involve the whole room or only the working area, which itself may be separated from the rest of the room by partial walls (glass or plastic). The various configurations of ultra-clean...
ventilation systems can have a dramatic effect on air contamination levels, as shown in table 1 (Lidwell 1984).

The next question was whether or not such ultra-clean systems improved the clinical outcome for surgery.

The results of a multicentre long-term trial on the effectiveness of ultra-clean systems on deep sepsis following total hip joint replacement surgery showed that operations performed in an ultra-clean air system using ordinary theatre clothing experienced about half the sepsis rate of those done in a conventionally ventilated room (Lidwell et al. 1983). It was concluded that a good ultra-clean system should have no more than 10 bacteria-carrying particles per cubic metre at the wound site when used with conventional clothing. When body exhaust gowns were worn in the ultra-clean environment, the sepsis rate was less than half that achieved with conventional clothing (contamination levels at the wound site could be below 1 bacteria carrying particle per cubic metre with these garments). Interestingly, there was no significant effect of the ultra-clean air systems on the incidence of superficial wound infection.

In this trial, some hip replacements were carried out using inflatable plastic isolators covering most of the patient with the surgeon and staff working through gloves attached to the isolator. Measurements showed that the air inside was sterile but that airborne particle counts during surgery showed extreme increases when the powder components of the acrylic cement were being mixed. Such high concentrations of non-pathogenic particles were nevertheless considered to pose a hazard to the wound site where the possibility existed for cellular changes to occur over time owing to the presence of the foreign particles even though they were sterile.

### Table 1. The approximate average airborne bacteria-carrying particles per cubic metre of air during total hip joint replacement surgery.

<table>
<thead>
<tr>
<th>ventilation system</th>
<th>airborne bacteria-carrying particles per cubic metre of air</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>clothing</td>
</tr>
<tr>
<td>conventional turbulent</td>
<td>164</td>
</tr>
<tr>
<td>unidirectional flow—horizontal</td>
<td>22</td>
</tr>
<tr>
<td>unidirectional flow—vertical, no walls around the operation table</td>
<td>10</td>
</tr>
<tr>
<td>unidirectional flow—vertical, with walls around the operation table</td>
<td>2</td>
</tr>
</tbody>
</table>

9. DESIGN AND OPERATION OF A SOPHISTICATED BURNS UNIT

Between 1973 and 1976, aerobiological studies were conducted at a specially constructed burns unit to the north of London (Clark et al. 1975; MRC Burns Research Team 1979). This was a 12-bed ward with four intensive care beds. Two intensive care rooms were equipped with the so-called ‘hoverbeds’ (Sanders et al. 1970) and two with ‘low air-loss beds’ (Scales & Hopkins 1971). The unit had varying degrees of positive or negative pressure depending on the isolation required for the various parts of the unit. In this way, all 12 rooms were protected, to a large extent, from airborne cross contamination by suitable air pressure differences.

The four intensive care beds were equipped with ultra-clean down-flowing air systems similar to those being developed at the time for orthopaedic implant surgery (figure 10). Barrier nursing techniques were employed throughout the unit and the restrictions on access, dress and procedures were extended to visitors. In the intensive care rooms, by and large, the patients were nursed with burns exposed to the down flowing sterile air streams. The principle of the hoverbed was to dry the burn to form a stable eschar as soon as possible both to prevent excess loss of body fluids and to stop the ingress of organisms that could cause infection. Once this had been achieved, the low air-loss bed was used to maintain patient support and avoid the development of pressure sores.

Severe burns are very susceptible to infections and the fluid loss from burned skin means that it is moist and evaporation from the surface of the patient is high and made more so by the increased evaporation caused by the down-flowing air streams of around 30 cm s\(^{-1}\). This meant that for patient comfort alone (to stop excessive heat loss and shivering) the dry bulb air temperature of the ultra-clean air streams was often in excess of 30°C. Such warm conditions were stressful for staff who wore impermeable clothing (as described above) in order to reduce skin and bacteria shedding. These environmental conditions were in comparison with the cooler conditions needed by the operating team in ultra-clean theatres of similar design.

Studies were conducted on the heat loss potential for patients at different down-flow air temperatures and air flow rates and these were related to the bacterial and particle contamination levels surrounding the patient (Clark 1974c; Clark & Edholm 1985; Nicholson et al. 1999). As already mentioned, for a supine patient, the convective air streams are slower than when in the standing position. Down-flowing ultra-clean air can modify the convective flow (possibly even stopping convective heat loss) by reducing the temperature gradients in this quasi-forced convective situation.

This work emphasized the increased complexity of thermal and airborne bacterial considerations in areas where patients were nursed for extended periods compared with short-period use of operating theatres.

Such was the severity of many of the burns treated in this unit that it was difficult to demonstrate any improvement in mortality rates by what were by any standards horrific injuries. Before any intensive treatment was begun, it always needed to be borne in mind that generally a burn was not survivable if the age of the patient added to the percentage of total skin area burnt to full thickness exceeded 90.
10. SURFACE AND AIRBORNE CONTAMINATION

Although this paper is concerned mainly with airborne transmission of organisms, there are reasons to consider features that are frequently inter-related where contact infection acts alongside the airborne route. Airborne particles that sediment onto surfaces become candidates for infection spread by contact: they may be further disturbed mechanically and made airborne again and the cycle can continue. Without such mechanical disturbance, it is difficult to dislodge particles from surfaces as the attractive forces are considerable and particles are unlikely to be moved by air movements at the levels encountered in the built environment where the shear forces in the airstreams are low.

People walking around can re-disperse dust particles from the floor (at the same time as shedding skin flakes from the body) (Bagnold 1960) and mechanical floor cleaning can substantially increase airborne particle concentrations.

An example of the effects of floor cleaning in an operating room is given below.

Studies were carried out to measure the changes of airborne bacteria and particle concentrations in a number of size ranges and floor settling contamination was also assessed in a turbulently ventilated operating room under full flow, half flow and zero flow conditions (Clark et al. 1985). Figure 11 gives typical results for the increase of airborne bacteria during cleaning.

Clearly, cleaning procedures that can increase airborne particle and micro-organism levels have important implications for wards and other hospital areas as well as operating rooms.

One outcome of this study was a proposal that, in the interests of energy economy, the ventilation in operating theatres that were not in use, overnight say, could be turned off as long as the system was turned on at least 1 h prior to surgery.

Corn & Stein (1966) concluded that ‘the most likely mechanism for the contamination of air by particles re-dispersed from solid surfaces involves the transfer of momentum from the activity of human beings’. This ‘momentum’ can be said to be present in the direct transfer of organisms from contaminated surfaces by the act of touching. This method of transfer and its control is presently receiving much attention and it is thought that MRSA and C. difficile infections are often transmitted by the ‘handborne’ route. Because of this, frequent hand washing and antiseptic gel application procedures are being promoted together with the use of disposable aprons, etc.

Antimicrobial surfaces are also being researched. Copper has anti-microbial activity and is one material where some success is claimed. The viability of S. aureus, Echerichia coli, Klebsiella pneumoniae, Acinetobacter baumannii, Enterococcus spp. and Candida albicans was progressively reduced over 3 hours on copper but not on stainless steel control surfaces (Noyce et al. 2006; Wheeldon et al. 2008).
Copper toilet seats, door push plates, tap handles, grab rails and light switches have been used in a pilot study where the copper-containing items harboured fewer micro-organisms than standard items on a control ward.

11. USE OF TRACERS TO MIMIC THE MOVEMENT OF PATHOGENS IN HEALTHCARE FACILITIES

In the late 1970s and 1980s, there was an intense activity to develop safe systems for handling pathogenic material and to demonstrate their effectiveness. In the UK, this was given impetus by the outbreak of smallpox described below. In particular, there was concern that microbiological safety cabinets (biohazard cabinets) that were used in hospitals and research institutions were not safe and could actually cause pathogens to be transmitted by the airborne route. A number of national standards were published worldwide and the UK government issued a series of reports and guidelines (Howie 1978).

Much of the concern about safety cabinet performance had come about because Schlieren visualization of airflows at the front of some of these cabinets had shown that potentially contaminated air could escape into the laboratory after enveloping the cabinet worker, as shown in figure 12 (Clark & Mullan 1978).

This work initiated new cabinet designs with greatly improved performance and also spawned an industry that would undertake maintenance and performance tests of cabinets on site. The concept of containment testing became generally accepted. In order to do this safely, quickly and accurately, a system known as potassium iodide (KI) Discus was developed (Clark & Goff 1981), the use of which is now incorporated into the requirements of national and international standards.

Before being adapted for safety cabinet (and fume cupboard or fumehood) work, the KI system had been used to trace particle movements through hospital buildings and had been compared with gas tracer systems (Foord & Lidwell 1972, 1975).

The principle of the KI system is that a small spinning disc generator produces a well-defined aerosol of KI droplets that rapidly evaporate to solid particles.
These are released in an area that is segregated from the surroundings by air or physical barriers. Special air samplers designed selectively to sample the KI particles are placed in ‘clean’ areas that are to be protected from contamination. By knowing the numbers of particles generated and the numbers sampled, it is possible to calculate a ‘protection factor’ that characterizes the protection between clean and potentially ‘dirty’ areas.

The system was used to determine the protection afforded by rooms at differing negative pressures with relation to the surrounds from which they were separated by airlocks (Clark 1983, 1995). Figure 13 shows an example of the way that the protection afforded varies with different negative pressure in a room with a double airlock.

The KI system was also used to evaluate the containment properties of an isolation ward within a burns unit (Nicholson 1995). It has also been used on a number of occasions to determine the ‘protection’ factor of laboratories used for handling pathogenic material and combining this performance with safety cabinets and fume cupboards that may be housed within the laboratories.

Additionally, the method was used to evaluate a smallpox laboratory as described below.

The KI system provides a safe and effective way of quantifying and monitoring the containment or isolation of sensitive hospital areas and of evaluating the effects of patient and staff movement, door opening events and any other activity that may be performed within the contained area. Sometimes, these areas will be designed to prevent a patient being exposed to infective agents from outside the facility and on other occasions infective patients need to be effectively isolated from the rest of the hospital. The concept of quantifiable containment coupled with regular airborne particle counts seems a sensible way forward for the design and operation of a range of healthcare areas within a hospital and is an approach that could be subject to standardization and validation.

12. COMPUTATIONAL FLUID DYNAMICS

It is important that hospital areas are properly assessed in terms of air flows and their interactions with humans. Comparisons have been made between gas and particle tracer methods and the relatively new technique of computational fluid dynamics (CFD) in a burns unit both as designed and after various changes had been made in consequence of shortcomings found in the performance of the original design. General conclusions were as follows.

(i) CFD was found to be useful in predicting how a design would function but not necessarily how it actually did function when built. It was still necessary to carry out physical tests to validate and commission the facility.

(ii) It showed great potential as an analytical tool for predicting the effect of design changes. In some instances, alterations that may have been thought to be beneficial could actually reduce performance.

(iii) CFD had the advantage over physical measurements in being able to ‘visualize’ airflows and contaminant dispersal within any region or plane in the facility. For the assessment of cross contamination, CFD enabled the position of the source to be placed anywhere. Physical measurements would be very limited in the number of assessments that could be made and CFD could be very useful in selecting the most suitable positions for experimental validation.

With the development of increasingly powerful CFD programmes, this technique may well become more versatile (Hathway et al. 2008) but at present it is still necessary to validate the method with direct physical assessments, especially when modelling human movement that may disrupt expected levels of containment. Scale models (including those using water) can...
also provide useful information as to how full-sized facilities will perform and they can also help in the validation of CFD simulations.

13. ELECTRONIC PARTICLE COUNTING TO EVALUATE OPERATING THEATRES

The design performance for an environment suitable for surgery could be defined by the number of bacteria-carrying particles per cubic metre, and in an ultra-clean operating theatre, this has often taken a value of 10. However, the results of bacteriological air sampling in theatres are known only some 24 h after sampling has taken place. Real-time particle monitoring of the air cleanliness at the operation site can give early warning of performance changes and can also form part of the audit trail for management of facilities suitable for surgery.

Electronic particle counting was compared with bacterial air sampling (Seal & Clark 1990) in an ultra-clean and a turbulent ventilated theatre. The results showed that particle counts in the 0–20 µm size range were sensitive to various activities and could be used to judge the performance of an ultra-clean air operating theatre including the efficiency and integrity of filter/ seal systems and the presence or absence of entrainment of bacteria and other particles. The sampling techniques and analysis reported were considered to be a suitable basis for standards. For turbulent ventilated theatres, particle counting techniques were not so well related to and could not replace bacterial counts.

The development of ‘multipoint’ sampling systems built into ultra-clean operating theatres could enable continuous online monitoring and also allow the automatic adjustment of air flows to pre-set particle concentration levels.

14. AIRBORNE TRANSMISSION OF VIRUSES

The work on reducing sepsis in the operating room carried out in the 1970s and 1980s made little reference to the transmission of viruses and indeed it was stated that ‘The respiratory tract viruses generally have no significance for surgery’ (Lidwell 1984). This may have been the case but the principles of dispersion and dissemination from the human body and the route of cross infection that involved the human convective flow were, and still are, relevant to the transmission of viruses in the built environment including operating rooms.

A notable example of this was the last known outbreak of smallpox in the world that occurred at the Birmingham University Medical School in the UK in 1978 (Lidwell et al. 1980). There was an apparent escape of virus from a smallpox laboratory leading to an infection and the death of a worker on the floor above the laboratory. The question was whether this could have occurred by transfer of airborne particles carrying the virus. There were, of course, innumerable routes by which virus transfer could have taken place including by foul play (not ruled out in the investigation). However, the object of the investigation was to discover whether there were any routes capable of transferring significant amounts of dispersed material to places where there might be a risk of infection for susceptible individuals.

The smallpox laboratory was in an old part of the building that was naturally ventilated. The laboratory contained two safety cabinets used for handling the virus. One was working satisfactorily and the other was not and had not been serviced or maintained for 10 years prior to this incident.

The KI system described above was used to trace particle movements around the medical school building. Two spinning disc KI generators were operated in the smallpox laboratory and some 20 air samplers were placed at strategic positions in rooms and corridors throughout the building.

The experiments demonstrated without any doubt that airborne particles could and did escape from the smallpox laboratory and could reach sensitive un-restricted areas. In addition to transfer to a corridor outside the smallpox laboratory and an adjacent seminar room, there was readily demonstrable and consistent transfer to a laboratory on the floor above the smallpox laboratory. This room was significant in the investigation as it contained a telephone in close proximity to a service duct (presumed responsible for the transfer) that was regularly used by the worker who died.

The particles of KI used in this investigation had a settling rate of about 30 cm min$^{-1}$. This is of the same order as that found for many naturally dispersed micro-organisms, both bacteria and viruses attached to carrier particles such as skin scales. However, it is quite possible that dispersal of much smaller particles may occur in some circumstances, especially from cultured materials. In this case, the losses by sedimentation would be less and the potential dose for a given dispersal greater. With small particles, it was estimated that the potential dose transferred could then be as much as 10 times greater than the values observed with the tracer particles. This difference is comparable to that found in a previous hospital study where the difference between the transfer of gas and tracer particles of KI varied between eight and 45 times depending on the distance between the source and receiving rooms (Foord & Lidwell 1975).

At that time, it was not widely acknowledged that smallpox viruses could travel by the airborne route and remain viable. The results from the UK government enquiry were never able to establish with certainty the cause of the outbreak. However, it may fairly be said that none of the containment facilities at Birmingham came anywhere near to those recommended at the time and that this coupled with suspect techniques could well have been responsible for the outbreak. It is altogether possible that a spillage of virus could have resulted in an infective dose being transmitted to the ‘telephone’ room.

15. SUMMARY

One of the most important aspects of the work described here was to take the results of various
visualization modalities and to quantify the phenomenon observed. In this way improvements in equipment and techniques may be specified that eventually could become the basis for standardization in healthcare. It is now possible to combine all of this knowledge and the techniques developed to tackle the infection issues of today.

The recent outbreaks of SARS, H5N1 bird flu and most recently swine flu H1N1 have focused attention on the airborne transmission of viruses that may be released from the respiratory tract, sometimes with great force. Schlieren photography has been used to great effect to help visualize and understand the patterns of exhaled air near to the body. Other visualization techniques have shown how these air streams may be modified, for example by oxygen administration masks (Hui et al. 2006).

The airborne transmission of viruses is now well accepted and the question of how far virus particles can travel and remain viable has received much attention in recent times. Their viability is dependent on a number of factors:

(i) their type—with or without structural lipids,
(ii) whether they travel on or within larger particles or droplets,
(iii) time of airborne travel, and
(iv) the temperature and humidity of the environment.

However, they are aerosol particles and well able to travel in the air streams found both indoors and outside. They move in ways which are increasingly understood and where tracers can give a good indication, in many situations, of where they can travel and in what concentrations.

There are clearly important and emerging issues in caring for patients who disseminate virus within healthcare premises, in terms of both protecting staff and stopping the wider spread of the infection. It is therefore vital that attention is given to the fate of virus particles once they have been discharged from the respiratory tract. This is where the quantification and management of containment facilities becomes an important part of the design and monitoring of hospital areas.

Coupled with this must be the provision of suitable assessed protective clothing and the implementation of rigorous procedures for medical and nursing staff. Effective face masks have an important role both in the hospital environment and possibly in the wider community. Modern materials and nanotechnology may well lead to the development of more effective masks.

The provision of ventilation systems must be carefully designed to remove airborne contamination as soon as possible after it has been generated. Filtration systems must have their integrity regularly checked and be able to be fumigated along with the treatment rooms. Online particle counting systems can provide continuous monitoring of ventilation performance.

It is now quite possible to design and test treatment rooms, etc., for quantifiable containment as has been described in this paper using the KI test system. This is perhaps one of the easiest and most cost-effective ways to test and produce rooms and isolation units with quantifiable levels of containment. On-going real-time monitoring of cleanliness using multipoint particle measuring systems is also now possible. Contact cross infection and the provision of properly cleanable surfaces also need to be incorporated and cleaning regimes need to be introduced that are microbiologically neutral. Hospital designers should consider provision of single rooms rather than larger wards.

In a recent review of factors involved in the aerosol transmission of infection, Tang et al. (2006) give an important list of references to work done that involves control of infection in healthcare premises and references Li et al. (2007), Roberts et al. (2006, 2008), Allen & Green (1987), Beggs et al. (2008) and Qian et al. (2006) are also a valuable source of further studies.

16. CONCLUSION

Hospital-acquired infections still account for some 5000 deaths a year in the UK (up to 80 000 in the USA) with an additional 15 000 serious treatable infections that result in a cost in excess of £1 billion a year. Many of these problems are avoidable.

Cross infection by the airborne route in operating rooms has been shown to be reduced with properly designed and working air ventilation systems and associated appropriate procedures. During surgery, contact and handborne transmission can also be managed to a large degree. However, in a ward, the problems of cross infection can be more difficult to control. Here the modalities of contact, airborne and handborne infection are interlinked in complex ways. Reduced infection by the airborne route needs to have architectural and air ventilation systems that are robust and where their effectiveness at providing quantifiable containment is routinely checked with meaningful metrics. Contact and handborne transmission should in theory be easy to achieve by management of work procedures and by visible measures such as hand disinfection. However, one of the most difficult things is to ensure that the work culture introduces and sustains such procedures in an effective way. It is naive to think that hand washing/disinfection alone will solve cross-infection problems in busy wards and other hospital areas where patients, visitors and staff can mix in an uncontrolled way. Any solution requires a holistic ‘joined up’ approach.

Architectural, bioengineering and operational strategies, if applied in a properly integrated way and with suitable encouragement for culture change, can be expected to overcome many cross-infection issues and allow patients to be treated more predictably and cost effectively. Our understanding of the mechanisms involved in cross infection of all kinds is now adequate to engineer and manage far better clinical outcomes than we have at present.

Despite the considerable body of knowledge gained over many years, some of which is described and referenced here, on the mechanisms of infection spread in hospitals, little has been done to radically redesign...
hospitals with contamination control at the forefront. This is due to a number of factors. New hospitals are often designed by architects with little experience of the function of contamination control. In other situations, designers are often hampered by not being able to implement features that are radical or that do not appear in national guidelines which frequently specify, in some detail, how a hospital should be constructed. Where hospitals are built under Private Finance Initiative schemes, and where a hospital is then leased back to the healthcare operator, there can be further operational difficulties in deciding areas of responsibility and funding when maintenance and building changes are needed. In such circumstances, it is virtually impossible for new designs to be trialled if they are outside nationally accepted norms. Once a hospital has been built on traditional lines, a retro-fit for greater patient protection is rarely an option. In many cases, the provisions for contamination control, particularly in relation to air-handling systems for ventilation, do not operate as designed. Usually, the hospital staff have not been trained to monitor such systems and report faults and in many cases the engineering controls are over complex with poor reliability and inappropriate performance monitoring.

With the increase in viral infections and the possibility of pandemics when large numbers of patients will have to be treated and where many others will be at risk of catching such infections, now is surely the time to invest in radical new design and management strategies to improve the treatment of patients. Ideally, such new designs would have greatly improved the performance that could become embedded in national and international standards (and even legislation) in due course, much in the same way that facilities for electronic and pharmaceutical manufacture have evolved to be fit for purpose.

All of the studies that have been carried out and the recommendations made will be for naught if improvements in hospital design and operation are not able to be implemented.

It would be possible to demonstrate (and this has been proposed recently) how a raft of strategies can work to produce an evolving, evidence-based and validated model of what may realistically be achieved within existing cost regimes in these vital areas of healthcare. This would involve the combined skills of bioengineers, human physiologists, healthcare professionals, psychologists and constructors. The goal would be to define, specify and mobilize technical, organizational and managerial skills to address the problem of safe and contamination-free patient handling within the built environment. Parallels to the skill sets necessary for the cultural changes required are available from sections of the car and aero manufacturing industries.

Finally, we do not believe that anybody would suggest making hi-tech electronic equipment or manufacturing pharmaceuticals (both of which have to be contamination free to satisfy consumer markets and regulators) in unsuitable environments. As medical care becomes increasingly sophisticated, so does the need for more appropriate hospitals and operational procedures to improve clinical outcomes. It could be argued that many modern hospitals are not the right places to practise modern medicine.

DVDs illustrating some of the points made in this paper, including Schlieren visualization, are available at nominal cost from the authors.

REFERENCES


Clark, R. P. 1974b Skin scales among airborne particles. J. Hyg. 72, 47–51. (doi:10.1017/S0022172400023196)


Clark, R. P. & Cox, R. N. 1974a An application of aeroa

Clark, R. P. & Cox, R. N. 1974b An application of aeroa
tical techniques to physiology. 2. Particle transport within
Clark, R. P. & Toy, N. 1975a Natural convection around the human head. J. Physiol. 244, 283–293.
Clark, R. P. & Toy, N. 1975b Forced convection around the human head. J. Physiol. 244, 295–302.
Foord, N. & Lidwell, O. M. 1975 Airborne infection in a fully air-conditioned hospital. II. Transfer of airborne particles between rooms resulting from the movement of air from one room to another. J. Hyg. Camb. 75, 31–44. (doi:10.1017/S0020221400047015)
MRC Burns Research Team 1979 An assessment of the effect of air support systems in the treatment of major burn injury, including an account of the experimental unit which was built to enable this extended clinical trial to take place. Available from Medical Research Council, London.
Qian, H., Li, Y., Nielsen, P. V., Hyldgaard, C. E., Wong, T. W. & Chwang, A. T. 2006 Dispersion of exhaled droplet nuclei in a two-bed hospital ward with three different


Settles, G. S. 2001 *Schlieren and shadowgraph techniques: visualizing phenomena in transparent media.* Berlin, Germany: Springer-Verlag.


