The effect of mechanical ventilation and clothing on airborne microbes and wound sepsis in hospital operating rooms, Part 1

W Whyte

School of Engineering, University of Glasgow, Glasgow G12 8QQ

Editor's Note: *For 50 years, Bill Whyte has been investigating the role of mechanical ventilation in minimising airborne microbial contamination. The first 25 years were used to investigate hospitals, and the second 25 years were concerned with industrial cleanrooms. His work on operating rooms occurred at an important time in the evolution of the design of unidirectional airflow systems, and when their effect on wound sepsis after surgery was determined. It is common to find that the experience and judgement of scientists who have worked extensively in a particular field of science is lost, and so we have persuaded Bill to write a personal account of this time. His reminiscences are divided into two parts, this being the first.*

Abstract

This article is the first part of a review of investigations carried out until about 1990 into the role of mechanical ventilation in reducing wound sepsis in hospitals. It deals with the design of mechanical ventilation systems to reduce airborne microbe-carrying particles (MCPs), and mainly discusses unidirectional airflow (UDAF) systems. The second part will deal with the effect of mechanical ventilation and occlusive clothing in operating rooms in reducing airborne MCPs and post-operative wound sepsis.

Introduction

This review is based on a commentary written prior to submitting a DSc thesis, which was used to explain the research I carried out during the 25 years before 1990 in the context of other research. The review is divided into two parts, this part being the first.

The author's publications are referenced as follows: (Reference 1 etc.). A superscript number is used for the works of others.

Airborne microbes and surgical infection: the early days

Isolating microbes from air occurred at the birth of microbiology to prove that fermentation and putrefaction were caused by microbes and not spontaneously, i.e. to prove the germ theory of disease. Pasteur in 1861[1] was able to estimate the number of bacteria in air by introducing a known volume of air into sterile containers and counting the number of containers that became infected. Knowledge of the germ theory of disease prompted Lord Lister in the 1860s to investigate the reason for wound sepsis and achieve a dramatic reduction by the application of carbolic acid (phenol) to the wound, wound dressings, and instruments[2]. Lister also sprayed carbolic acid into the air in the hope of killing airborne bacteria but by 1890 he concluded that the spray had not contributed to his success. Lister's antiseptic approach to surgery was superseded by aseptic surgery, where anything brought into the wound area was sterilised. The proponents of aseptic surgery made no attempt to prevent airborne infection, and it was not until after the 1939-1945 world war that a strong interest in airborne infection was rekindled.

During the 1939-45 world war, investigations were carried out into airborne infection of burned service men, infections transmitted in overcrowded conditions in barracks and ships, and the generation and sampling of airborne microbes that could be used in microbiological warfare. In 1941, Bourdillon, Lidwell and Thomas[3] invented the first efficient microbial air sampler known as the Casella slit sampler. After the war, scientists knowledgeable in the transmission of airborne microbes were in place to ascertain the importance of airborne infection during surgery.

After the 1939-45 war, it had been hoped that the invention of antibiotics would solve the problem of hospital infection. However, antibiotic resistance developed, and this was often associated with the development of more virulent hospital strains of pathogenic bacteria such as *Staphylococcus aureus*, which were a major cause of wound sepsis. When an effective method of typing of *Staphylococcus aureus* by bacteriophage, which are viruses that selectively attack bacteria, was published by Blair and Williams in 1961[4], a significant tool was in place for studying wound infection in hospitals.

The effect of mechanical ventilation in a surgical ward on the transfer of microbes and wound sepsis

The author's first research work was in hospital surgical wards. An experimental ward was built at Hairmyres Hospital in East Kilbride by the UK National Health Service and was sub-divided into 1, 4 and 5-bedded rooms, and air conditioned with 7-8 air changes per hour of filtered air. It was the first ward of its type built by the UK health service, and they wished to know how well it performed.

The microbial effectiveness of the air conditioning plants that supplied the ward was studied (Reference 1) with respect to (a) the particle size, concentration, and types of microbe-carrying particles (MCPs) in fresh and recirculated supply air, (b) the effectiveness of air filters in removing MCPs, (c) microbial growth in air filters dampened by humidifiers, (d) microbial aerosols (humidifier spray) caused by microbial growth in the humidifier water tanks and, (e) microbes on duct surfaces.

Experiments were carried out into air movement between rooms and the degree of protection provided by positive, negative and balanced air movement control systems, air supply volumes, and the time doors were open (Reference 2). The air movement across open doorways was also found to be influenced by temperature difference, and a further study was carried out

(Reference 3). This showed large airflows were caused by temperature differences. For example, a transfer of 0.19m^3/s in each direction occurred across an open doorway of 2.05m x 1.40m when there was no temperature difference, but increased to 0.24m^3/s when the temperature difference was 2°C. To prevent such airflow, 0.75 m^3/s had to pass through the doorway when the temperature was 1°C, and 1.05m^3/s when it was 2°C. It was not practical to provide sufficient air volume to counteract large temperature differences, and it was best to ensure the temperature difference did not exceed 1°C. In that case, an airflow of about 0.26m^3/s for each square metre of door area is required for a temperature difference of 1°C.

Information was also obtained about air transfer between adjacent rooms (Reference 4) when, a) air passed through cracks round a closed doors, b) a person opened a door, passed through, and shut it, c) a person walked through a doorway; these variables were investigated in relation to temperature difference. The information about airflows across both open and closed doors was used to design the air movement control system described in DHSS Working Group 10 Report (Reference 5), and further discussed in the next section.

A comparison was also made of the microbial transfer between patients in the experimental ward compared to two older open wards that were ventilated only by windows (Reference 6). Patients admitted to all three wards had nasal swabs taken on admission and twice-weekly. Any *Staphylococcus aureus* isolated were typed, and rates of nasal acquisition, which were considered to be indexes of airborne transfer, were determined.

It was found that the nasal acquisition of new strains of *Staphylococcus aureus* was somewhat less in the experimental ward, and this was particularly noticeable in patients during their first two weeks of residency. However, there was no difference in the acquisition of antibiotic-resistant staphylococci, which were (at that time) mainly found in hospitals and considered a good indicator of hospital-acquired infection. Wound sepsis rates after surgery were also compared between the experimental and open wards, and it was found that sepsis caused by all types of bacteria, and by only *Staphylococcus aureus*, was not lower in the experimental ward.

The above results suggested that mechanical ventilation of wards was unlikely to give a significant reduction in sepsis after surgery. A further study of a mechanically ventilated ward, and a review of similar studies, was carried by Lidwell et al[5] who reached the same conclusion. This suggested that the author's research might be more fruitfully directed towards the use of mechanical ventilation in operating rooms to reduce wound sepsis.

Design of conventionally-ventilated (non-unidirectional) operating rooms

Prior to the 1960s, in the temperate climate of the UK, it was not unusual for operating rooms to have no mechanical ventilation or, more commonly, to have an extractor fan on the outside wall to expel warm air to the outside. However, extract ventilation caused contaminated air to be drawn into the operating room, which often came from adjacent surgical wards. This problem was studied by Shooter et al[6] in an operating room that had a small supply of fresh, filtered air but a greater extract volume, so that air was drawn into the operating room from adjacent hospital areas. This caused the airborne bacterial concentration during surgery to be as high as 1400/m^3. When the extract ducts were blocked off, and the air supply increased to positively pressurised the operating theatre, the airborne concentration was reduced by about 3-fold. A very similar problem and solution was reported by Blowers et al[7].

It was clear from the above studies that large volumes of filtered air should be supplied to the operating room to both positively pressurise the operating room against the ingress of bacteria and dilute microbes dispersed by the operating team. Blowers and Crew[8] concluded that 1200 ft^3/min (0.6 m^3/s) of fresh filtered air was required, along with the use of pressure-relief dampers to maintain pressurisation of the room and divert air through a door when opened. Improvements to the ventilation of an operating room were shown by Shooter et al[5] to decrease wound sepsis. Blowers et al[7] carried out a similar study, and although he concluded the reduction of sepsis was caused by improvements in ventilation, other improvements were made at the same time. However, Lowbury[9] carried out a scientifically designed trial and showed that 20 air changes per hour of filtered air significantly reduced infection in a burns dressing room.

In 1972, a Joint Working Party (JWP) of the Department of Health and Social Security (DHSS) and the Medical Research Council (MRC), chaired by Dr OM Lidwell, of which I was a member, produced a report entitled 'Ventilation in Operation Suites' (Reference 7). This set the requirements for conventionally-ventilated operating rooms in terms of air supply volumes, air filtration, recirculation of air, control of airflow through doorways, dilution of anaesthetic gases, and comfort of staff. Information obtained at the Hairmyres experimental ward (References 1 to 4) was used in this report.

The JWP report laid down ventilation requirements but did not give practical engineering information on how to achieve these. Inter-authority Engineering Working Group 10, of which I was a member, was therefore set up by the DHSS to produce a design guide to fulfil the recommendations of the JWP. This guide was issued in 1983 and called 'Ventilation of Operating Departments – a Design Guide' (Reference 5). A difficult requirement of the brief was the achievement of an air movement control scheme to ensure that contaminated air did not flow into clean areas when a door is opened, and about half of the guide was devoted to this. Peter Robertson, Jeremy Cockcroft and I, of the Building Services Research Unit, University of Glasgow, developed a method to achieve this (Reference 8 and 9) that was incorporated into the Working Group 10 report. Much of the information in the Working Group 10 Report was transferred into the Hospital Technical Memorandum 2025[10], and is now in the current Health Technical Memorandum 03-01[11].

Conventionally-ventilated operating rooms built to the principles given in the above reports gave airborne microbial counts during surgery of between 50 and 400 MCPs/m^3. This upper level is higher than that set by the JWP Report and HTM 30-01, and occurs if there is a high activity and a large number of people present, as in orthopaedic implant operations carried out in teaching hospitals. However, ultra-clean operating rooms, mainly of the unidirectional airflow type, were now becoming available and could give substantially lower concentrations of MCPs.

Evolution of unidirectional airflow (UDAF) operating rooms

In their 1960 research article, Blowers and Crew[8] reported an attempt to obtain a downward 'piston' of air (unidirectional airflow, although they did not call it that) from an air diffuser (a hessian sheet) fitted over the complete operating room ceiling. They used a similar amount of air supply volume as a conventionally-ventilated operating room, and the downward velocity was therefore low. Because of this, thermal air currents from people and the operating room lamp, as well as movement of people, disrupted the airflow and it was not possible to achieve unidirectional airflow. This was the situation in 1961 when Professor Sir John Charnley, with assistance from Hugh Howorth of Howorth Air Conditioning decided to improve the ventilation in his operating room.

Charnley was a pioneer of hip joint replacement surgery and devised an operation to replace a diseased joint with an artificial plastic and metal joint. The implantation of such a large amount of foreign material, with a large exposure of wound, in an operation that could last up to two hours, gave an initial sepsis rate in Charnley's very poor airborne conditions of about 9%[12, 13]. This was a major problem, as antibiotics often did not clear this sepsis and the artificial joint had to be replaced. To reduce sepsis, Charnley initiated a number of preventative measures and, using the knowledge that existed at the time (1961), Howorth and he attempted to perfect the 'piston effect' of a downward flow of air. Instead of using the whole ceiling (as Blowers and Crew had done) they restricted the air supply to a small area by using a 7ft x 7ft-area 'greenhouse' placed within the operating room. This increased the downward velocity of the air, and a reduction of the concentration of MCPs. This was described in 1964[14] and the airflow is shown in Figure 1.

In 1965, Allander published a description of a system which also used a small ceiling area to increase the air supply velocity over the operating table. The description was published in Swedish but the system is described in English in a US Patent[15]. The air was supplied through a perforated ceiling but, instead of using walls to constrain the downward air flow, Allander used air curtains. This system gave a lower airborne MCP concentration (about 50/m^3) than conventionally-ventilated operating rooms.

Both Charnley's and Allander's designs did not produce good unidirectional airflow, but were a large step in the right direction. Charnley and Howorth increased the air supply volume and incorporated ideas from 'laminar' (unidirectional) flow systems, so that good unidirectional airflow was achieved. Charnley also designed the total-body exhaust gown, which used tightly-woven cotton (Ventile®) and exhausted air from the gown (Figure 2). The dispersion of MCPs from the surgeon was substantially reduced, and, hence, the airborne concentration in the operating room.

Charnley found that improvements to the ventilation of his operating room and use of occlusive clothing substantially reduced the airborne concentration of MCPs. This was paralleled with reductions in deep hip sepsis[12, 13] from about 9% in 1959, when his airborne conditions were very poor, to less than 1.0% by 1970 when all his improvements were complete. However, his changes were not set up as a scientifically designed trial, as changes were introduced step-by-step, and also included changes to surgical technique. It was also unclear if a modern conventional operating room would give suitable airborne conditions and there was a strong lobby that was doubtful of the role of unidirectional airflow systems[16]. To confirm, or otherwise, Charnley's work, a trial of ultra-clean operating rooms was carried out by the Medical Research Council (MRC). The MRC study will be discussed in the second part of this review, the remainder of this article being devoted to the design of UDAF operating rooms. Further information on Charnley's research is given in a review written by Lidwell[17].

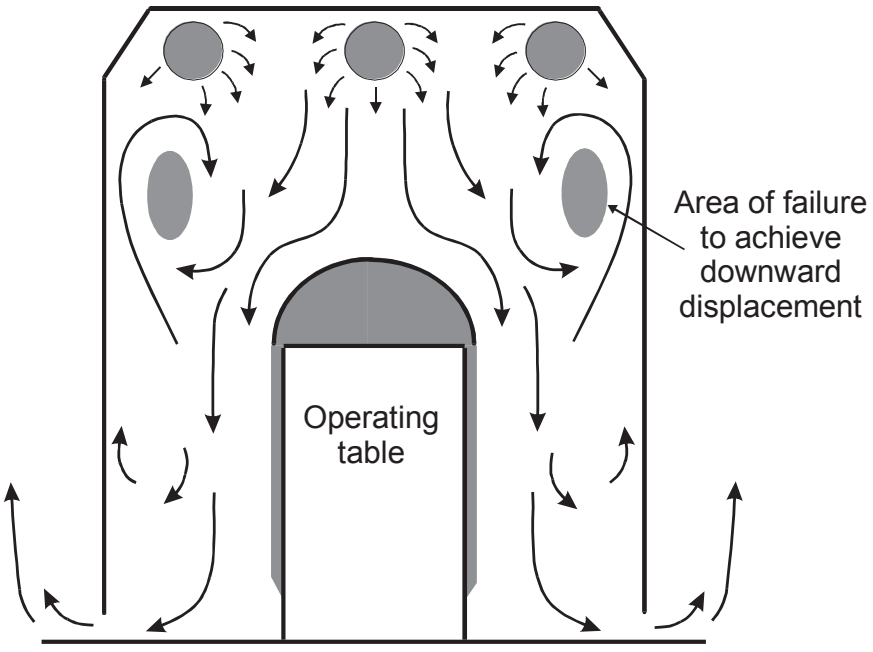

Figure 1: Section through Charnley's original 'greenhouse' system showing the airflow

Figure 2: Charnley total-body exhaust gown

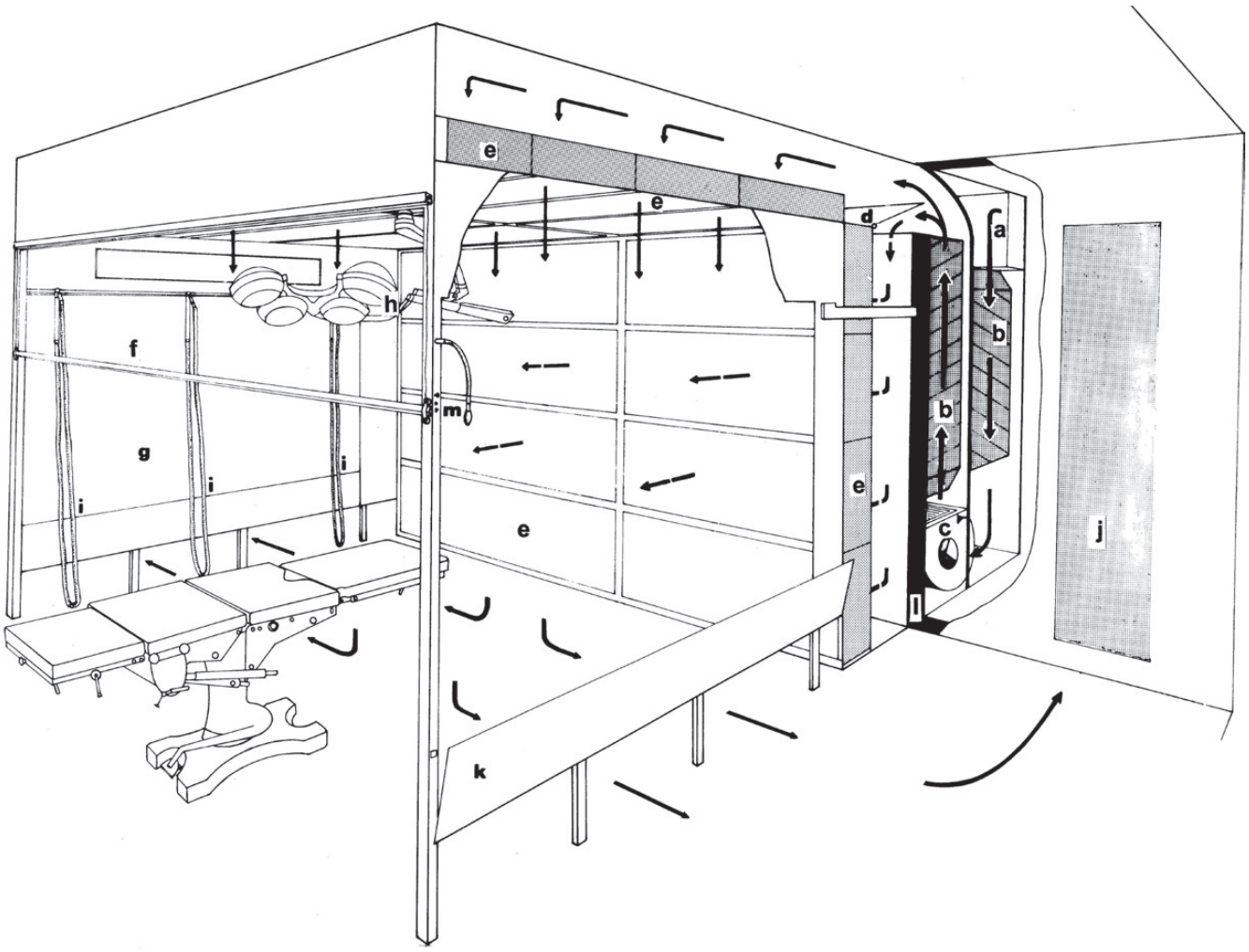

Figure 3: Experimental downflow/crossflow, variable-velocity system: a, pre-filters; b, sound attenuators; c, variable-speed fans; d, flap to change direction; e, HEPA filters; f, plastic movable curtain; g, glass walls; h, skeletal light; i, total-body exhausts; j, return grille; k, side flaps; m, audio system for total-body exhaust.

Design of UDAF operating rooms

In the early 1960s, Willis Whitfield and his co-workers at Sandia Corporation in the USA[18] invented a new type of clean air ventilation called 'laminar' air flow. It was incorrectly called 'laminar flow', as the airflow was not 'laminar' in the scientific sense, and is now correctly called unidirectional airflow (commonly abbreviated to UDAF). A bank of high-efficiency air filters was used to supply particle-free air at 90ft/min (0.4m/s) that swept in a piston-like manner across the area to be kept clean, and achieved cleanliness conditions very much superior to those found in conventionally-ventilated systems.

Unidirectional airflow systems were quickly installed in operating rooms[19] but the following design questions still had to be answered:

- Should the airflow be downflow or crossflow?
- What is a suitable air velocity?
- What removal efficiency of final air filters is necessary?
- Would thermals and obstructions disrupt the airflow?
- Should the system's walls reach down close to the floor, or could they be high enough to allow access for large pieces of equipment, such as X-ray machines?

In these early days of UDAF, it was not possible to purchase a system for such a research study. It was therefore necessary to design and build one and, with the co-operation of the Department of Orthopaedics, it was installed at Killearn Hospital in 1970, and then moved to Gartnavel General Hospital, where it was used until 1999. It is described in Reference 10, and shown in Figure 3.

A novel feature of this experimental system was its capability of changing its air velocity (between 0.1 to 0.6m/s) and air direction (between downflow to crossflow). By moving over a flap (item d), and regulating the variable speed fans (item c), the velocity and air direction could be changed during an operation without compromising asepsis.

Unidirectional airflow moves in reasonably straight lines from HEPA filters to floor, and air sampling must be carried out close to the surgical wound if it is to be representative of the concentration at the wound. Air sampling was therefore carried out using a high-volume Casella slit sample (700 l/min) mounted on a small movable trolley. The sampler was connected to a flexible duct which in turn connected to a sterilised stainless-steel tapered section terminating at an intake opening. This section was draped and the intake placed 20-30 cm from the wound.

It was found (Reference 11) that the downflow system was more effective than a crossflow. Compared to an adjacent conventionally-ventilated operating room, the crossflow system gave 11 times, and the downflow system gave 35-90 times, lower microbial concentrations. Measurements carried out at different air velocities showed that in the downflow system a velocity in the region of 0.3 to 0.35m^3/s gave the best returns for effort (Figure 3), but in a crossflow system

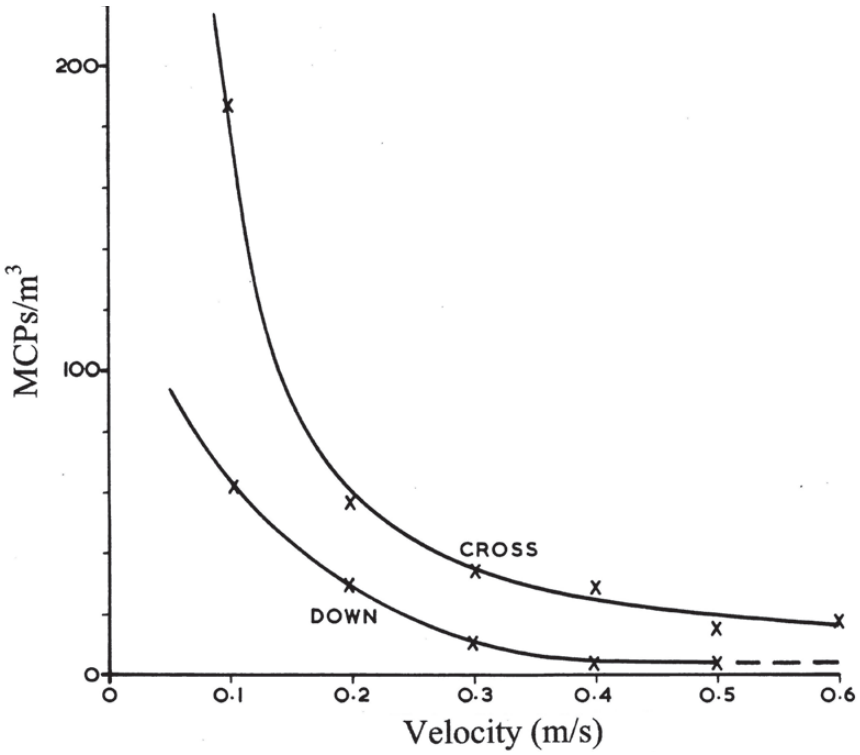

Figure 4: Bacterial counts at the wound with respect to unidirectional velocity and direction.

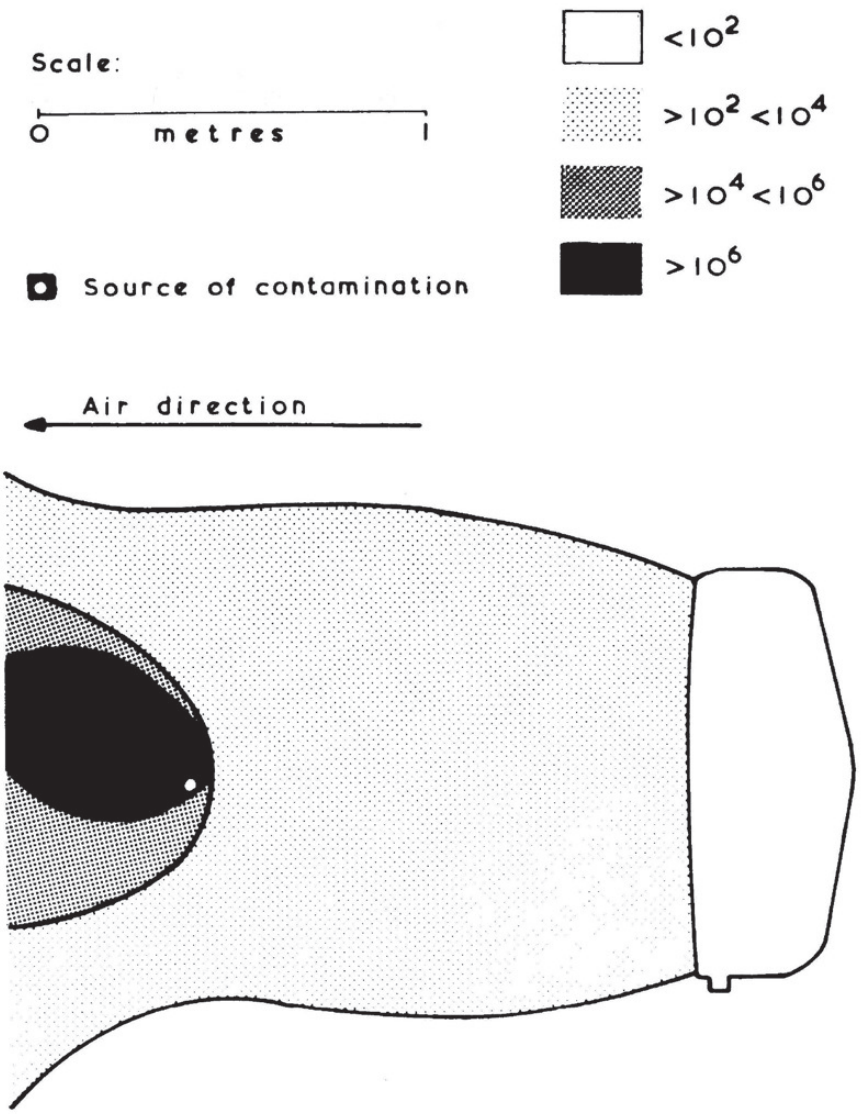

Figure 5: Dispersion and penetration of particles from a source in front of a large operating room lamp.

a minimum velocity of 0.4m/s was best. It was assumed that when these suggested velocities are reached, the airflow changes from an unsteady and mixed airflow to a unidirectional airflow that will quickly be reinstated after any disturbance by movement of personnel.

Another feature of the UDAF system was the surgical lamp, which was modified to give a skeletal shape. It was unknown at that time if the large area of the current design of operating room lamps (1m diameter) would disrupt airflow and cause high bacterial concentrations in the wound area below. It was also unknown whether the hot air thermals from operating-room personnel and the surgical lamp would adversely affect the air flow, as had been the case during Blower and Crew's[8] studies. Research was therefore carried out using (a) smoke challenge tests to quantify the amount of turbulent backflow of air from sources in front of the lamp (b) neutral-buoyancy helium-filled detergent bubbles to obtain airflow patterns around the light, and (c) Schlieren photography to show whether the thermal currents coming from a hot lamp pod are controlled by a downflow of air. Typical results are shown in Figures 5, 6 and 7, and a full description of these methods, and the results obtained, are given in Reference 12. It was shown that a downward velocity of 0.3m/s would control thermal currents from the lamp and that a skeletal form of lamp would be necessary in a downflow system.

Experiments had been previously carried out (Reference 1) into the removal efficiency of air filters in a hospital ward, as well as the size distribution of the MCPs approaching the filters. This information showed that filters 90% efficient against particles of about 0.5µm should be suitable, and these were installed into the Glasgow University UDAF system. The concentration of MCPs in the supply air was measured during operations using the high-volume Casella air sampler and no MCPs were found. Recent investigations have been carried out (Reference 13) and showed that filters 87% efficient against the most penetrating particle size, as specified in EN 1822, were likely to have a removal efficiency against MCPs of 99.995%.

Design of partial-walled UDAF systems

Investigations were carried out into the design of partial-walled UDAF systems (References 14, 15, and 16). Most of the UDAF systems at that time had walls that came from the perimeter of the air supply filters to within about 30cm of the floor (Figure 8a). These walls constrained the air and ensured good air flow passed the wound. However, partial walls that terminated about 2 metres above the floor gave better communication, and access for larger pieces of equipment, such as X-ray machines. Unfortunately, as the airflow is not constrained (Figure 8b) the air velocity at the wound is reduced. Also, if the supply air is hotter than the air outside the clean zone, buoyancy can reduce the amount of air getting to the wound (Figure 8c). In addition (Figure 8d), air may be entrained from outside the clean zone and reach instrument trolleys, and possibly the wound area.

An investigation of a unidirectional airflow system at the London Hospital (Reference 14) showed that when there were no walls at all, and therefore no constraint of air within the unidirectional airflow zone, air would short-circuit to an adjacent air exhaust in the ceiling. Lighting tracks, which crossed over the filter bank, induced air to run below and across the tracks, and into the clean area. Partial walls corrected these problems and assisted in the downward flow of air. However, even with partial walls, the air flow still diverged and reduced the airflow velocity at the operating table. A comparison between a partial and full-walled system showed that the velocity at the wound height was about 20 -25% less in the partial wall system. Therefore, the air supply velocity for partial-walled systems should be increased from a minimum of 0.3m/s required for a full-walled system to a minimum of 0.38m/s.

Another investigation (Reference 15) of two partial-walled UDAF systems showed that when the temperature of the air supply was higher than the surrounding operating room, the supply air, being buoyant and unconstrained by walls, did not efficiently reach the wound. The two sets of results are shown in Figure 9, where it may be seen that when the supply air temperature was about 1°C warmer than the surrounding room, practically no air reached the wound. However, as the air supply became colder, the velocity at wound height increased, and when the supply air was 1.4°C lower than the surrounding room air, the velocity was twice that obtained when the supply and room temperature were the same.

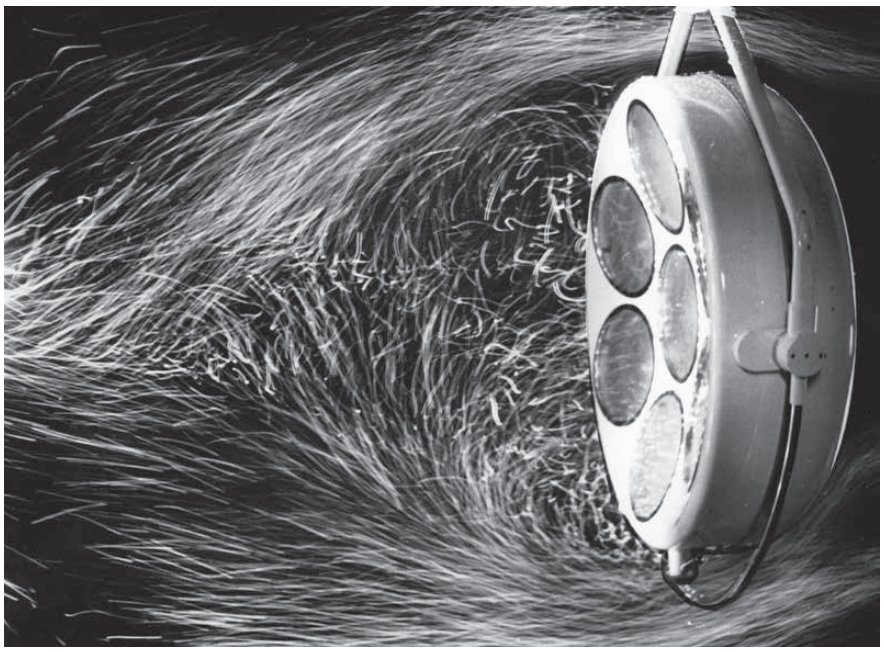

Figure 6: Helium-filled detergent bubbles showing airflow round large operating room lamp

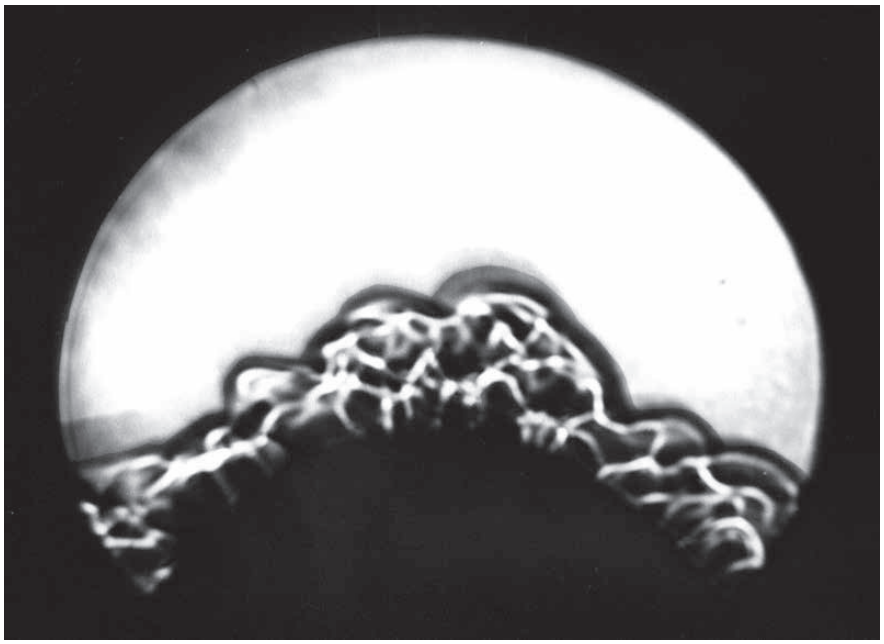

Figure 7: Schlieren photograph showing hot air on the surface of a high-temperature operating lamp being controlled by a downward unidirectional airflow of 0.3m/s

Experiments were also carried out to show the penetration of test particles into the clean air zone caused by temperature differential (Reference 15). Figure 10 shows little entrainment into the clean zone of a partial-walled system when the air supply was at the same temperature as the surrounding room. However, Figure 11 shows a greater penetration when the supply air is 0.65°C hotter than the surrounding room. A centrally-located operating table is likely to avoid much of the entrained contamination but instruments on trolleys at the periphery of the unidirectional airflow clean zone, would be exposed to these microbes.

In some UDAF systems, the supply air is drawn from the surrounding operating room, and as the air passes through the fans, its temperature will increase by about 0.5-0.7°C. This increase in air temperature will cause a reduction in air velocity at the wound. Because of heat gains from people and

machinery, most operating rooms use supply air that is colder than the room to maintain comfort conditions. If this air passes through the UDAF system, the heat gain from the fans can be negated. However, the opposite situation may occur if heat losses from the operating room are high, as can occur in a cold day in an operating room with outside walls, and warm air may need to be supplied to maintain comfort. This problem needs consideration during the design process.

Further investigations into entrainment in partial-walled systems were carried out, including the use of a 1/10 scale water model to visualise the expected airflow, and are discussed in Reference 16.

Many of the conclusions discussed above, were used by Working Group 10 of the UK Department of Health to write a set of guidelines for ultra clean ventilation systems that were completed in 1986. Also included in the guidelines were the MRC committee's recommendations for maximum airborne MCP concentrations during surgery, and test methods for checking the performance of a system (Reference 17). These DHSS guidelines were never formally published but incorporated into the Hospital Technical Memorandum (HTM 2025)[10], and then into the current Health Technical Memorandum (HTM 03-01)[11] which superseded it.

Acknowledgement

I would like to thank Craig Mackintosh for reviewing this article and providing useful comments for its improvement.

References (W Whyte)

1. Whyte W (1968). Bacteriological aspects of air-conditioning plants. Journal of Hygiene, Cambridge, **66**, pp.567-583.
2. Baird G and Whyte W (1969). Air movement control for treatment and isolation rooms. Journal of Hygiene, **67**, pp.225-232.
3. Shaw BH and Whyte W (1974). Air movement through doorways – the influence of temperature and its control by forced airflow. Building Services Engineer, **42**, pp.210-218.
4. Whyte W and Shaw BH (1973). Air flow through doorways. In 'Airborne Transmission and Airborne Infection'. Editors J.F.Ph Hers and K.C. Winkler. Oosthoek Publishing Co., The Netherlands.
5. Ventilation of operating departments; a design guide (1983). Prepared by Inter-Authority Engineering Working Group No. 10 of the DHSS.
6. Whyte W, Howie JGR and Eakin JE (1969). Bacteriological observations in a mechanically ventilated experimental ward and in two open-plan wards. Journal of Medical Microbiology, **2(3)**, pp.335-345.
7. Ventilation in operating suites (1972). Report of the Joint Working Party of the DHSS and MRC. Chairman: Dr OM Lidwell.
8. Cockroft JP, Robertson P and Whyte W (1977). A comparison between measured and computed airflow in an operating suite. B.S.R.U. Report No.197, University of Glasgow.
9. Robertson P, Cockroft JP and Whyte W (1977), Air movement control in critical hospital areas. B.S.R.U. Report No.198, University of Glasgow.
10. Whyte W, Shaw BH and Barnes R (1971). An experimental laminar-flow operating room. Lancet, **ii**, pp.905-906.
11. Whyte W, Shaw BH and Barnes R (1973). A bacteriological evaluation of laminar-flow systems for orthopaedic surgery. Journal of Hygiene, **71**, pp.559-564.
12. Whyte W and Shaw BH (1974). The effect of obstructions and thermals in laminar-flow systems. Journal of Hygiene, **72**, pp.415-423.
13. Whyte W, Green G and Whyte WM (2012). Removal of microbe-carrying particles by high efficiency air filters in cleanrooms. International Journal of Ventilation, **10**, pp.339-351.
14. Whyte W, Shaw BH and Freeman MAR (1974). An evaluation of a partial-walled laminar-flow operating room. Journal of Hygiene, **73**, pp.61-77.
15. Whyte W and Bailey PV (1978). The effectiveness of partial-wall laminar-flow system with special regard to air supply temperature. Journal of the Society of Environmental Engineers, **17(4)**, pp.1-4.
16. Whyte W, Shaw BH and Bailey PV (1974). An assessment of partial-walls for a down-flow laminar-flow system. Proceedings of the International Symposium on Contamination Control, London.
17. W Whyte, OM Lidwell, EJL. Lowbury, and Blowers R (1083). Suggested bacteriological standards for air in ultraclean operating rooms. Journal of Hospital Infection, **4**, pp.133-139.

Other references

1. Pasteur L (1861). Mémoire sur les corpuscles organisés qui existent dans l'atmosphère; examen de la doctrine de générations spontanées, Annales des Sciences Naturelles, **16**, pp.5-98.
2. Lister J (1909). Collected Papers, Clarendon Press, Oxford.
3. Bourdillon RB, Lidwell O M and Thomas J C (1941). A slit sampler for collecting and counting air-borne bacteria, Journal of Hygiene, **41**, pp.197-224.
4. Blair JE and Williams REO (1961). Bulletin of the World Health Organisation, **24**, 771-784.
5. Lidwell OM, Brock B, Shooter RA, Cooke EM and Thomas GE (1975). Airborne infection in a fully air conditioned hospital; IV Airborne dispersal of *Staphylococcus aureus* and its nasal acquisition by patients. Journal of Hygiene, **75**, pp 445-474.
6. Shooter RA, Taylor GW, Ellis G and Ross J.P (1956). Postoperative wound infection. Surgery, Gynecology and Obstetrics. **103 (3)**, pp.257-263.
7. Blowers R, Manson GA, Wallace KR and Walton M (1955). Control of wound infection in a thoracic surgery unit. Lancet, **ii**, pp.786-794.
8. Blowers R and Crew B (1960). Ventilation of operating theatres. Journal of Hygiene, **58**, pp.427-448.

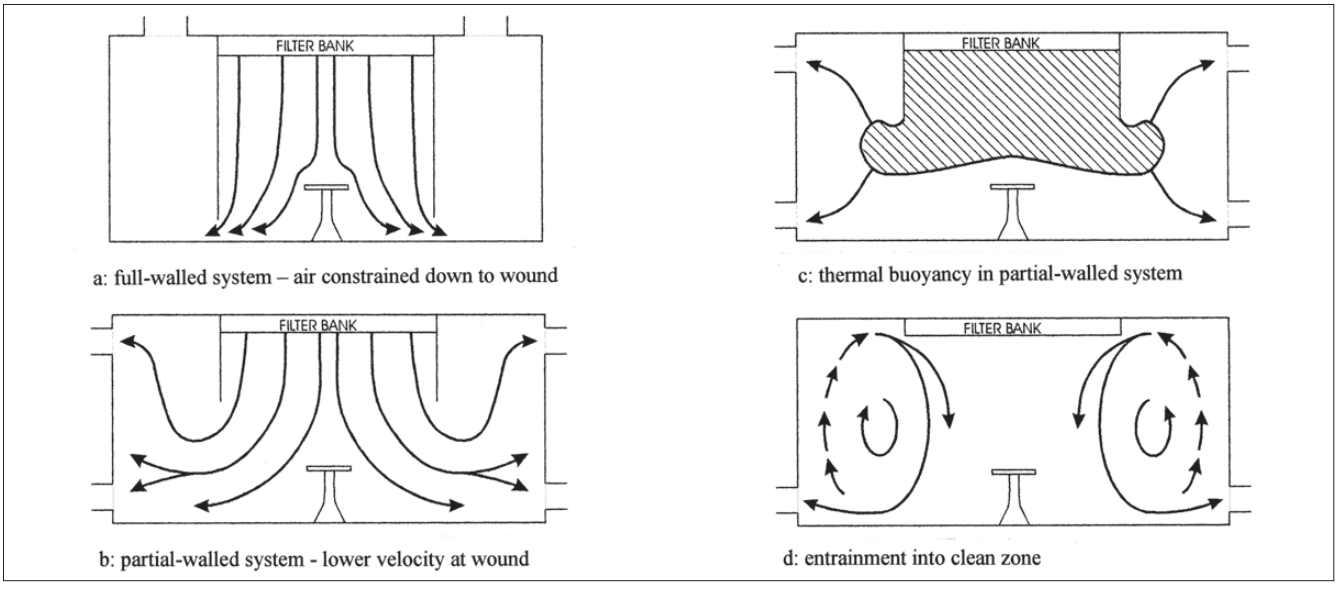

Figure 8: Airflow in full, partial, and no-wall systems

9. Lowbury EJL (1954). Air conditioning with filtered air for dressing burns. Lancet, **i**, pp.292-294.
10. Hospital Technical Memorandum, Number 2025. Ventilation in Healthcare Premises-Validation and Verification (1994). National Health Services Estates.
11. Heating and Ventilation Systems; Health Technical Memorandum 03-01: Specialised ventilation for healthcare premises; Part A: Design and validation. Department of Health.
12. Charnley J and Eftekhar N (1969). Postoperative infection in total prosthetic replacement arthroplasty of the hip-joint. British Journal of Surgery, **56**, pp.641-649.
13. Charnley J (1972). Post-operative infection after total hip replacement with special reference to air contamination in the operating room. Internal Publication No.38, Centre for Hip Surgery, Wrightington Hospital, Wigan.
14. Charnley J (1964). A sterile-air operating theatre enclosure. British Journal of Surgery, **51**, pp.195-202.
15. Allander C (1966). System for ventilating clean rooms. United States Patent 3380369.
16. Laufman H (1979). Air-flow effects in surgery. Archives of Surgery, **114(7)**, pp.826-30.
17. Lidwell OM (1993). Sir John Charnley, Surgeon (1911-82): the control of infection after total joint replacement. Journal of Hospital Infection, **23**, pp.5-15.
18. Whitfield WJ (1962). A new approach to cleanroom design. Sandia Corporation Report SC-4673 (RR), Office of Technical Services, Department of Commerce, Washington 25, DC, USA.
19. JG Whitcomb and WE Clapper (1966). Ultraclean Operating Room. The American Journal of Surgery, **112(5)**, 681-685.

W (Bill) Whyte is an Honorary Research Fellow at Glasgow University. He has been involved with cleanrooms for over 50 years and has the useful qualifications of a B.Sc. in microbiology and a D.Sc. in mechanical engineering. He has published over 120 reports and papers on contamination control and cleanroom design. He has edited a book 'Cleanroom Design', published as a second edition in 1991, and a book called 'Cleanroom Technology – the Fundamentals of Design, Testing and Operation', published as a second edition in 2010. He is a founder and former chairman of the Scottish Society for Contamination Control and the Cleanroom Testing and Certification Board - International. He is a member of the BSI committee involved in the writing of cleanroom standards. He has extensive experience as an industrial consultant and running cleanroom courses.

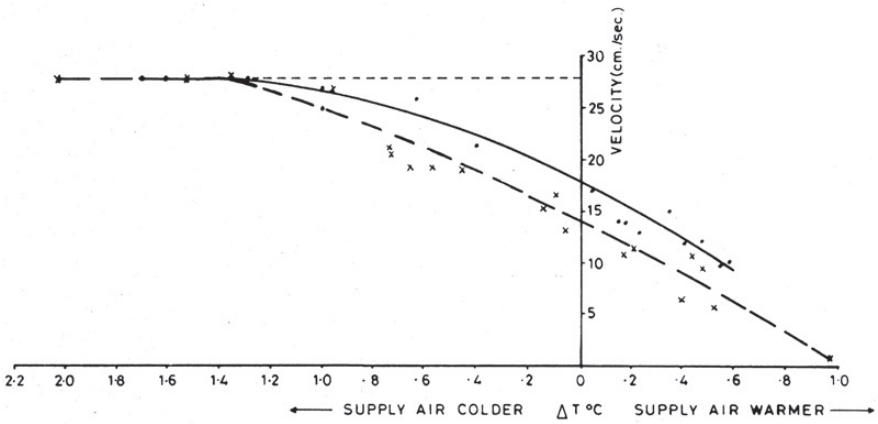

Figure 9: Effect of the temperature difference between supply air and the surrounding room air on air velocity at table height.

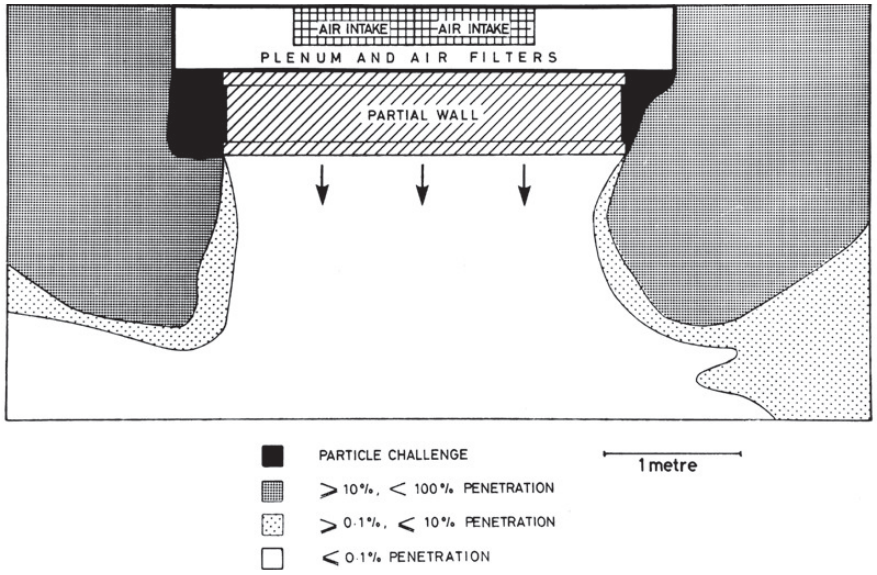

Figure 10: Penetration of particles into clean zone of partial-walled system: iso-thermal conditions

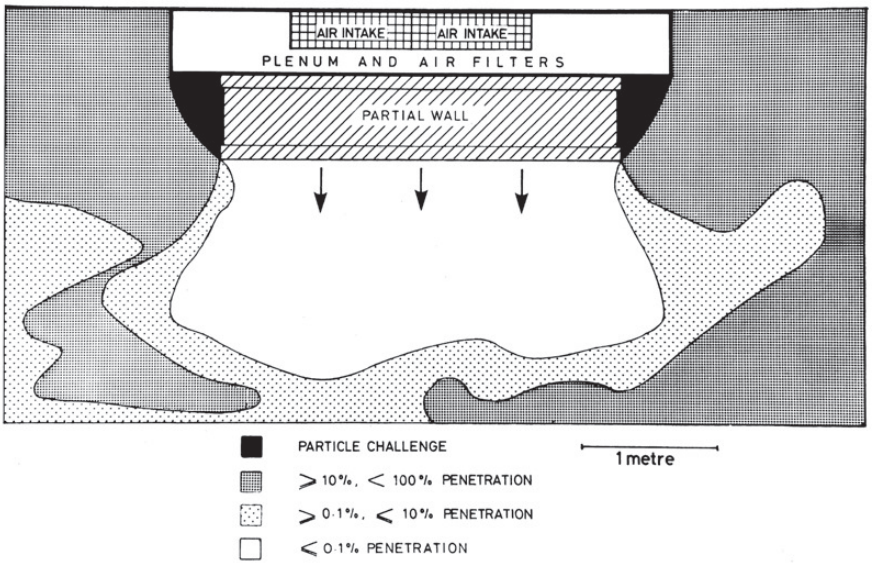

Figure 11: Penetration of particles into clean zone of partial-walled system. Supply air 0.65°C hotter than surrounding room