The evolution of the control of airborne infection in operating rooms

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Cite this article:
Bone Jt Open 2026;7(5):
636–642.

DOI: 10.1302/2633-1462.
75.BJO-2025-0377.R1

This article describes advances in the knowledge of airborne infection in operating rooms since 1867 when Joseph Lister first provided methods of controlling surgical site infection. However, it was not until the mid-20th century that evidence became available to show that airborne microbes were a cause of surgical site infection, and the design of operating rooms was improved to control this route of infection. The contributions from various researchers who investigated the importance of airborne infection and the design of operating rooms are discussed. It was concluded that further progress is still required to fully control airborne infection in operating rooms.

Take home message

- Since Lord Lister first introduced antiseptic methods to prevent postoperative infections, accumulating evidence, including the studies by Sir John Charnley and the Medical Research Council of the UK, have shown that airborne microorganisms are a major cause of surgical site infection, particularly in implant surgery.
- Significant progress has been achieved in reducing airborne microbial contamination through improvements in ventilation systems and surgical attire; however, further advances are required.
- Surgical teams must be aware of the importance of appropriate behaviours to avoid undermining the substantial resources invested in airborne contamination control, as well as the need for air quality monitoring to ensure compliance within recommended microbial limits.

The early work of Joseph Lister

Prior to 1865, the cause of wound infections in hospital patients was uncertain. The breakthrough came from Joseph Lister,[1] who heard of Louis Pasteur's discovery of microbes and his theory that microbes caused disease. Lister also knew of Pasteur's experiments that showed if airborne microbes were unable to enter flasks containing heated and sterile meat broth there was no decomposition but, when there was access of air to the flask, there was decomposition. Lister was also aware of the properties of carbolic acid (the old name for the antimicrobial chemical, phenol), and he linked these pieces of information together to successfully prevent infections in compound fractures, by applying dressings containing carbolic acid to patient's wounds. Two years later, in 1867, he extended this method to the operating room (OR), and by applying carbolic acid to instruments, the surgical wound, surgeon's hands, and by spraying it into the air, he was able to reduce surgical site infection (SSI) from 45% to 15%.[1]

Lister's early opinion was that surgical wounds were infected by airborne microbes, and by spraying carbolic acid into the air, SSI could be reduced. An instrument used to spray carbolic acid was devised by Lister, and shown in Figure 1 is a photograph taken in 1889 of a group of surgeons using Lister's spray that is on the small round table. A version of Lister's spray is shown in Figure 2.

Spraying phenol into the air of an operating room was unpleasant for the occupants and Lister stopped its use because of this, and on the incorrect ground that microbes that caused infections were not in the air of the operating room.

The mid-20th century

Joseph Lister used antiseptic methods to prevent SSI, which included the airborne

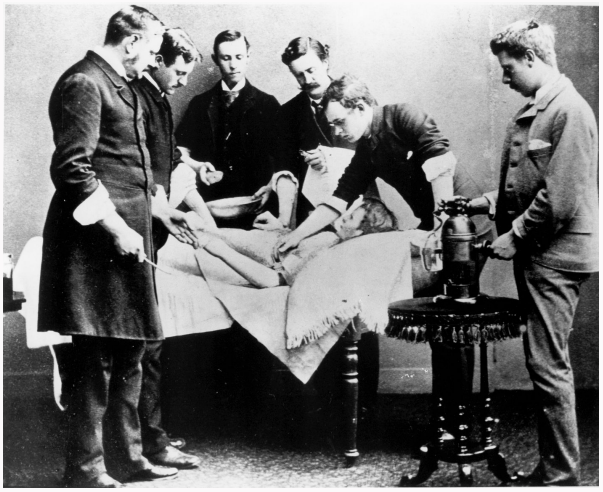


Fig. 1
A group of surgeons with the Lister spray. The figure was made available by Aberdeen City Council, Library and Information Services.



Fig. 2
A Lister steam spray. The figure was obtained from the Huntarian Museum, University of Glasgow, UK.

route. However, it was not until the mid-20th century that scientific evidence became available to show that airborne microbes caused SSI, and good operating room design could provide low concentrations of airborne microbe-carrying particles (MCPs) that reduced SSI. It should be noted that when discussing particles that carry microbes in air currents, we use the term 'microbe-carrying particles'; however, when discussing the concentration of MCPs obtained after incubation and counting of microbial colonies, we use the term 'colony forming unit' (CFU).

Prior to the mid-20th century, ORs lacked air conditioning, and were often hot and uncomfortable. Because of this, a fan was frequently used to extract hot air from the OR to outside the building. However, a negative pressure was produced that drew contaminated air from the outside hospital corridors into the OR. An OR with an extract fan was shown by Shooter et al[2] to have airborne concentrations of MCPs that reached as high as 1,400/m^3, and a wound infection rate after general surgery of 11%. A change to a positive supply of filtered air, which controlled the entry of contaminated air from the hospital corridors and diluted the airborne MCPs dispersed from staff, reduced the airborne MCPs to less than 180/m^3, and the infection rate to 1%. Lowbury[3] also carried out an investigation that showed a positive supply of filtered air reduced infections in a burn treatment room.

Bacteriophage typing of *Staphylococcus aureus* was introduced in the 1950s, and was used to show the relative importance of sources of wound infections, including air, in the OR.[4] Similar investigations showed that some outbreaks of infections in the OR were caused by one individual who was present in the OR but did not come into physical contact with patients, and air was presumed to be the route of transmission.[5,6]

Design of conventionally ventilated ORs

The scientific articles discussed in previous paragraphs demonstrated the requirement for a positive supply of filtered air to an OR, and research was carried out by Blowers and Crew in 1960[7] on the design of ORs to provide information on: 1) the removal efficiency of MCPs by air supply filters; 2) the type of air movement that gave the lowest airborne concentration of MCPs; and 3) the air volume supply rate to maintain the required air flow through an open doorway and avoid entry of contaminated air.

The publication by Blowers and Crew,[7] and similar publications, on the design of conventionally ventilated ORs suggested improvements were required to current architectural and engineering design of ORs, and this prompted the Department of Health and the Medical Research Council of the UK to set up a Joint Working Party (JWP) to report on requirements for ventilating operating theatre suites to control SSI caused by airborne MCPs, and a report was published in 1972.[8] The Department of Health accepted these recommendations, and set up Study Group 10, who published a report in 1972[9] that provided engineering solutions to the JWP recommendations. These solutions were incorporated, and still remain, as part of the National Health Service England's Hospital Technical Memorandum (HTM) on Specialised Ventilation for Healthcare Premises.[10]

The JWP report gave information about conventionally ventilated ORs, but no advice about ultra clean ventilation (UCV) ORs, as they were just being installed.

Ultra clean air operating rooms

As previously discussed, Blowers and Crew investigated the design of conventionally ventilated ORs, and found that the air movement system that gave the lowest concentration of airborne MCPs was a downward 'piston' of air. They used a sheet of textile fabric over the entire ceiling of an OR to straighten the filtered air supply, so it flowed downwards in a unidirectional way and efficiently removed airborne MCPs. However, they used the same air volume supply rate as a conventionally ventilated OR, and could only provide a low air velocity that was easily disturbed, and gave less-effective air flow. This was the situation when Professor Sir John Charnley decided to improve the ventilation of his OR.

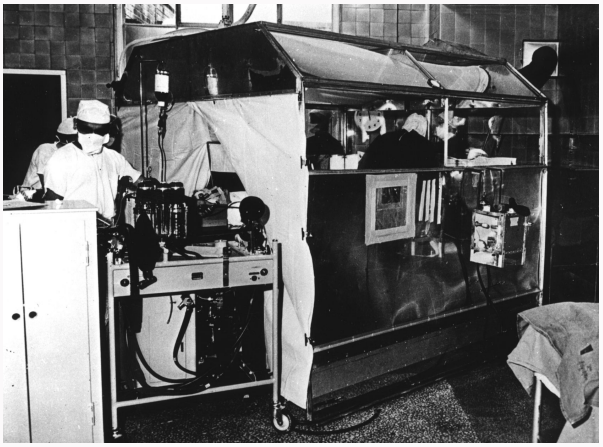


Fig. 3
The original Charnley-Howorth enclosure. The photograph was provided by the late Hugh Howorth.



Fig. 4
Drawing of the Charnley total body exhaust gown, provided by the late Hugh Howorth.

Professor Sir John Charnley devised an operation to replace a diseased hip joint with an artificial joint. However, his initial operations were carried out in an exhaust-ventilated OR, where the concentration of MCPs averaged 636/m^3, and the deep joint infection rate was in excess of 7%.[11] This was considered unacceptable.

Using the knowledge that existed at that time (1961), the ventilation effectiveness of the 'piston effect' of downward air flow in the OR was improved. Instead of supplying air through the whole ceiling, as Blowers and Crew had done, they restricted the air supply to a much smaller area by using a 2.1 m by 2.1 m enclosure that is shown in Figure 3, and this increased the air velocity. A reasonable downflow of unidirectional air was achieved, but it was improved by increasing the air supply and incorporating other design improvements.

Duguid and Wallace in 1948,[12] and Blowers and McCluskey in 1965,[13] investigated surgical clothing, and used closely woven textile fabric to reduce the airborne MCPs dispersed from people that passed through the fabric. However, this clothing did not cover every part of the body, and a reduction of air exchange across the fabric made it uncomfortable to wear. Charnley developed the total body exhaust gown shown in Figure 4. This gown was made from a tightly woven cotton fabric (Ventile), and an exhaust helmet that removed air from underneath the gown. These gowns substantially reduce the dispersion of airborne MCPs.[14]

Improvements to Charnley's OR were introduced in steps that were paralleled by reductions in airborne MCP concentrations, and rates of infections. The results are shown in Table I. At the end of these improvements, the concentration of airborne MCPs was reduced to an average of 0.7 CFU/m^3, and the deep joint infection rate to 0.61%.[11]

MRC study of ultra clean air systems

The results of Charnley's study had a considerable influence on orthopaedic surgeons, and the Department of Health (DoH) in the UK came under pressure to install UCV systems. However, they were resistant to spending large sums of money if it was unnecessary, and came to the Medical Research Council (MRC) for advice. The MRC set up an ad hoc committee to study the evidence, and they concluded that as improvements to surgical procedures were introduced at the same time as improvements to the ventilation system, the evidence lacked strong scientific proof. The committee suggested that a research study should be carried out to ascertain whether Charnley's results were correct. The MRC ran such a study, which was carried out in the late 1970s and early 1980s. It was a prospective, multi-centred, and randomized study that investigated the correlation between the concentration of airborne MCPs and deep infections after total joint arthroplasty operations.

As the MRC study was a prospective study, an initial statistical analysis was required to avoid the problem of failing to show a positive result because too few operations were studied. This analysis showed that to demonstrate a difference between a control group with a 2% incidence of infection, and a test group where the incidence dropped to 1%, about 2,500 surgical operations were required. As the study would compare a control group with two test groups, a total of 7,500 joint arthroplasty operations would be needed. The MRC study lasted five years, and 8,052 operations were studied in 19 hospitals in the UK and Sweden. Conventionally ventilated ORs, and a variety of UCV ORs were included to obtain a wide range of airborne concentrations of MCPs during surgery. These ventilation systems are shown in Table II.

Patients were randomly allotted to either a conventionally ventilated or to a UCV OR. Each week, after the operating list had been prepared, a sealed envelope was drawn that

Table I. Charnley's results on the influence of airborne microbe-carrying particles on deep joint infections.

		Microbial air contamination		
Phases	**Air changes per hour**	**CFU/ft³ (CFU/m³)**	**CFU/8 cm* settle plate/h**	**Deep joint infections, %**
Exhaust ventilation	0	18 /ft³ (636 /m³)	70	7
First enclosure	10	2.5 /ft³ (89 /m³)	10	3.5
First enclosure with higher air supply	130	0.2 /ft³ (7 /m³)	0.4-1.8	3.0
Second enclosure	300	0.1 /ft³ (3.5 /m³)	0-0.2	1.5
Second enclosure with front aprons	300	NR	NR	1.07
Second enclosure with body exhaust gowns	300	0.019 /ft³ (0.7 /m³)	NR	0.61

*It is likely that 9 cm plates were used.
CFU, colony forming unit; NR, not reported.

Table II. MRC results of airborne microbe-carrying particle concentrations per m³.

	Clothing type	
Ventilation system	**Conventional***	**Total body exhaust gowns**
Conventionally ventilated†	164	51
Allander‡	49	14
Horizontal UDAF§	22	1
Vertical UDAF, without walls	10	-
Vertical UDAF, with walls	2	0.4
Isolator¶	0.5	-

*Conventional clothing was a cotton shirt, trousers, and surgical gown.
†Conventionally ventilated operating rooms have air supply inlets in the ceiling that supply filtered air that mixes and dilutes airborne microbial contamination.
‡Allander systems gave a low velocity downward air flow with air curtains round the air supply perimeter.[15]
§UDAF systems provide a flow of unidirectional air to the sterile field from a bank of filters.
¶Isolator systems are described in[16]
UDAF, unidirectional air flow.

allocated the patient to a type of OR. The study was not set up to determine the effect of antibiotics, and surgeons were free to use their preferred approach, with about two-thirds of the patients receiving prophylactic antibiotics. Whether antibiotics were given, or not, was the same in both conventional and UCV groups and, therefore, should not affect the balance of the study. In addition, the confounding effect of antibiotics was studied by a multiple regression analysis and not found to be a problem; this analysis is discussed later.

The onset of deep infections was monitored for an average of 2.5 years, with a maximum of five years. The rate of deep infections was compared, as they are more severe and difficult to treat, and more likely to be linked to contamination occurring within the operating room, while superficial infections may depend on postoperative wound care. The deep infections were identified by the criteria explained,[17], but were only considered to be deep infections after being confirmed by re-operation. Research nurses, employed only for the study, recorded patient and other information, which was sent to the MRC Biostatistical Unit for checking and analysis.

The first paper that reported the outcome of the study was published in 1982.[17] However, it should be noted that this paper, which is often cited in a way that suggests it gave the final conclusions of the study, did not include all the results, or a comprehensive analysis of the results. These were given in subsequent papers[18–23] and these articles have been reviewed.[24,25]

During the study, the concentrations of airborne MCPs were regularly measured during surgery and the effects of the type of ventilation system and surgical clothing on the average airborne concentration of MCPs are shown in Table II.

A portion of the surgical wounds was washed at the end of an operation to determine the number of microbes. Initial experiments showed that 98% of the microbes in the patient's wounds came from the air,[26] and the overall results of the MRC study showed it was greater than 95%.[18] It should be noted that the study reported in article[26] also showed that surfaces in a sterile field could transfer at least as great a proportion of microbes into the wound as direct deposition from air.

The result of an overall comparison of all operations carried out in conventionally ventilated ORs with all of those carried out in UCV systems showed the deep infection rate was significantly reduced ($p < 0.01$) from 1.5% in conventionally ventilated ORs to 0.6% in UCV systems.[24,25]

Table III shows a breakdown of the deep infection rates according to type of OR, clothing, and use of prophylactic antibiotics. These results show that UCV and prophylactic antibiotics combine independently and multiplicatively to reduce deep joint infection. The use of UCV in place of conventional ventilation gave a 2.1-fold reduction (3.4% to 1.6%), and when the UCV system was combined with special occlusive clothing there was a 3.7-fold reduction (3.4% to 0.9%). These reductions were further increased when prophylactic antibiotics are used.

As well as carrying out a simple comparison of the rates of infection, 23 possible risk factors that might affect infection rates were analyzed by multiple regression analysis.[21] This analysis not only produced information on significant risk

Table III. MRC results of deep joint infection rates after total joint arthroplasty.

Type of ventilation system	No antibiotics given, n (%)	Antibiotics given, n (%)
Conventional air flow with conventional clothing	39/1,161 (3.4)	24/2,968 (0.8)
UCV systems with conventional clothing	8/516 (1.6)	9/1,279 (0.7)
UCV systems with total-body exhaust gowns, plus isolators	5/544 (0.9)	1/1,584 (0.06)

UCV, ultra clean ventilation.

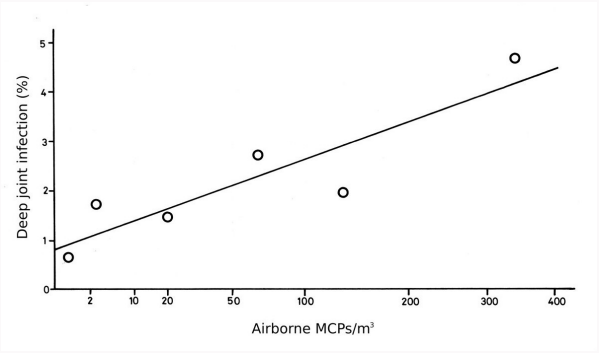


Fig. 5
Scatter plot showing the relationship between deep joint infection and the concentration of airborne microbe-carrying particles (MCPs).

factors, but on any imbalance in the study by risk factors, such as prophylactic antibiotics. Statistically significant 'incidence ratios' were obtained that gave the magnitude of the effect of the risk factors on deep joint infection. The incidence ratio that showed the drop in deep wound infections was 1:1.82 in favour of UCV systems compared with conventional ventilation systems, and 1:4.55 in favour of the group that included UCV systems with body exhaust gowns, and isolators. These ratios are close to the magnitude of the simple ratios that can be obtained from Table III, and confirm the effectiveness of UCV systems.

The relationship between the airborne concentration of MCPs and deep infection rates was studied, and shown in Figure 5.[18] Each point on the line is an average of results from six to nine hospitals. Figure 5 shows that at a MCP concentration of ≤ 1/m^3, infection caused by airborne contamination is close to a minimum. However, this desirable concentration of ≤ 1/m^3 will only be achieved in well-designed UCV systems with the surgical team wearing effective occlusive clothing, which may not always be possible. However, if an average value of 10/m^3 is not exceeded, then a worthwhile reduction in the deep infection rate to about half of that in conventionally ventilated ORs is likely to be achieved. The MRC steering committee recommended that an average airborne concentration of ≤ 10/m^3 should not be exceeded in UCV system, and as stated in EN 17141:2020, 'this value is internationally accepted for surgery susceptible to infection, such as orthopaedic and trauma surgery'.[27] However, a greater benefit will be obtained in total joint arthroplasty if the average airborne concentration is ≤ 1/m^3.[18,19]

A paper was also published about the possible financial savings generated by the installation of ultra clean air systems. The added costs of extended patient stay and revision operations required by infected patients was compared with the cost of installing ultra clean systems, and possible financial savings identified.[23]

There have been criticisms of the MRC study, but these have been rebutted.[28] Also, Bischoff et al[29] carried out a meta-analysis study that showed operations carried out in UCV systems did not have a lower infection rate than conventionally ventilated operating rooms. However, the data came mainly from wound registers, and the authors accepted that their evidence was 'very low quality'. Also, the information they reviewed contained no information about the types of UCV, or the concentration of airborne MCPs, and some ORs were likely to have the demonstrated problem of being no better than conventionally ventilated ORs.[30] A more critical analysis of data from the Norwegian Joint Registry that was included in the study showed that the type of ventilation systems had not been identified correctly,[31] and when the data was re-analyzed to compare the better designed UCV systems with conventionally ventilated ORs, a significant reduction in infection was found.[32]

Further MRC and DoH studies on the design of UCV systems

The MRC study investigated a variety of UCV systems, including Allander systems, isolators, and horizontal unidirectional air flow (UDAF) systems, but the vertical-flow UDAF system was shown to be effective, and was being commonly installed during and after the MRC study. Therefore, research was commissioned by the MRC and the Engineering Division of the Department of Health in the UK to investigate the optimal design of vertical UDAF systems, and an article summarizes these studies.[33] These results are incorporated into the recommendations for the design and testing of UDAF systems in HTM 03- 01 of the National Health Service, England.[10]

Conclusion

It has been over 150 years since Lister introduced the first methods to reduce SSI in ORs, and in the mid-20th century it was demonstrated that airborne microbes can cause SSI. Since then, evidence has been gathered to show that modern orthopaedic surgery requires low concentrations of airborne MCPs, and significant progress has been made in improving ventilation systems to provide this requirement.

Strong consensus has been expressed at the International Consensus Meeting on Periprosthetic Joint Infection[34] that 'the numbers of bacteria in the operating room environment correlate directly with the probability of surgical site infections' and 'airborne particulate bacteria are a major source of contamination in the OR environment, and that bacteria shed by personnel are the predominant source of these particles. The focus of our recommendations is to reduce the volume of bacteria in the OR with particular attention to airborne particles.'

Airborne MCPs can enter the OR from adjacent rooms and in the air supply, but ORs can be designed to avoid contamination from these sources. However, the major source of airborne MCPs that still remains is people in the room. People present during surgical operations are the source of most, if not all, of airborne microbial contamination in present-day ORs. An effective approach to minimize airborne MCPs is the use of occlusive clothing and the removal of remaining MCPs by ventilation. However, in present-day ORs, airborne microbial contamination still remains, and further progress is required. Perhaps, in the future, surgeon-controlled robots will be used,[35] and people will not be present during surgical operations, but, at present, it should be possible to approach closer to sterile conditions through superior ventilation systems, better-quality occlusive clothing, and effective routine testing of the ventilation system to ensure the correct quality of air is provided in the OR. By use of these control measures, progress will be made to lowering airborne infection in operating rooms. These requirements will be more costly but there are advantages, particularly after total joint replacement operations, where there will be fewer patients suffering pain, temporary or permanent disability, and loss of earnings, as well as cost reductions to the health service by avoiding extended hospital stays and revision surgery.

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Funding statement

The authors received no financial or material support for the research, authorship, and publication of this article, other than the open access funding outlined below.

ICMJE COI statement

The authors have no conflicts of interest to disclose.

Open access funding

The open access fee was funded by the University of Parma, Italy.

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