J. Hyg., Camb. (1974), 72, 415
With 4 plates
Printed in Great Britain

The effect of obstructions and thermals in laminar-flow systems

BY W. WHYTE AND B. H. SHAW
Building Services Research Unit, University of Glasgow G12 8RZ

(*Received* 28 *September* 1973)

SUMMARY

The influence of obstructions and thermals on the air flow in unidirectional or laminar flow systems was studied with special reference to operating rooms. It was shown that thermals induced in the operating rooms would have little influence in the normal laminar-flow system. The importance however of obstructions such as operating lamps and personnel was shown.

INTRODUCTION

At the present time, the air conditioning systems of the vast majority of operating rooms are being designed and built to conventional air-conditioning principles. These principles are embodied in the M.R.C. report on the air conditioning of operating theatres (Report 1962), and more recently in the Joint Working Party Report on the Ventilation in Operating Suites, (M.R.C. Report 1972).

Before the development of the laminar-flow principle of ventilation, work had been carried out in the conventionally ventilated operating-rooms to increase their efficiency in removing bacteria. Blowers & Crew (1960) studied, under experimental conditions, two different methods of distributing air to the operating room, namely uniform mixing with turbulence and downward displacement with a minimum of turbulence. They concluded on the evidence available at that time that the displacement system was best, and this they found to be best obtained with a finely perforated ceiling. This method was obviously a forerunner of the laminar-flow system but was shown to be ineffective owing to the use of low volumes of air 0·56 m.^{3}/s. (1200 ft.^{3}/min.) and the turbulence produced by convection and staff movements (Stanley, Shorter & Cousins, 1964; Lidwell, Richards & Polakoff, 1967).

Although it is possible, with conventional ventilation systems, to make a considerable reduction in the number of bacteria in the air compared with those in a room with no ventilation at all, there is still a substantial number of bacteria present. In order to realize the hope that a reduction in the airborne bacteria in operating-rooms will be associated with a drop in wound sepsis, investigations have been made into ultra-clean environment for use in operating-rooms (Charnley, 1964; Whitcomb & Clapper, 1966).

A large number of systems of this type are now being installed throughout the world but it will be a long time before they are up to the standard of conventional systems as many questions require to be answered. Two such questions are related to the effect of obstructions and of thermals in laminar flow. Although unidirectional flow has an advantage over turbulent flow in that bacteria produced should be swept away immediately they are generated, the effect of obstructions and thermals would tend to make the laminar flow into a turbulent one.

METHODS AND RESULTS

In carrying out this research we have used three techniques which may be of interest to those involved in the study of air flow. The flow of unidirectional air is often represented in diagrams by arrows or straight lines which frequently have little resemblance to the actual flow. This type of diagrammatic visualization arises often from the sheer lack of knowledge as to what is actually happening in a given situation. We describe therefore three techniques which may be useful to other investigators.

Schlieren photography

Hot air rising from an object hotter than the surrounding atmosphere is lower in density than the air around it. As the refractive index varies with density, light passing through the hot air will be refracted. By use of suitable optical techniques this effect can be used to show up the hot air round an object.

This technique to show up differences in density is not new and was used by the German glass industry to show up the 'Schlieren' or flaws in their glass. It has been scientifically developed by workers in the field of aeronautics and these methods are described in a comprehensive review by Holder & North (1963) but the use of this system to study heat flow round humans is described by Lewis *et al.* (1969). The method we have employed is similar to that used by Lewis and his colleagues.

The light source in our system was a high-intensity film projector bulb which was brought into focus by a condenser onto a pin hole which was at the focal distance from a high quality 12″ diameter mirror. The parallel light beam then passed through a 1 ft. diameter hole in the partition of the laminar flow system and out through a similar hole in the other wall. Any object to be studied was placed in the light beam in this area. The light beam was then focused by a second mirror on to a pinhole and photographs taken by a single-lens reflex camera without the lens. By use of this camera the shutter speed was easily obtained for a given type of film. Any hot air rising from an object in the parallel beam would cause refraction of the light rays which would then fail to pass through the pinhole and be shown as dark areas in the photograph.

In order to study the effect of heat rising from a hot body, we chose to examine one pod of the lamp (Drayton Castle 'Daystar') which we had used in our laminar flow operating room (Whyte, Shaw & Barnes, 1971). This was one pod of a four-pod lamp assembly. This lighting pod, because of the quartz-halogen system, used 250 watts as compared with about 350 watts for a complete conventional operating lamp and the 100 watts of sensible heat produced from a surgeon working fairly hard.

It may therefore be seen that the thermal effect of this lamp is likely to be the most intense of any heat source in an operating theatre and if the unidirectional flow is capable of overcoming these adverse effects it is likely to overcome all others. This is confirmed by measurements of velocity we took with a hot wire anemometer which showed that the velocity of the air rising from a pod of our operating lamp could be up to 0·6 m./s. (120 ft./min.) whereas it was only 0·2 m./s. (40 ft./min.) from a person.

These effects were investigated in the case of the lamp by Schlieren photography and in the case of a man by bubble generators.

Plate 1*a* shows the heat rising from the lamp in still air and Plate 1*b*–1*f* show the effect of a downflow of air of velocity, 0·1, 0·2, 0·3, 0·4 and 0·5 m./s. Shown in Plate 2*a*–2*f* is the effect of a crossflow of unidirectional air of velocity 0, 0·1, 0·2, 0·3, 0·4 and 0·5 m./s. There was a certain amount of variability in the effect of air at a given velocity and the photographs shown are typical of what happens but the same effect could occur on a small percentage of times at a velocity 0·1 m./s. greater or less than the given speed.

Bubble generator technique

It is normal practice to show the flow of air by use of smoke. This technique however has severe limitations, in that smoke quickly diffuses and also fails to give any indication as to the relative air speeds. It is also true that although smoke tests are of use to the person who is actually using them, they are of little use for permanent records of the observed air flow. In order to study and report the flow of air in different laminar-flow conditions we adopted a method recently developed by the National Institute of Agricultural Engineering in Britain, and now fully described by Carpenter & Moulsley (1972). This system uses an air supply mixed with helium and a simple bubble generator* to produce a flow of neutral-buoyancy detergent-bubbles of 4 mm. average diameter. We are also aware of a similar system produced in the U.S.A. by Sage Action, Inc., New York, and have been favourably impressed by the reliability of the two systems.

Carpenter and Moulsley advocated a relatively elaborate camera shutter-system which shows the direction of flow of the bubble as a series of dashes diminishing in size away from the direction of movement. This system is necessary where the direction of flow is arbitrary or unknown, but fortunately this is not so with unidirectional flow. It was only necessary in our case to photograph the bubble mass at a time exposure of 1 sec. to achieve photographs of the type shown in Plate 3*a*, *b*, and Plate 4*a*, *b*.

The original light source we used was a series of spot lights set up in a duct, the light being projected through a slit facing the flow of air to be studied. In the case of the obstruction being large and cutting off the light illuminating the area behind it, a further light source was added at the air supply and facing the direction of the air movement. We have now found a single fog lamp on each side of the object to be successful. They have a narrow light beam the intensity of which can be

* Further details about this bubble generator are available from the National Institute of Agricultural Engineering, Silsoe, Bedford, U.K.

https://doi.org/10.1017/S0022172400023652 Published online by Cambridge University Press

controlled either by blanking off the light beam or by a variable transformer and they also have a small surface area and therefore do not disturb the air flow. The air movement bubbles were illuminated and the background kept dark with a backcloth. Two or three bubble generators were used in our studies and it may be seen that the bubble movement is shown up as a streak, its length being proportional to the velocity of the streamline. Knowing the actual length of the bubble streak by reference to a known object size in the photograph and the exposure time of the camera, the velocity of the air stream at a particular point may be ascertained.

Shown in Plate 3*a* is the airflow (0·4 m./s.) round a lamp 1 m. in diameter. This type of lamp is typical of those used in Europe and this shape of lamp is probably installed in over 99 % of the operating rooms in Britain. It may be seen from the direction of the bubbles and the lower velocity of those present at the lamp face that a large area of stagnancy exists behind the lamp. Plate 3*b* shows the way that the air flow is not disrupted when the lighting surface is parallel to the air stream.

Plate 4*a* is a bubble generator photograph of the lighting system we have adopted for our laminar-flow operating-room. This is a Drayton Castle 'Daystar' lamp which has two of the six pods of the lamp removed. The removal of two pods gives a lamp with satisfactory lighting for the surgeon and a better airflow pattern. It should however be realized that this lamp is asymmetrical and the bubbles are generated in one plane so that this photograph gives a better than average picture of the airflow pattern round the light as quite a number of the bubbles are passing, without resistance, through the centre of the lamp.

The photographs shown in Plates 3*a*, *b* and 4*a* are very similar to those obtained by Lidwell (1971) when using smoke trails and a model to investigate airflow in unidirectional flow systems.

It should also be noted that Plates 3*a*, *b* and 4*a* were of lamps in a horizontal air flow and in this flow the stream lines will converge again after passing round the light. However in the case of vertical flow the floor will tend to counteract this effect so that a larger stagnant area will result.

It may be seen in Plate 4*b* that the thermal effect from a person is overcome in a horizontal airflow of about 0·4 m./s. This is to be expected as the heat output of a human is not as great as one of the tested pods. It should be noted, however, that there is considerable turbulence behind a person and this appears to us to be a major factor in reducing the efficiency of laminar-flow systems.

Smoke challenge test

It should be realized that what is significant about the above bubble generator photographs is not the fact that the air downstream of an object is turbulent, or even stagnant, but that any contamination generated in this area, e.g. by a surgeon, would linger and make the area one of gross contamination. If there was no contaminating source, then the turbulence would be of little consequence. In order to illustrate this, observations were made of the route taken by smoke released in the highly turbulent zone after the lamp. A simple smoke source was

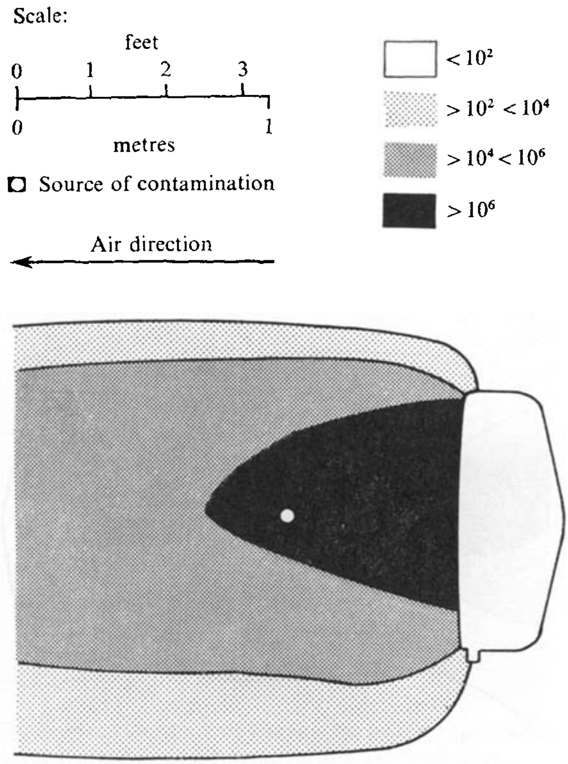


Fig. 1. Diagram showing the backflow of contamination from a source 0·8 m. from a large lamp.

used – a cigarette. This produced a surprisingly uniform source of smoke which, although it initially tended to rise, gave very reproducable results of the type illustrated in Fig. 1. Samples of air were analysed by a Royco Particle Sampler in a given plane at 20 cm. intervals and zones of equal contamination determined. These zones were expressed in concentrations per cubic foot of particles $\geqslant 0{\cdot}5\ \mu$m. The zones were $< 10^2$, between 10^2 and 10^4, between 10^4 and 10^6 and $> 10^6$ particles per cubic foot. These lines of equal contamination are known as isopleths.

Fig. 1 is an isopleth diagram demonstrating the effect of a 1 m. diameter operating lamp on a contaminating source placed 0·8 m. (30 in.) away from it. The contamination, instead of being carried forward, is actually drawn back into the stagnant area to give a zone of high contamination. If the contamination source is placed a further 0·6 m. (24 in.) away from the lamp, one would expect from the bubble generator photographs that the contamination would all now be blown forward. This in fact did not happen, as shown in Fig. 2. Although a reasonable percentage of it did move forward a surprising amount found its way back up to the lamp.

Fig. 3 shows the advantage of the smaller podded lamp. The contamination was 0·8 m. (30 in.) away and therefore similar to Fig. 1, but highlights the fact that even using this type of lamp, zones of high concentration can occur as seen by the flow back of contamination.

https://doi.org/10.1017/S0022172400023652 Published online by Cambridge University Press

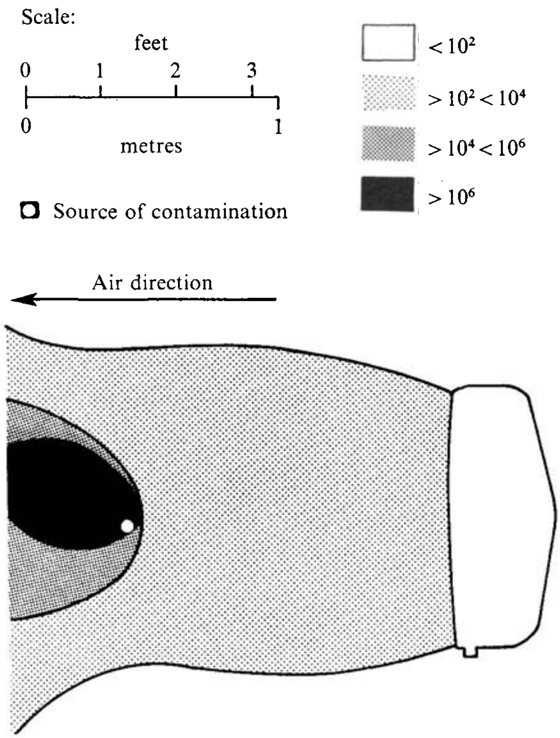


Fig. 2. Diagram showing the small amount of backflow and stagnancy from a source 1·4 m. from a large lamp.

DISCUSSION AND CONCLUSIONS

Unidirectional or laminar flow has an advantage over conventional turbulent ventilation systems in that the contamination generated is swept immediately away instead of being diluted. However several factors could tend to destroy the unidirectional nature of the airflow and negate its inherent advantages. One of these factors is the effect of thermals, the other that of obstructions.

Effect of thermals

Discussion of the conclusions reached in this paper with regard to thermal effects may be divided into two parts – one part concerned with the reaction of hot objects in an operating theatre to the down-flow of unidirectional air and the other with a cross-flow of air.

Hot air rising from the operating-lamp and people in an operating-room will tend to disrupt the downward flow of sterile air which would normally wash away the contamination produced in the area of the wound. We have studied the downward velocity that is required to overcome this effect from what must be the most intense source of heat likely to be found in an operating theatre, namely a pod of the Drayton Castle 'Daystar Lamp'. By use of Schlieren photography it has been demonstrated that the upward thermals are overcome at downwards air speeds of 0·3 to 0·4 m./s. (60–80 ft./min.). Smaller heat sources will of course

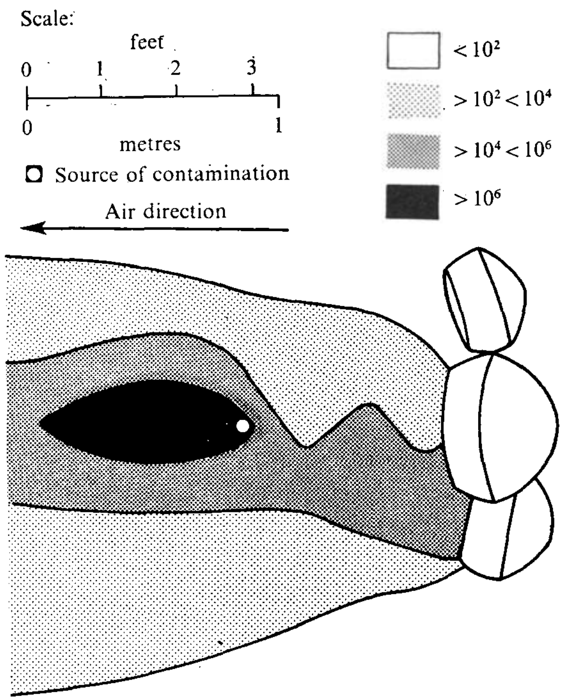


Fig. 3. Diagram showing much less backflow of contamination from a source 0·8 m. from a skeletal lamp.

require a lower velocity. This speed of between 0·3 and 0·4 m./s. coincides with the velocity we have advocated for laminar-flow operating rooms from studying the contamination concentrations at different velocities during operations in a down-flow or crossflow laminar-flow system. (Whyte, Shaw & Barnes, 1973).

The results obtained from the crossflow of air require fuller interpretation as there is no point at which the heat rising was completely overcome. Because the two forces (thermal and air velocity) were at right angles to each other the resultant thermal force of the heat rising from the lamp was up and in the direction of the air. As the air rose, however, it would be quickly overcome by further air velocity forces and turned in the direction of the horizontal air supply. Unfortunately owing to the small field of view of the Schlieren system it was not possible to see this effect but bubble generator studies which are not reproduced here demonstrated that at normal velocities, i.e. over 0·3–0·4 m./s., there was little discernable difference between the airflow round the lamp when it was on, and therefore hot, and when it was off. The main factor influencing the airflow was the obstruction by the lamp.

These above facts were confirmed by observation of airflow around a man where the thermal effects were easily overcome but the disruption of flow was caused by his obstruction and movement.

In conclusion it would appear that thermal effect may be discounted in laminar-air flow in an operating theatre.

Effect of obstructions

One of the most significant obstructions in an operating room is the operating theatre lamp, and we have studied this effect by two methods which may be of use to others. Using these two methods we hope we have shown that when a lamp with a large surface area is used there is a considerable stagnant area behind the lamp. The stagnant area would not be a problem if this air was not in contact with any source of bacterial dispersion, or if the area was not required to be sterile. This can be achieved in many types of surgery with a knowledge of what is happening to the air flow and how to overcome it by judicial siting of the lamp. Most people, however, in operating rooms have not the experience to do this, and it is therefore necessary to overcome this problem. An over emphasis, however, of this problem can lead to solutions such as the placing of lamps outside the air flow. This would normally remove the control of the lighting from the surgeon and use of the currently available equipment could result in a poor system which is more expensive. We therefore advocate at the present time an in-flow system with lamps of small enough diameter to produce turbulence which will not come into contact with the operating field. The benefits are shown in the use of our modified Drayton-Castle 'Daystar' lamp, but we are also aware of several other operating theatre light manufacturers who produce lighting systems which would also be suitable. The need for small operating lamps is far greater in down flow systems of ventilation, where the lamp may be in a position over the critical area of the wound and cause a stagnant area with a high concentration of bacteria.

In the case of cross flow, however, the need for modified lighting is much less, as the chance of the lamp being in such a position as to cause a stagnant area at the wound is more remote. However, use of lamps with a smaller surface area could do nothing but help the air flow pattern.

In a fast developing field such as that involved in the production of ultra-clean ventilation systems, many new ideas will be produced which will no doubt supersede ours, but it is hoped that the methods outlined above will help to evaluate these systems.

This study was financed by the Medical Research Council, U.K. We should like to thank Mr P. Bailey for his skilled technical assistance.

REFERENCES

BLOWERS, R. & CREW, B. (1960). Ventilation of operating-theatres. *Journal of Hygiene* **58**, 427.

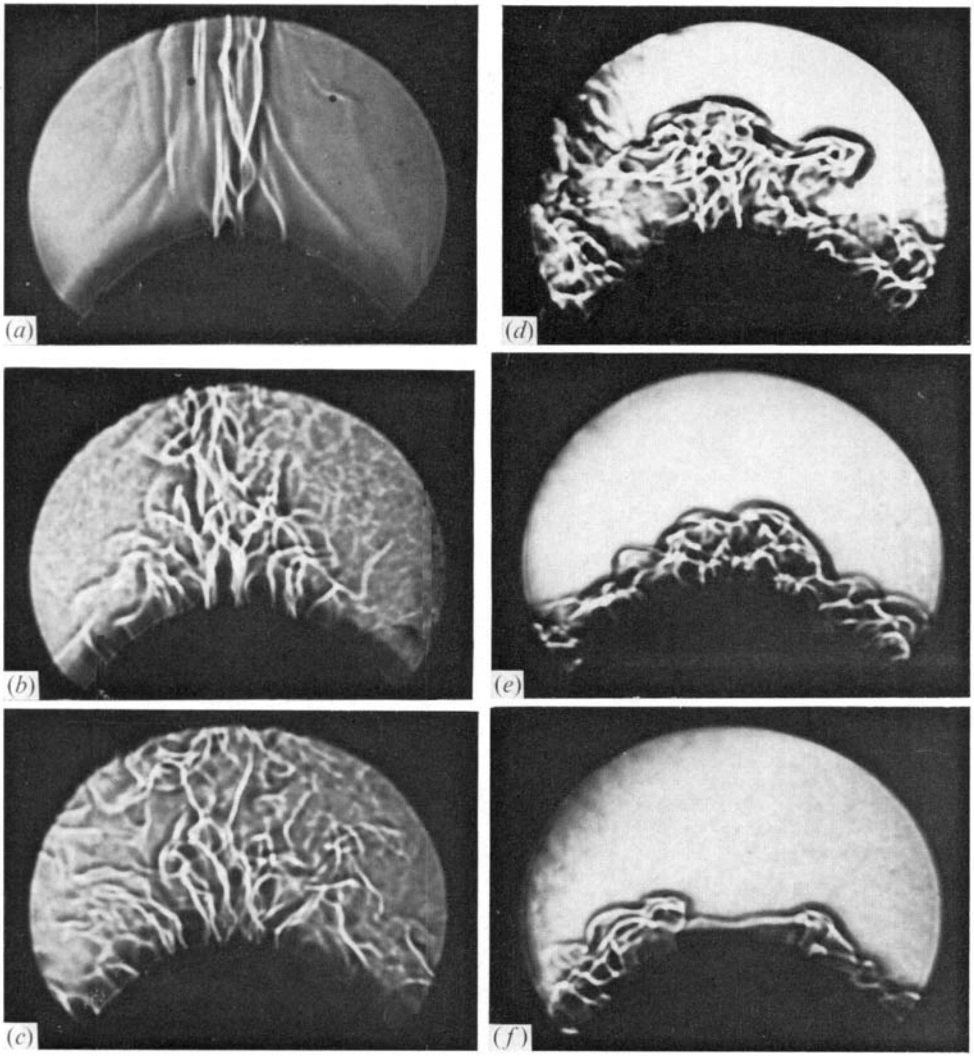
CARPENTER, G. A. & MOULSLEY, L. J. (1972). A visualisation technique for studying air movement in large enclosures over a wide range of ventilation rates. *Journal of the Institution of Heating & Ventilating Engineers* **39**, 279.

CHARNLEY, J. (1964). Sterile-air operating theatre enclosure. *British Journal of Surgery* **51**, 195.

HOLDER, D. W. & NORTH, R. J. (1963). Schlieren methods. *N.P.L. Notes on Applied Science No.* 31, H.M.S.O.

LEWIS, H. E., FOSTER, A. R., MULLAN, B. J., COX, R. N. & CLARK, R. P. (1969). Aerodynamics of the human microenvironment. *Lancet*, i, 1273.

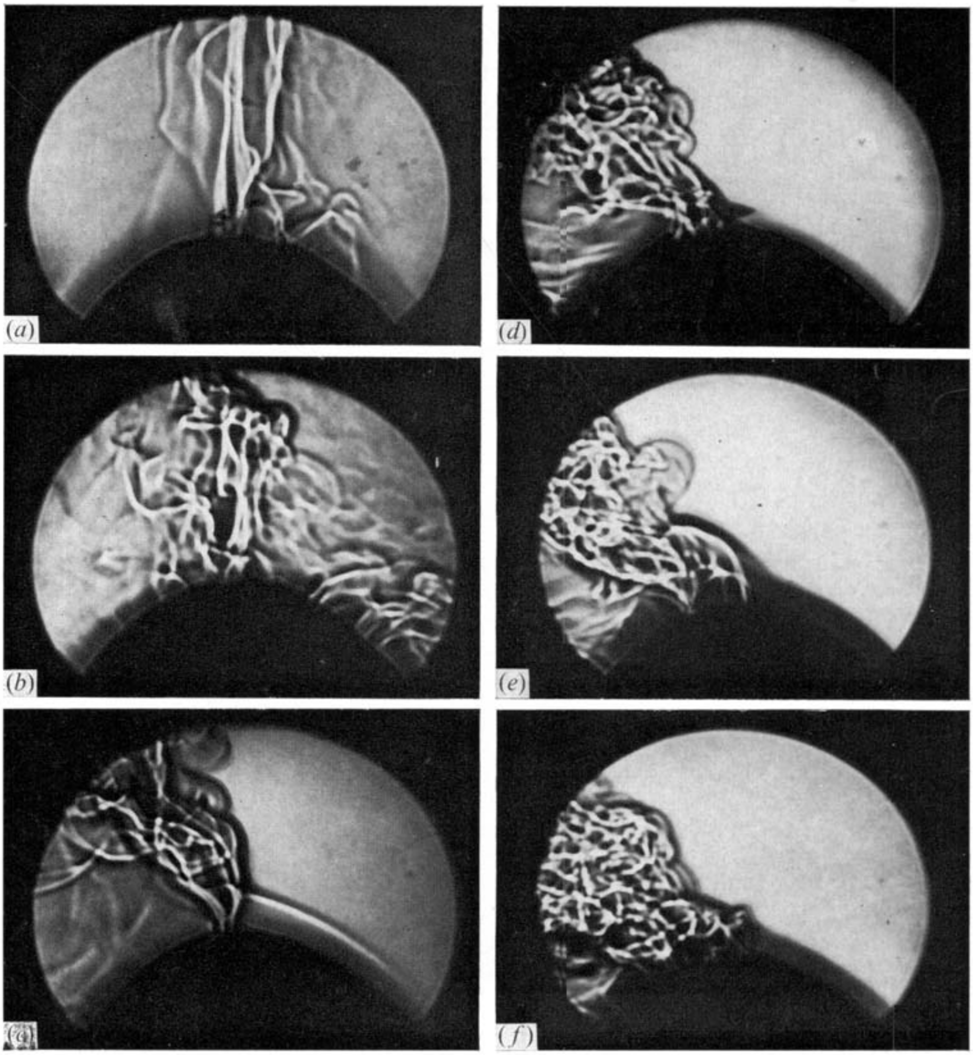
https://doi.org/10.1017/S0022172400023652 Published online by Cambridge University Press



W. WHYTE AND B. H. SHAW

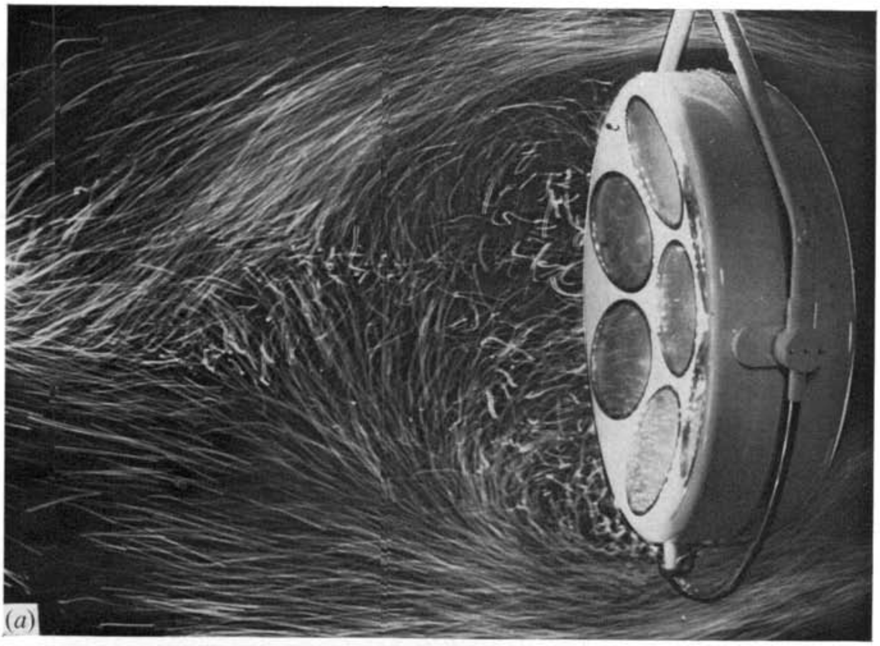
(*Facing p.* 422)

https://doi.org/10.1017/S0022172400023652 Published online by Cambridge University Press

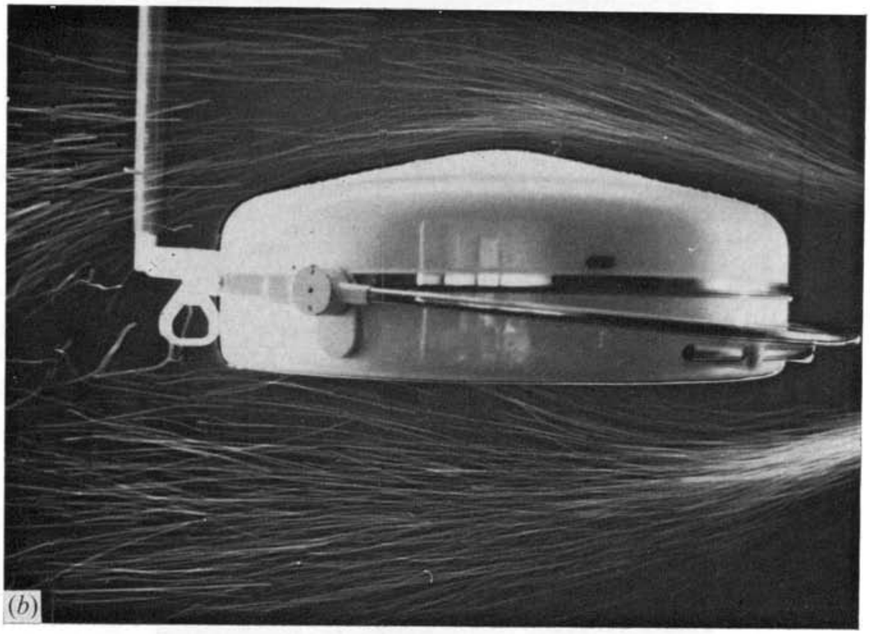


W. WHYTE AND B. H. SHAW

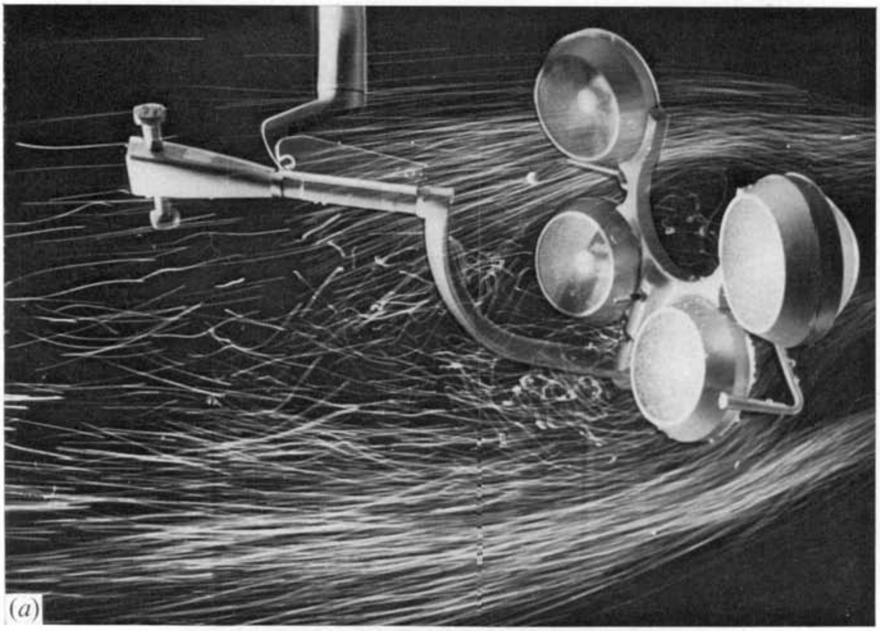
https://doi.org/10.1017/S0022172400023652 Published online by Cambridge University Press



(*a*)



(*b*)



(a)

(b)

W. WHYTE AND B. H. SHAW

https://doi.org/10.1017/S0022172400023652 Published online by Cambridge University Press

Lidwell, O. M. (1971). Smoke trails and models for the exploration of unidirectional flow ventilation systems. *Journal of the Institution of Heating and Ventilating Engineers* **39**, 131.

Lidwell, O. M., Richards, I. D. G. & Polakoff, S. (1967). Comparison of three ventilating systems in an operating room. *Journal of Hygiene* **65**, 193.

Report (1962). Design and ventilation of operating-room suites for control of infection and for comfort. *Lancet* ii, 945.

Report (1972). *Ventilation in operation suites*. Medical Research Council, London.

Stanley, E. E., Shorter, D. N. & Cousins, P. J. (1964). A laboratory study of the downward displacement system of ventilation in operating theatres. *The Heating and Ventilating Research Association, Laboratory Report* No. 19.

Whitcomb, J. G. & Clapper, W. E. (1966). Ultraclean operating rooms. *American Journal of Surgery* **112**, 681.

Whyte, W., Shaw, B. H. & Barnes, R. (1971). An experimental laminar flow operating-room. *Lancet* ii, 905.

Whyte, W., Shaw, B. H. & Barnes, R. (1973). A bacteriological evaluation of laminar-flow systems for orthopaedic surgery. *Journal of Hygiene* **71**, 559.

EXPLANATION OF PLATES

Plate 1

Effect of a downflow of air on the heat rising from a single pod of the Drayton Castle Daystar operating lamp. (*a*), 0 m./s.; (*b*) 0·1 m./s.; (*c*), 0·2 m./s.; (*d*), 0·3 m./s. (*e*), 0·4 m./s.; (*f*), 0·5 m./s.

Plate 2

Effect of a crossflow of air on the heat rising from a single pod of the Drayton Castle Daystar operating lamp. (*a*), 0 m./s.; (*b*), 0·1 m./s.; (*c*), 0·2 m./s.; (*d*), 0·3 m./s.; (*e*), 0·4 m./s.; (*f*), 0·5 m./s.

Plate 3

(*a*) Stagnant area resulting from the use of a conventional lamp in vertical laminar-flow conditions. Direction of flow from right to left.

(*b*) Airflow condition resulting from the use of a conventional lamp in horizontal laminar-flow conditions. Direction of flow from right to left.

Plate 4

(*a*) Airflow resulting from the use of a modified Drayton Castle 'Daystar' lamp. Direction of flow from right to left.

(*b*) Turbulent effect from a person in a horizontal airflow of about 0·4 m./s.