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27. AIR-CONDITIONING IN OPERATING ROOMS*

P. A. BOSSERS

1. INTRODUCTION

Air-conditioning is designed to control the environment of humans within an enclosed room such that the factors determining the climate, i.e. the temperature, the velocity and the relative humidity of the air, remain within certain limits. These limits are chosen such that a percentage as high as possible of the people experience the climate thus offered as comfortable. The temperature and relative humidity are chosen in dependence on metabolism, clothing and other factors. We might call this: the thermal climate control.

Besides, air-conditioning is meant to control the climate in a hygienic sense. For that purpose an amount of fresh air is fed to a room so that human smells or odours, carbon dioxide from the air resulting from expiration and solid or gaseous impurities that are released into the room, all remain below the limit at which they are inconvenient or noxious. The way in which the air is fed to a room has an effect on the local concentration of these admixtures. Furthermore, heat sources play a role as to the distribution of such impurities in the room. In the following chapters we shall mainly deal with airconditioning in the hygienic sense.

2. SOURCES OF AIR POLLUTION IN OPERATING ROOMS

Two types of air pollution prevail in operating theatres: solid particles (dust), and gaseous impurities. The first type especially affects their bacteriological purity because germs adhere to the dust. This type of pollution will not be discussed in further detail here. We shall now focus on gaseous impurities; they originate in particular from the anaesthesia facilities and from the very persons in the operating room. The most important 'human' impurities are water vapour via exhaled air and via evaporation at the skin, carbon

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dioxide and smells exuded along with perspiration. Long before any carbon dioxide concentration can be noxious to human health, the concentration of water vapour and those smells will have become a nuisance. In particular the latter group of admixtures causes a sultry and stuffy atmosphere. A relatively small amount of fresh air (minimum approximately 30 m^3/h a head) is sufficient to maintain an adequately hygienic atmosphere.

Anaesthetic gases are odourless, in the concentrations that normally occur in operating rooms, and as a result they are not directly objectionable. As there are indications, however, that they may have noxious side effects for humans on prolonged exposition, it is useful to ascertain what levels of concentration may be expected, if exhaust of these gases is effected into, and not away from, the operating room. Moreover, also at low concentrations they tend to cause headaches.

It is assumed that the anaesthetic gases are mixed with air to such an extent that they have no rate of fall of their own, and that they do not unmix either. Measurements have shown that these assumptions are justified.

3. TRANSPORT OF GASES IN A ROOM

If exhaust of anaesthetic apparatus is into the operating room, the highest concentration of gases will occur close to the apparatus. This concentration is equal to that administered to the patient.

When the air is perfectly stationary (an imaginary situation), spreading of anaesthetic exhaust can only occur because the gas discharged is 'pushed up' by a new supply, and by diffusion. Then, finally, a cloud with a high concentration of anaesthetic gases would occur, which, at its edges, has a somewhat lower concentration than in its core, just because of diffusion. The air movements that occur in a room are so intense, however, that the occurrence of such an exhaust cloud is prevented. Incidentally, the causes of air movements will be discussed in the next chapter. The distribution of anaesthetic gases by diffusion can, in fact, be neglected. Even hydrogen, which has a relatively high diffusion rate, does not attain any more than some cm/sec at great differences in concentration (1).

Movement of anaesthetic gases of their own accord can be observed in very quiet air, at rather high concentrations. Because of their greater specific mass, the anaesthetic gases will tend to drop.

From measurements it has been found that, if these gases are mixed with air, such movements because of differences in mass are negligible. As a result, there is no unmixing.

4. THE GENESIS OF AIR MOVEMENTS IN ROOMS

For transport of impurities in a room, it is mainly the movements and flows of air that are responsible. Such a pattern of movements can only result from the influence of some driving force. The generating forces that play a role here may be divided as follows:

1. the impulse of the air which, at a certain speed, flows into the room;
2. differences in temperature;
3. the 'stirring effect' of moving objects, and that of human beings.

4.1. *Movement of air as a result of ventilation*

Practically always an amount of air will enter a certain room and an equal amount will leave that room, even if there is no mechanical ventilation. Under the influence of wind pressure upon the façades of a building, and the differences in temperature of the air that are usually present in the building,

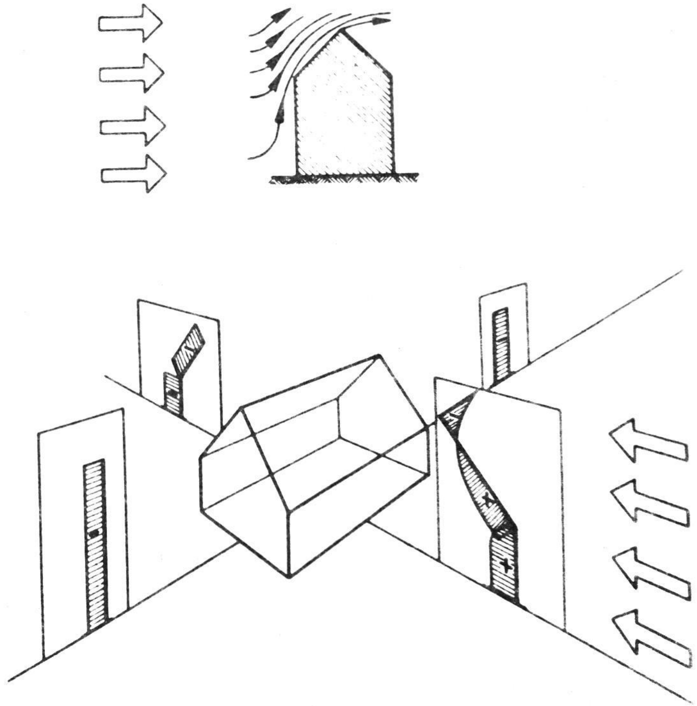

Fig. 1. Air pressures on a building subjected to wind.

and also outside it, differences in pressure will arise. These differences in pressure cause a transport of air. For instance, via cracks of windows and doors, open windows and the like. In this way, 'natural' ventilation takes place (fig. 1). Operating rooms are generally provided with a mechanical ventilation system, so that the pressure ratios are better controlled and undesirable air transports, e.g. from the nursing departments or patients' rooms to the operating theatre, can thus be avoided. The supply of air, whether by perforated panels, grills, ceiling outlets or the like, is practically always implemented in the form of one or more 'jets' of air. Whether such a jet is great or small does not essentially affect its composition. Basically it is always composed of a core zone, in which the quality and speed of the air are equal to those of the air in the inlet opening, and a mixing zone in which mix the air fed to and that present in the room (fig. 2). The entering air jet mostly has a higher speed than that of the air in the room. The circumference of the air jet then entrains particles of air and, in the eddies thus created, the mixing process takes place. This mixing relates to speed, differences in temperature and to impurities present in the room.

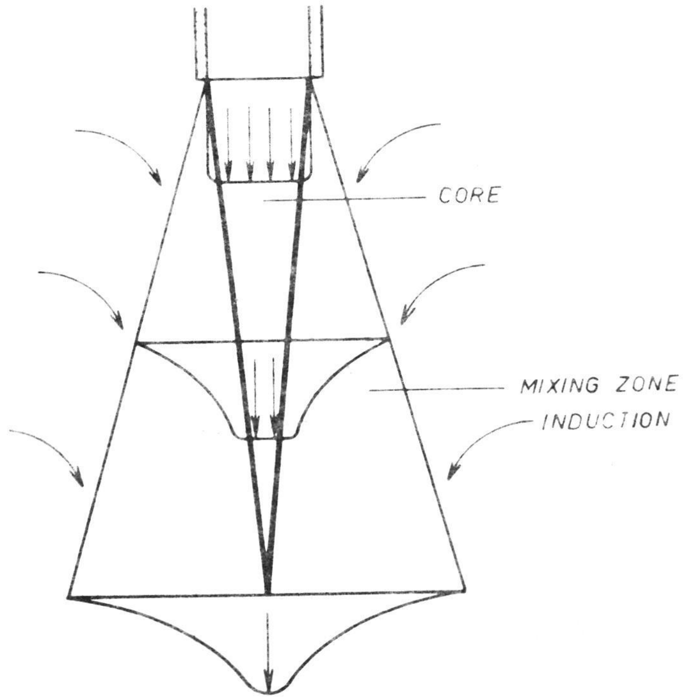

Fig. 2. Sketch of an air jet

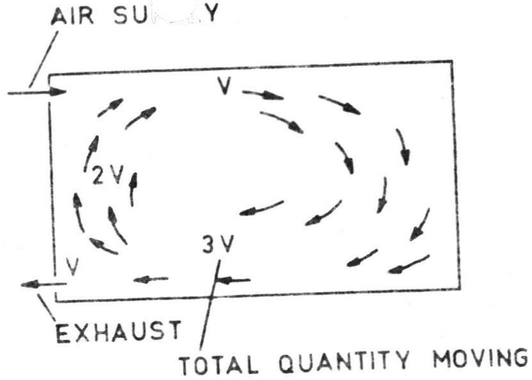

Fig. 3. Quantities of air moving in a ventilated room.

In its course through the room, an air jet puts an amount of air into motion that is approximately two times its own volume. Since as much air is exhausted as is supplied, the amount of air that is moving will be about three times as large as the amount fed, though at relatively low speeds (fig. 3).

The mixing process, as much as it relates to speed and temperature, benefits the degree of comfort experienced in the room. If the air jet would not be subject to this process, then persons present in the route followed by the jet would feel a draught. With regard to the impurities carried, mixing is often less desirable; particularly so in view of bacteriological impurities. In proportion as mixing intensifies, the impurities are better divided over the entire room.

The difference in temperature between the air in the jet and that in the room also has an effect on the course of the jet. If the air in the jet is warmer than that in the room, the jet will tend to rise and if the air in the jet is colder, the jet will decline. This influence of differences in temperature on the course of a jet also highly depends on the way it is blown in (fig. 4). For instance:

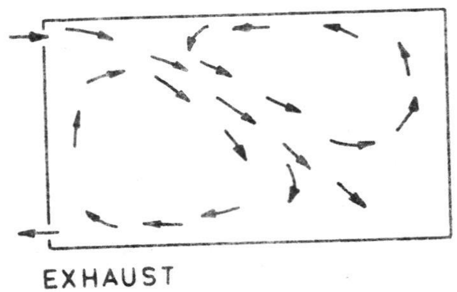

Fig. 4. Air-flow pattern when cold air is supplied.

the course of a jet of air that has been blown in horizontally and has a temperature lower than the air in the room, will decline and a jet directed vertically downwarhs will gain some extra speed.

Some examples of flow patterns resulting from ventilation are shown in figures 5-8.

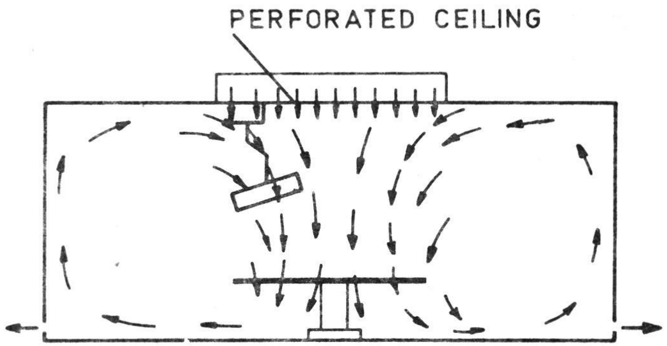

Fig. 5.

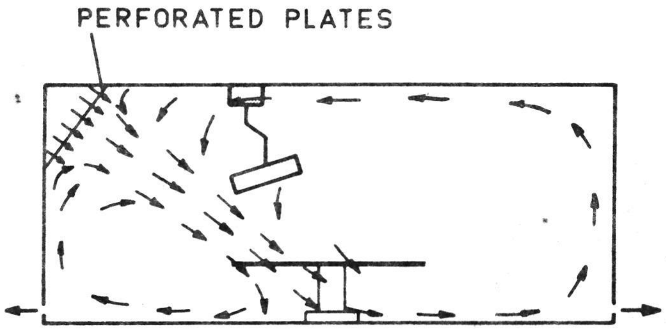

Fig. 6.

It will be clear from the above that the way of supply has much influence on the shape of the flow pattern. For an operating theatre that is not in use, the very way in which the air is fed to it is determinative for its air-flow pattern.

In contrast to our remarks about ways of feeding air to operating rooms, the place where exhaust takes place, and even the speed in the exhaust device, have hardly any influence on the total air-flow pattern. As appears from figure 9, the speed rapidly decreases with the distance to the exhaust opening. With a circular opening, of a diameter d, at a distance of 1 d the speed is only approximately 10% of the speed in that exhaust opening.

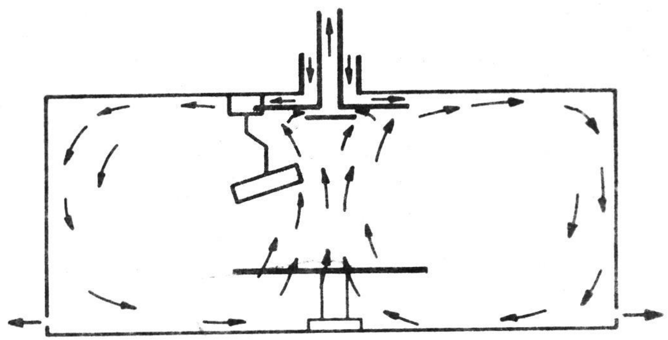

Fig. 7.

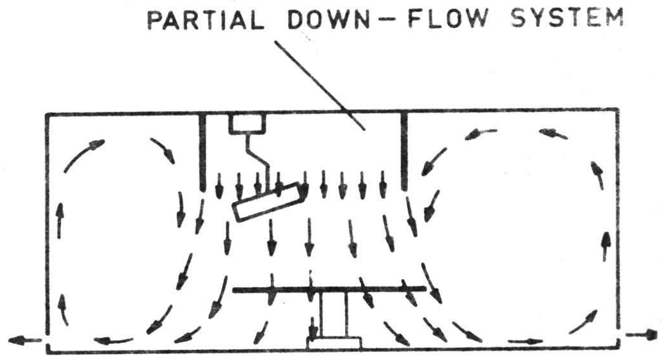

Fig. 8.

Figs. 5-8. Air-flow patterns in rooms with different systems of air-supply; without heat load in the rooms.

4.2. *Air movement caused by differences in temperature*

A second important factor in the genesis of air movement in a room, and accordingly for the transport of impurities, is that of air movements resulting from differences in temperature.

The specific mass of air highly depends on temperature; if air in a room is heated locally, then the heated part will rise in respect of the rest of the room's air. This heating may take place simply because there are persons present in a room and, also, it may be caused by equipment that is mounted in it and that produces heat; think of monitors, lamps, and the like.

At the surface of these heat sources heat is transferred to the air which therefore rises and is replaced by cooler air. Let us consider, by way of example, a person standing in quiet air. The surface temperature of his/her clothing is higher than the environmental temperature because internal heat production is partially discharged via clothing. As a result a layer of warm air flows upwards past the body. Over the head, this flow of air reaches a speed

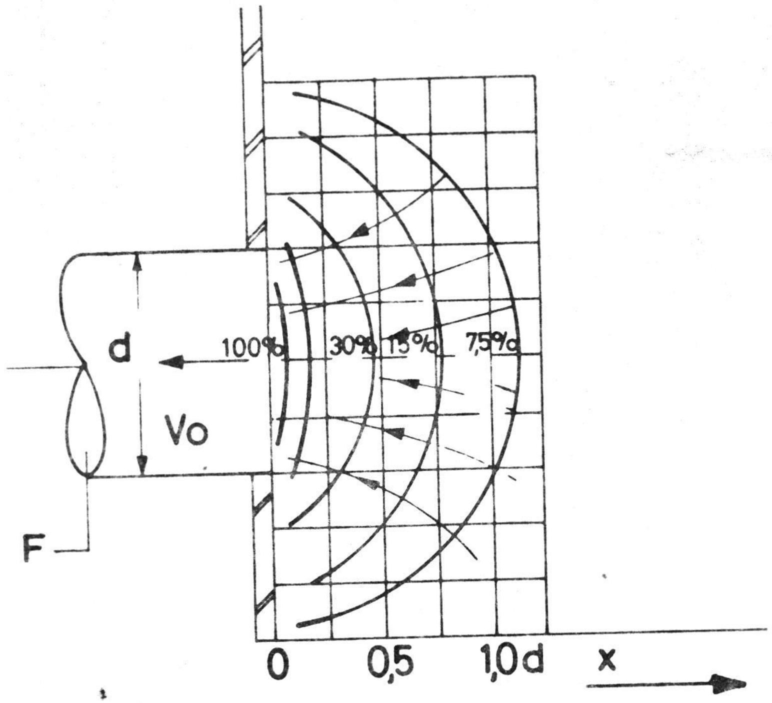

Fig. 9. Velocities near an exhaust opening.

of 0.2-0.3 m/s (fig. 10) (2). Largely determinative for the final speed of this convectional flow are two things: the magnitude of the difference in temperature, and the height over which this temperature difference prevails. It will be clear that the air-flow pattern in a room, as a result of the supply of air for ventilation, is also influenced by these convectional flows. In particular when the human and other heat sources are rather near, one to another, as is the case with a team of operating surgeons around a patient, the convectional flows are of some considerable intensity. For the same ventilation systems as shown in figures 5-8, the influence of convection on flow patterns is presented in figures 11-14. In this way, the temperature of the air blown in has also an influence on the air-flow pattern, as has already been elucidated. The movements as a result of the differences in temperature in the jet have been pinpointed by a number of investigators, and can be largely predicted via calculations (4).

An important source of air movement as a result of differences in tem-

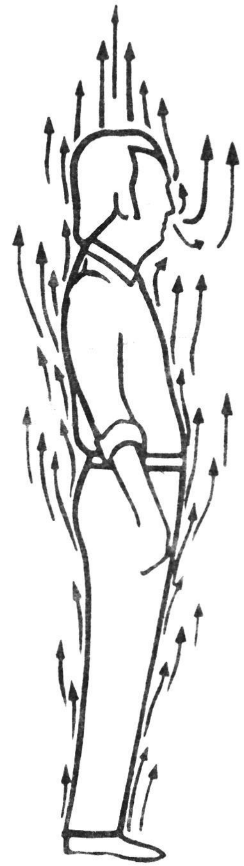

Fig. 10. Convection along a stationary person.

perature is that via the door opening between two adjacent rooms. If there is a difference in temperature between rooms, then in the door opening, or in the cracks when the door is closed, two opposite flows of air will occur. In the lower half, air flows from the cooler room to the warmer one, and in the upper half from the warmer to the cooler. To give an impression about the size of these flows, the following example may serve: at a difference in temperature between the rooms of only 1 °C, at least 350 m^3/h flows from one room into an other (4). Even when the door is closed, and without particular measures to seal the cracks, still approx. 30 m^3/h flows under these conditions from one room into an other (5).

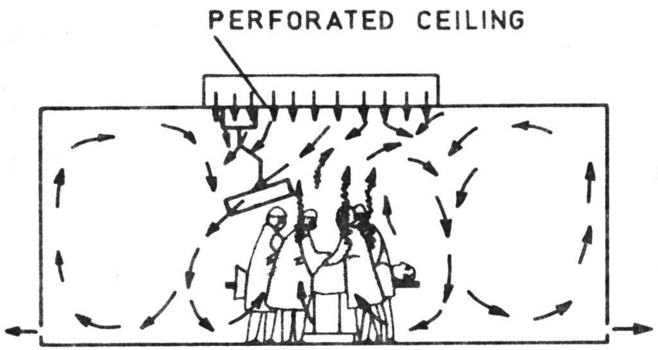

Fig. 11. Air-flow pattern in rooms with different systems of air-supply: with heat load in the rooms.

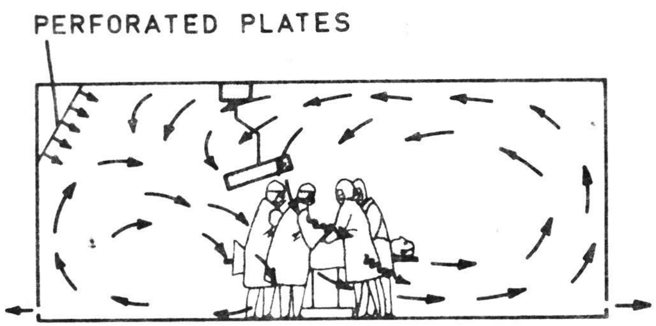

Fig. 12. Air-flow pattern in rooms with different systems of air-supply: with heat load in the rooms.

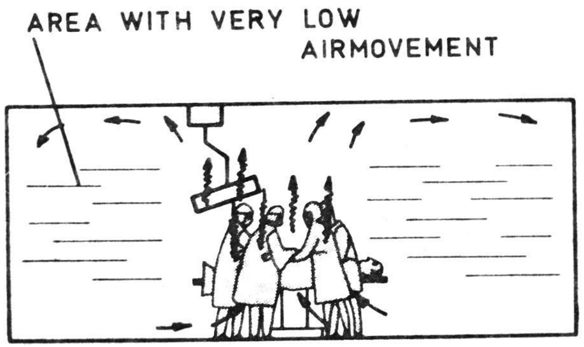

Fig. 13. Air flow pattern caused by natural convection of the operating team in the absence of mechanical ventilation.

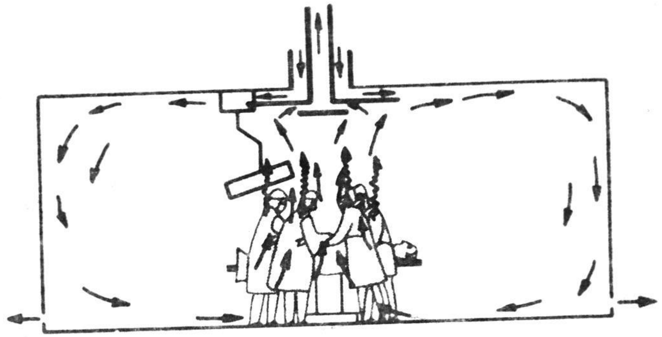

Fig. 14. Air-flow pattern in rooms with different systems of air-supply: with heat load in the rooms.

4.3. Movement of persons or objects

The third cause of air movement is that which results from movement of persons or objects. When people are walking, a vortex area is produced behind them and air is brought from one spot to an other. Naturally, this likewise applies to all objects that are moved. If, locally, there are differences in concentration of impurities, these will be smoothed down by this 'stirring' effect.

5. CONCENTRATION OF IMPURITIES

If, in a restricted space, a known amount of impurities is released, how great is then the concentration to be expected? This question can only then be answered exactly, if mixing of the impurities takes place immediately and completely. Though in practice this will never happen, investigation of the pertinent phenomena will give an insight in the process.

How the concentration will proceed from a point of time t = 0, in which concentration $C_0 = 0$, can be shown by the formula:

$$C_t = \frac{q}{aV} (1\text{-}e^{-at})$$

Where C_t = concentration at point of time t
q = amount of anaesthetic gas that is supplied (in l/h)
a = air change rate (h^{-1})
V = volume of the room in m^3.

Product aV represents the amount of ventilation air that per hour is fed into the room. From the formula it can be seen that the final concentration only depends on the amount of air that is fed, for after a sufficiently long period of time term e^{-at} has approached zero. The size of the room has no influence on the final concentration. There is a relationship, though, between the size of the room and the period of time in which the final concentration is reached. In figure 15 this has been pictured for rooms of 50 m³, 75 m³ and

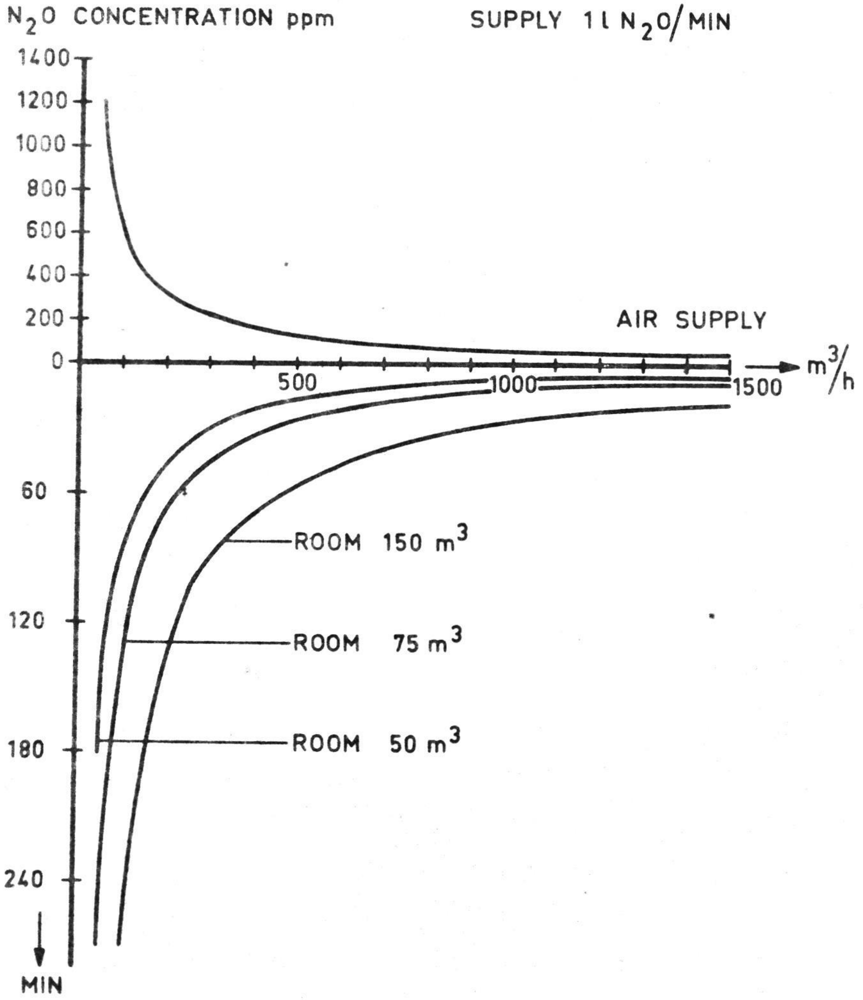

Fig. 15. N_2O concentration depending on the amount of air supplied. The time to reach 95% of the end concentration for rooms with different volumes.

150 m³. The horizontal axis plots the amount of air supplied that is responsible for the concentration plotted on the upper vertical axis. A supply of nitrous oxide of 60 l/h (1 l/min) has been assumed. For other amounts, the concentrations can be multiplied with the real amount of nitrous oxide supplied. On the lower vertical axis is plotted the period of time in which 95% of the final concentration is reached. From this can be concluded that human beings in a large room, with one and the same amount of air for ventilation, receive a dose (i.e. concentration x period of time of exposure) that is smaller than the dose in a smaller room. This will especially be of importance for rooms that are fed with a small amount of clean air, such as is the case when ventilation is natural.

Immediate and complete mixing is a purely theoretical case; it suitably serves as a base of comparison for conditions found in practice. In practice, if clean air is supplied to a room, it will take some time before mixing has taken place. As a result, in a surgery there will be locations of highly different concentrations. The distribution of anaesthetic gases very much depends on the flow pattern that is: on the way in which the air is supplied to the operating theatre, and on the nature and the positions of its heat sources. If we consider the outlet of the anaesthetic equipment as a point-source, it will make a great difference for the anaesthesist or the operating team, in respect of the concentration of anaesthetic gases, whether the air movements carries those gases directly in their direction or whether they first pass through the entire room. The longer path thus covered gives more opportunity for mixing, the concentration level meanwhile dropping.

If a flow with a high concentration goes past exhaust opening, the average concentration in the room will be lower than follows from the above theoretical approach; effectively, fewer impurities have then been introduced. The extreme case, which in respect of the persons present would have to be aimed at, is that exhaust for the room air is being implemented at the very location of exhaust of the anaesthetic equipment. Then the effective source of pollution approaches zero and, of course, so do the concentrations in the room. The concentration that is measured at a certain point in the room varies rather considerably with time. Apparently the mixing process takes place in such great eddies that, as it were, waves with alternate high and low concentrations pass the measuring point. If the surgeons and nurses walk much in the room, the amplitude of the 'waves' is smaller and then the differences in concentration from place to place are also smaller (see also Burm, this volume).

6. FINAL REMARKS

Restriction of the concentration of the anaesthetic gases to which persons working in a operating room are exposed, can be warranted in different ways. The most obvious way is: directly discharging the gases to outside the room. This has practically the same effect, both with naturally and mechanically ventilated rooms. Leakages, if any, in the anaesthetic system result in a greater concentration in case of rooms that are not ventilated mechanically. Mechanical ventilation achieves a reduction in the concentration in respect of rooms that are ventilated naturally. The differences in concentration, from place to place, then depend on the air-flow pattern. If that pattern is not known, measured concentrations may show a distribution over the operating theatre that seems inexplicable. Furthermore it may be expected that a greater distance from the exhaust of the anaesthetic equipment to the persons concerned results in a lower concentration near those persons. The longer path then covered creates more opportunity for mixing. This measure would generally be most beneficial to the anaesthesist, as he stands closest to the path of gases being discharged.

The best method for restricting exposition to anaesthetic gases remains, of course, their direct discharge from the operating room. In many places, the construction of systems suitable for this purpose, and perfectioning of existing solutions, are in progress. In particular for operating theatres that are not ventilated mechanically, the use of this method is necessary in view of the high concentration that may be expected in them.

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