NASAL FILTRATION OF AIRBORNE DROPLETS

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(With 8 Figures in the Text)

Tyndall (1883) considered that all dust particles were removed from air when it passed through the nose, but Owens (1923) showed that particles of the order of 1 μ diameter penetrate the nose and may be present in exhaled air.

An apparatus for measurement of the ability of the individual human nose to filter dust from the air was devised and used by Lehmann (1933). In this apparatus a cloud of mine dust was drawn through the nose and the change in concentration determined with a konimeter. After measuring the filtering ability of the noses of several hundred mine workers, Lehmann (1934, 1936) concluded that poor nasal filtration was often associated with silicosis or asbestosis, but this conclusion has been criticized by Reichmann (1938). Similar experiments were carried out by van Wijk & Patterson (1940), who measured the change in concentration of siliceous dust particles in air passing the nose, with thermal precipitators. With subjects breathing at about 17 l./min., 25 % of 0·2 μ particles and about 80 % of 2 μ particles were removed; between those ranges the percentage removal was nearly proportional to the square root of the particle diameter.

Determinations of the filtering capacity of the rabbit's nose, which were carried out in conjunction with the present authors using a sedimentation cell technique, have been described by Davies (1946). The results obtained agree with those of the present experiments.

Droplets were used in most of the present experiments because liquids are more easily dispersed to give uniform clouds than are solids. The droplets produced are spheres instead of the irregular shapes of dust particles, so that their behaviour is more uniform and one variable, the particle shape, is eliminated. The results are presented as examples of a new method for examining the filtering ability of the nose, as a comparison of the filtration in man and other species, and to show the variation in penetration of particles with change in the rate of flow.

METHODS

Clouds of droplets were produced by a Collison nebulizer (Collison, 1935) operated by compressed air at 20 lb./sq.in., when the output was 6·5 l./min. Most of the experiments were carried out with dibutylphthalate, since this substance has a low volatility. Attempts were made to use Apiezon oil which is even less volatile, but no dye or easily estimated substance was found to dissolve in this oil. Sudan black (2 %) or α-naphthylethylenediamine (1 %) were dissolved in the dibutylphthalate to act as labels for the easy colorimetric estimation of samples collected. A few experiments were carried out with aqueous solutions of methylene blue.

The cloud produced by the nebulizer passed down wide tubes—in some cases with extra air—to the nostrils. Rates of flow of air were measured with rotameters or with flowmeters (cf. Just & Kauko, 1911) calibrated against rotameters. The output of the nebulizer was checked by weighing before and after running for known times, while measuring the air flow out of the apparatus. In the experiments with rats and rabbits where the rate of flow through the nose was usually less than 2 l./min., the cloud was sampled by sucking it through glass-wool filters. In other experiments where the rate of flow was 2 l./min. or more, the cloud was sampled by sucking through a cascade impactor and an impinger. In the cascade impactor described by May (1945), which is the subject of British Patent Application No. 13763/44, the particles of an aerosol are separated into four ranges with effective drop sizes (E.D.S.) of 10–200 μ (A), 14·5 μ (B), 4 μ (C), and 2·5 μ (D) in diameter. The E.D.S. is defined as the diameters of drop (or particle if approximately spherical) which when plotted against the percentage of the total mass sampled up to and including the corresponding plate give a good approximation to the mass distribution curve. The range of sizes on the first plate depends upon the nature of the cloud so that no mean value can be given. With the figures given for ranges B, C and D, and the diameters corresponding to the mean mass values, 80 % of the particles would be between the diameters of 5 and 20 μ for B, 3·5 and 5 μ for C and 1·5 and 3 μ for D.

This separation is obtained by passing the cloud at 17·5 l./min. through four impinging jets of decreasing sizes against microscope slides at progressively increasing speeds (5, 30, 50 and 80 m.p.h.). The apparatus has maximum efficiency with particles in the range of 1·5–50 μ. The impinger (cf. Drinker & Hatch, 1936), which backed the cascade impactor, had a jet 1·6 mm. diameter, so that air passed through it at over 300 m.p.h. Particles from 0·2 to 2·5 μ in diameter would be collected by the impinger.

Using this method of analysis of particle size ranges, the particles in the original cloud of butylphthalate had a mean mass of 2·7 μ diameter, with 20 % of the material in particles of 1 μ diameter or less, and 20 % of 7 μ diameter or over.

Rabbits and rats were anaesthetized by intraperitoneal injections of sodium pentobarbitone (30 mg./kg. as Veterinary nembutal). Goats and sheep were anaesthetized with sodium barbitone (2 ml. 10 % solution per kg. body weight) injected into the jugular vein. An incision was made into the neck and a suitable sized cannula, bent in a right angle, inserted into the trachea and tied so that it communicated with the lungs. The trachea was cut and a T-shaped cannula introduced and tied in the upper part of the trachea. In some cases with rabbits the lips were sewn in order to make quite certain that no cloud passed through the mouth.

Rats and rabbits

In the case of rats and rabbits the muzzle was introduced into the apparatus through a hole in a rubber diaphragm which was stretched over a circular hole in a glass tube (Fig. 1). This formed a sufficiently airtight connexion without compressing the nostrils. Slight suction was applied to the cannula leading to the nose to ascertain that the flow of air through the nose was unobstructed. One arm of the T-shaped cannula was connected through a water manometer to the sampling hole opposite the animal's muzzle. This allowed the resistance of the nose to be measured. The arm of the cannula in the line of the trachea was connected to the sampling apparatus.

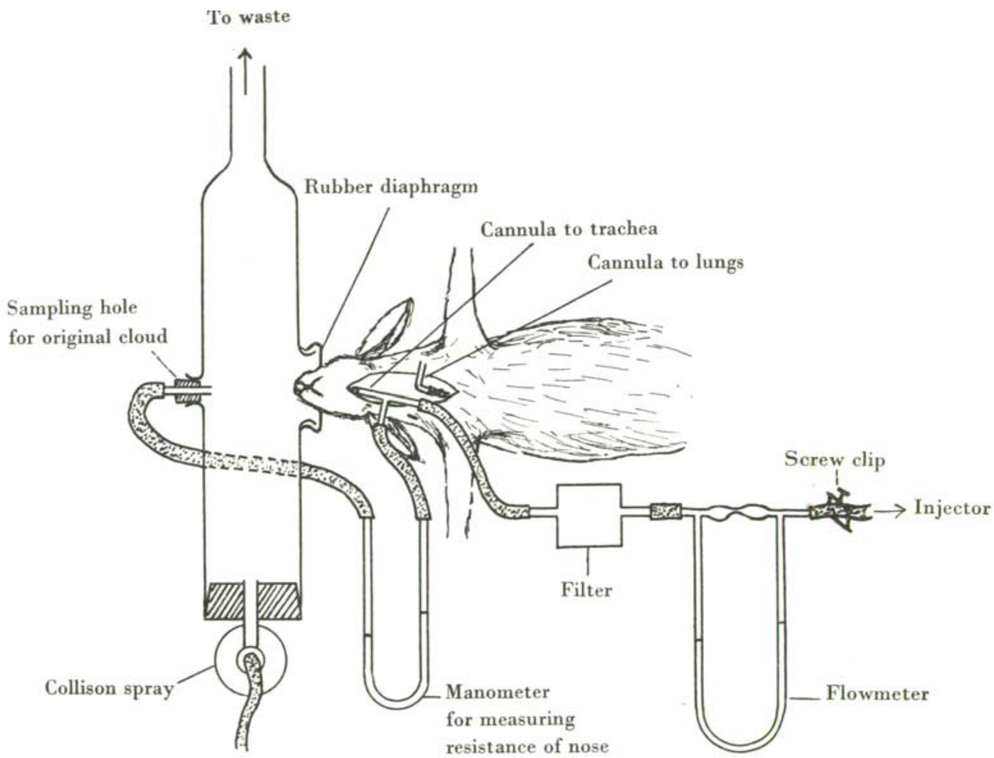

Fig. 1. Apparatus for measuring the penetrations of droplet clouds through a rabbit's nose.

Air was sucked through the nose and the tracheal cannula, and then through a small filter packed with glass-wool and a flowmeter by means of an injector, in which a jet of compressed air causes suction. The suction was increased slowly till the rate of flow was steady at a desired rate. If suction was applied rapidly the air passage collapsed in the region of the pharynx, and the preparation was useless for further experiments. When the air flow was steady the resistance was read on the manometer, the rate of flow read on the flowmeter and the spray was turned on for a definite time varying from 10 sec. to 2 min. In some of these experiments a sample of the original cloud was taken simultaneously through the sampling hole opposite the animal's nose. The dye present in the droplets caught in the filter was extracted with alcohol (if butylphthalate were used) or with water (in the experiments with aqueous methylene blue). Two filters each about 1 cm. in diameter closely packed with glass-wool were used. If there was any indication of material passing the first filter and being caught on the second filter the amount of glass-wool was increased until none of the cloud passed the first filter. These filters increased in efficiency with increase in rate of flow of air as the force impacting the particles on to the glass-wool filters was then greater.

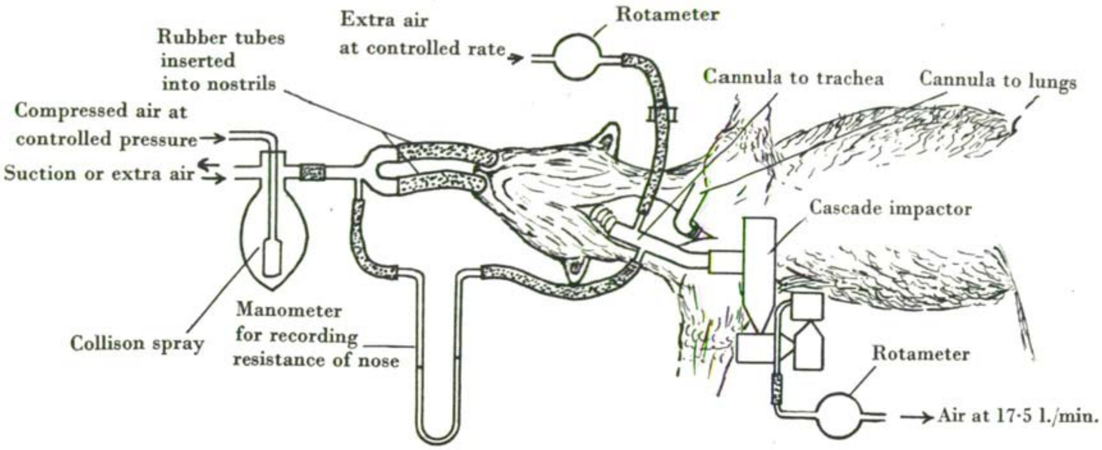

Fig. 2. Apparatus for measuring the penetrations of droplet clouds through the noses of sheep or goats.

Goats and sheep

With larger animals the rate of flow through the nose was sufficiently great to make it possible to use the cascade impactor and so analyse the cloud. With goats and sheep, it was found difficult to introduce the nostrils into the cloud so that the joint was airtight. Two different types of facepiece were tried but both were liable to obstruct the passage of air in the upper respiratory tract. Insertion of soft rubber tubes of suitable size which fitted into the nostrils was found to be the most satisfactory method and was used in all the experiments described. The two tubes were connected to the nebulizer with a wide bore (1·5 cm.) Y-tube. Some samples were taken through the nose at the rate (6·5 l./min.) equal to the output of the nebulizer. In other experiments some of the cloud was drawn off, and in others extra air was drawn through the second hole in the head of the nebulizer. The cannula from the upper part of the trachea was connected directly to a cascade impactor. If the flow through the nose was less than 17·5 l./min. extra air was admitted through a side tube in the cannula. If it was greater than 17·5 l./min., part of the cloud issuing from the trachea was drawn off through this side tube at a rate measured on a flowmeter. The air was sucked through the cascade impactor and then through an impinger and flowmeter by a 'Speedivac' pump (Fig. 2). The flow was adjusted so that 17·5 l./min. passed through the cascade impactor by adjustment of a variable leak between the flowmeter and the pump.

In all the successful experiments with goats and sheep, the animals were dosed with atropine (10 mg./kg.) before operation. If this treatment was omitted or smaller doses given large volumes of secretion collected in the nasal passages and blocked the respiratory tract. It is possible that this treatment makes the respiratory tract drier and the air passages more open than they would be under normal conditions.

Man

Clouds of droplets were drawn in through the noses of men and out of the mouth through a mouthpiece, while the breath was held. The cloud was led to the nose through a facepiece (Fig. 3). The resistance and rate of flow were measured while the spray was turned on for periods of 10 or 20 sec. The issuing cloud was sampled with an impactor and impinger and compared with the original cloud sampled from the facepiece.

RESULTS

Rabbits

In the experiments with aqueous methylene blue (1 %) solution, the water of the droplets evaporated, so that a very fine cloud of solid methylene blue with maximum diameter of 3 μ was produced. Such clouds were drawn through the noses of rabbits at a standard rate of 1 l./min. In a series of rabbits 73, 92, 64, 63, 73, 61 and 70 % (mean 71 %) of the methylene blue passed through the nose. With the

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fine cloud used it is possible that some of the particles would be small enough to be removed by diffusion (Brownian movement) to the nasal membranes, rather than by impingement which is the process by which larger particles are removed.

obtained are plotted in Fig. 4. In Fig. 4 the results of the continuous lines refer to samples taken while the rabbit was alive, while the broken lines refer to experiments carried out after the rabbit had been killed by intravenous injection of sodium cyanide.

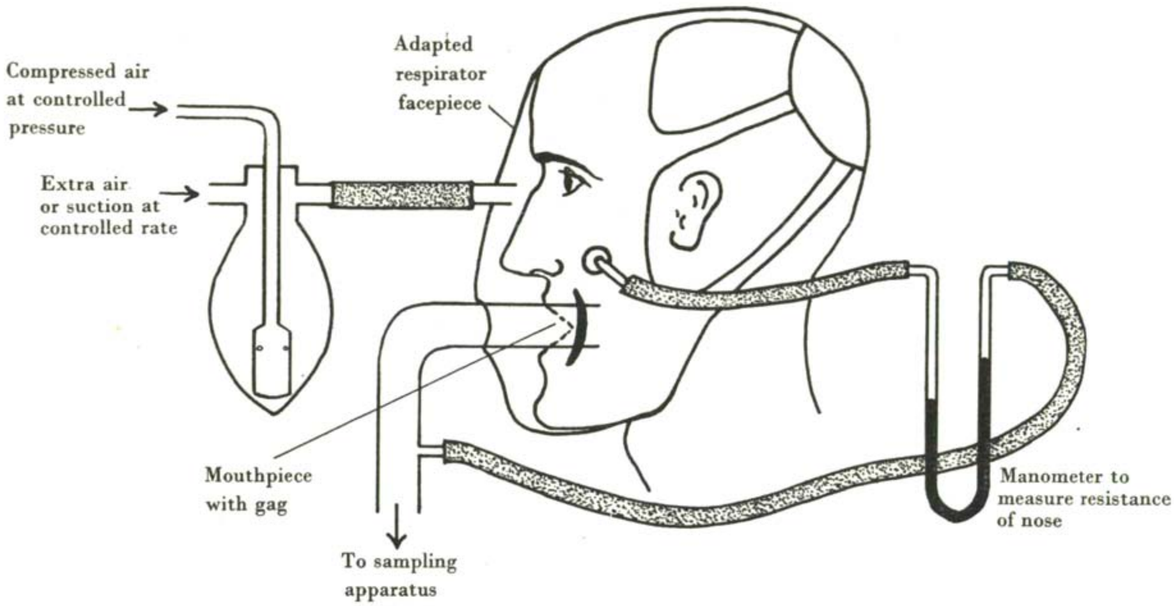

Fig. 3. Apparatus for use with human nose.

Table 1. *The resistance to air flow and the penetration of fine particles through the noses of rabbits*

Weight of rabbit (kg.)	Rate of flow through nose (l./min.)	Resistance (mm. water)	Airborne material passing nose (%)
2·0	0·66	11	70
	1·0	28	44
2·4	1·4	40	22
2·6	0·4	12	55
	0·6	—	47
	0·9	—	37
2·7	1·0	22	22
2·7	1·2	25	39
2·7	0·035	—	94
	0·37	10	55
	1·05	18	23
2·8	1·0	12	44
3·4	0·8	40	22
	1·1	60	17

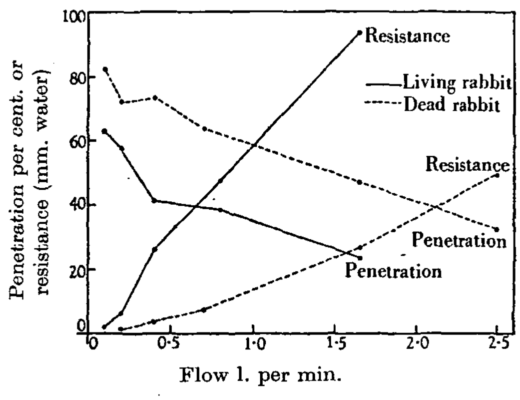

Fig. 4. Resistance to air flow and penetration of fine particles through the noses of rabbits. Each point represents the average of two readings.

In experiments with clouds of dibutylphthalate droplets in rabbits the penetration and resistance were measured simultaneously with various rates of flow. The results of experiments in which only one to three samples were taken through the nose of each rabbit are given in Table 1 and results in which a number of samples on one rabbit were

The results show clearly that the efficiency of filtration and the resistance both increased with the rate of flow. Under resting conditions the total ventilation of such rabbits is probably about 0·6–1 l./min. (Gaddum, 1944) and the mean rate of flow during inspiration is probably about 1·8–3 l./min. At such rates of flow the percentage of the

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airborne material passing the nose would probably be less than 20%. In the experiment shown in Fig. 4 it was about 23% during life and 47% after death with flows of 1·65 l./min. The fall in the efficiency of filtration was associated with a fall of resistance to about one-quarter its former value.

Rats

With the same apparatus and technique as used with rabbits no air could be drawn through the nose of living anaesthetized rats. If the operation was performed on rats recently killed by injection of sodium cyanide, air could be drawn through the nose, and the results in Fig. 5 refer to rats treated in this way. The total ventilation of resting rats weighing 200 g. is probably about 0·15 l./min. At rates of flow corresponding to this about 30% of the cloud passed the nose, which is of the same order as the corresponding figure for rabbits.

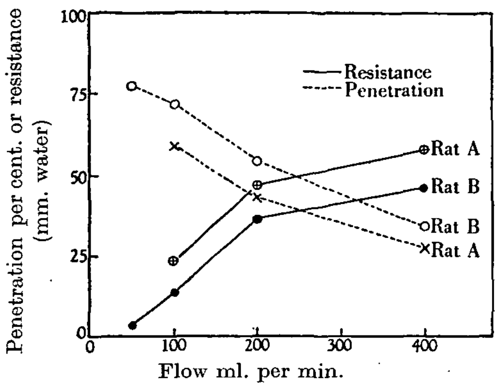

Fig. 5. Resistance to air flow and penetration of fine particles through the noses of rats. Each point represents the average of two readings.

Table 2. *Penetration of droplets of* 1μ *mean diameter through the nose of a goat, sheep and man*

Subject	Rate of flow (l./min.)	Material passing (%)
Goat	1·0	104, 106
	3·0	96, 96
	6·5	92, 98
	13·5	98
	14·3	98
Sheep	3·25	108, 96, 104
	6·5	103, 93
	13·0	103, 101
	20·5	97, 102
	26·0	96
	32·5	101, 104
Man (F.F.M.)	3·0	70, 92, 91
	11·5	92, 121
	16·5	114, 94
	21·5	82, 69
Man (E.B.)	6·5	78, 62
	17·5	97, 99, 94
	35·5	94, 82

Goats and sheep

The data plotted in Figs. 6 and 7 show how the amount of penetrating material in each particle size range falls as the rate of flow increases. The penetration of particles in the smallest size range, which pass through the impactor and are caught in the impinger, is shown in Table 2. The fact that these small particles pass almost quantitatively

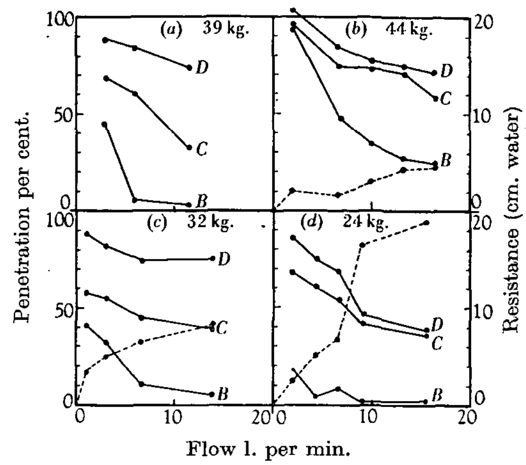

Fig. 6. Resistance to air flow and penetration of fine particles through the noses of four goats. Continuous line: Penetration per cent. at different rates of flow. Each point represents the average of two or three readings. Diameters of drops: B, 14·5μ; C, 4μ; D, 2·5μ. Dotted line: resistance (cm. water).

makes it possible to use them as a measure of the amount of cloud which has passed through the nose. It is therefore probably more accurate to estimate the amount of material absorbed in the nose by comparing the ratio of amount of material in any particular size range with the amount in the smallest range. The results have been worked out on this basis.

The results show the variability among animals. While the penetration of particles of range B is considerable at low rates of flow (2 l./min. or less) few of these relatively large particles penetrate with higher rates of flow. Thus with flows of 10 l./min., less than 10% of the material in range B generally penetrates. In one goat (cf. Fig. 6*b*) something between 30 and 40% of these particles penetrated at that rate of flow. This particular goat therefore appeared to be less efficient in filtration than the other goats and sheep examined. This same effect was shown in the penetration of the finer particles—about 70% of the range C particles penetrated at 10 l./min. flow with this particular animal, while less than 50% of such particles penetrated in the case of the other goats. This goat with relatively inefficient nasal filtration was the largest of the series, but the difference in filtration is much with increase in rate of flow, but a less steep fall in the penetration of particles of the C range than is the case in the goats examined.

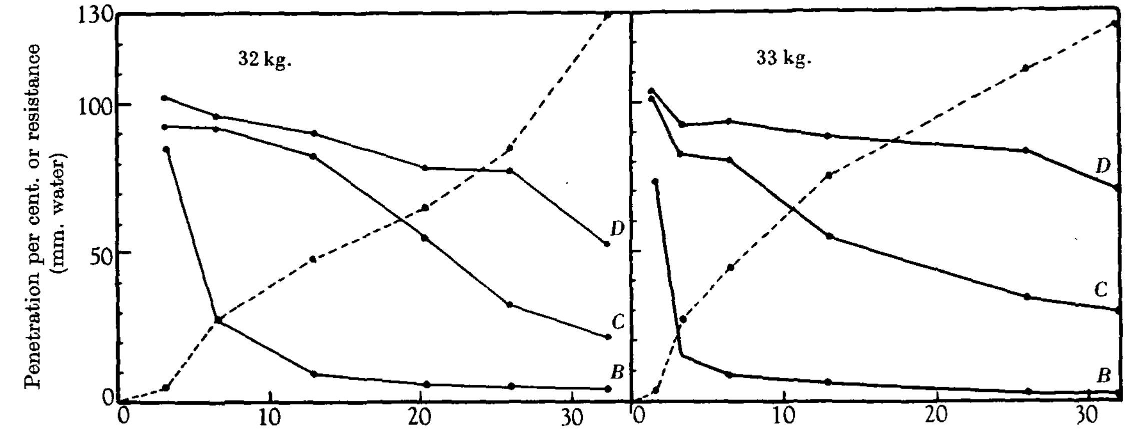

Fig. 7. Resistance to air flow and penetration of fine particles through the noses of two sheep. Continuous line: penetration per cent. at different rates of flow. Each point represents the average of two or three readings. Diameters of drops: B, 14·5 μ; C, 4 μ; D, 2·5 μ. Dotted line: resistance (mm. water).

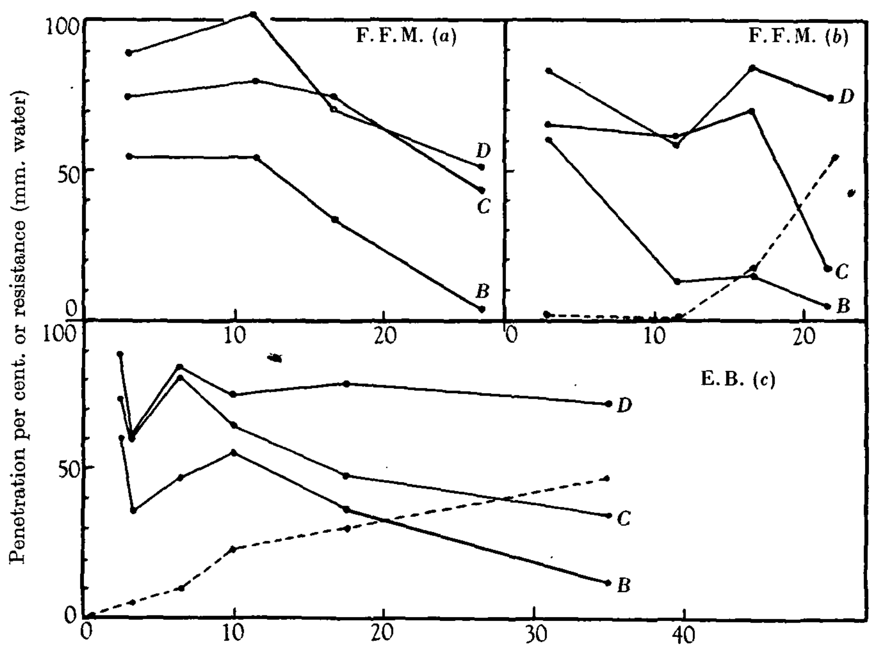

Fig. 8. Resistance to air flow and penetration of fine particles through the noses of two men. Continuous line: penetration per cent. at different rates of flow. Each point represents the average of two readings. Diameters of drops: B, 14·5 μ; C, 4 μ; D, 2·5 μ. Dotted line: resistance (mm. water).

greater than one would have expected from the difference in size.

The two sheep examined show a remarkably steep fall in penetration of particles of the B range

Man

The few experiments carried out on human noses (Fig. 8) show similar relationships between penetration and rate of flow of air. The two sets of experiments carried out on F.F.M. suggest that there is considerable day to day variation in filtering ability. On the occasion of the second set of measurements (Fig. 8*b*) the subject thought that 'only one nostril was working'. The flow through the open nostril would be more rapid than if both nostrils were open and the consequent increased rate of flow may be responsible for the decreased penetration observed on that occasion. The data in Fig. 8 suggest that the human nose is slightly less effective as a filter than the goat's nose, but the difference is not very great.

DISCUSSION

The results obtained, although showing variation, indicate how great is the change in penetration of airborne particles of certain size range (5–15 μ diameter) with rate of flow through the nose. In actual breathing the rate of flow must vary almost continuously. At the beginning and end of inspiration the flow is very slow for a short period, and with the low rate of flow large particles may pass through the upper respiratory tract. During the middle of inspiration the rate of flow must be higher than the mean rate of inspiration and fewer particles will be able to penetrate.

In considering the data it should be remembered that the particles in each size range are not uniform. Thus in the second range (B) 10 % of the material is in particles smaller than 5 μ and 10 % in particles larger than 20 μ, so that 80 % are within the 5–20 μ range. It is obvious that the particles which penetrate most readily will be the smaller particles of the range.

With normal breathing in man very few particles larger than 5 μ in diameter would penetrate the nose. The work of Owens (1923) indicated that particles of 1 μ are inhaled and exhaled again in normal breathing; with deep breathing some of those particles would be deposited in the lung. If it is desired to administer a spray so that material is deposited in the lung the spray should either be given by mouth breathing or the particles should be in the range of 2–4 μ in diameter. If particles are to be deposited in the nose they should be over 5 μ in diameter. If the usual Collison nebulizer or spray is used with a non-volatile liquid the cloud produced will be such that half the material will pass through the nose. If dilute (e.g. 1 %) solution with a volatile liquid such as water as solvent is used then the particles after evaporation will be so small that most will pass through the nose, but many will be so small that they will also be exhaled.

If airborne material is sampled by the cascade impactor and impinger as used in the present experiments then it is possible to estimate how much of the material would penetrate the nose. From this it should be possible to predict whether the material is likely to have effects on the lungs or the upper respiratory tract. Such samplings should be of value in assessing the hazard of a siliceous dust cloud or of airborne carcinogenic soot. Comparison of clouds of therapeutic or prophylactic agents sampled by the sampling device used in the present work, or by a more simple arrangement which would indicate the relative amounts of material which would be expected to be caught in the nose and pass into the lungs should be of more value than determination of the total amount of airborne material.

SUMMARY

Apparatus for determination of the penetration of particulate airborne material through the nose is described. The penetration of aerosols of liquid particles produced by a spray has been measured in rats, rabbits, goats, sheep and men. The penetration decreased with increase in the rate of flow through the nose.

Particles of the order of 1 μ diameter penetrate the nose at all rates of flow, while very few particles larger than 15 μ can penetrate except at low rates of flow.

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