FILE NAME: Smoking (SMOK)

DATE: 1959 May

DOC#: SMOK052

DOCUMENT DESCRIPTION: Journal Article - Air Hygiene for Hospitals

JAMA 1959

Annual Meeting • Atlantic City • June 8-12, 1959

This Issue Exceeds 170,000 Copies

THE JOURNAL

OF THE

American Medical Association

MAY 16, 1959

Volume 170, No. 3 Published Weekly at 535 North Dearborn Street, Chicago 10, Illinois. Subscription, $15. Single Copy, 45 cents.

tion in blood cholesterol levels. The dietary alteration was accomplished simply, easily, and inconspicuously, and with an excellent degree of patient acceptability.

P. O. Box 1656 (6) (Dr. Boyer).

Dr. C. L. Williams, Superintendent of Central State Hospital, provided facilities for this study.

The corn oil margarine used in this study was supplied as Emdee margarine by Pitman-Moore Company, Indianapolis.

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AIR HYGIENE FOR HOSPITALS

II. EFFICIENCY OF FIBROUS FILTERS AGAINST STAPHYLOCOCCIC DROPLET NUCLEI AND BACTERIA-BEARING DUST

Henry F. Allen, M.D., Boston

A laboratory and operating room study shows that it is possible to provide absolute filtration of bacteria on dust particles and high retention of bacterial droplet nuclei through installation of certain deep-bed glass-fiber material in the hospital ventilating system. A glass-asbestos paper offered retention in the same range. No hospital should accept an installation which has not been found to retain at least 85% of atmospheric dust or its equivalent. Careful performance testing of the installation is essential.

There is general agreement that air supplied to delivery rooms, operating rooms, and nurseries should be free from dust and bacteria. On the one hand, pure air is needed to maintain dilution of airborne contaminants derived from human sources inside these areas; on the other hand, the demonstrated fact that pathogenic organisms may enter such spaces via air-conditioning ducts [1] must be guarded against by efficient cleaning of air supply.

To insure satisfactory performance over long periods, devices for delivering clean air should be simple and trouble-free and should require a minimum of maintenance.[2] Recent developments in the field of air filtration permit realization of these objectives at reasonable installation expense and low operational costs. This paper reports studies of the arrest of bacteria-bearing particles by fibrous filters in experimental and actual situations.

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Bacteria in air occur as droplet nuclei or are attached to minute particles of dust, lint, or skin. The former are produced by the atomization of re-

spiratory secretions, as during talking, laughing, coughing, or sneezing. These droplets approximate 10μ in diameter and evaporate almost instantly in air of a relative humidity of less than 100%.[4] The droplet nuclei which remain after evaporation consist of one or more bacteria with a coating of dried organic material. They are usually between 1.34 and 2.68μ in diameter [4] and settle at an average rate of 0.04 ft. per minute in still air. As convection currents tend to keep room air in constant motion, bacterial droplet nuclei tend to remain in a state of continuous suspension.

Bacteria-bearing dust particles are thought to vary greatly in size and to be much larger than droplet nuclei. Most of them settle at 1 or 2 ft. per minute in still air,[5] but some may be continuously suspended in moving air.

may be bonded together by phenolic resins; or papers of cellulose and asbestos, glass, glass and asbestos, or ceramic fibers with or without a binder. A great increase in filtering surface can be achieved by pleating these materials. Air velocities through the medium usually range from 5 to 25 ft. per minute. In general, units presenting a superficial area of 4 sq. ft. provide an air flow of 1,000 cu. ft. per minute at an average duct velocity of 250 ft. per minute. Retention of particles by these mediums is largely the result of inertial impaction of particles on fibers. In addition, the static gas film around fibers may interfere with the passage of particles.

Although physicians do not ordinarily carry out performance tests on air filters, an understanding of the basis for efficiency rating is important. This is because a filter which is highly efficient against

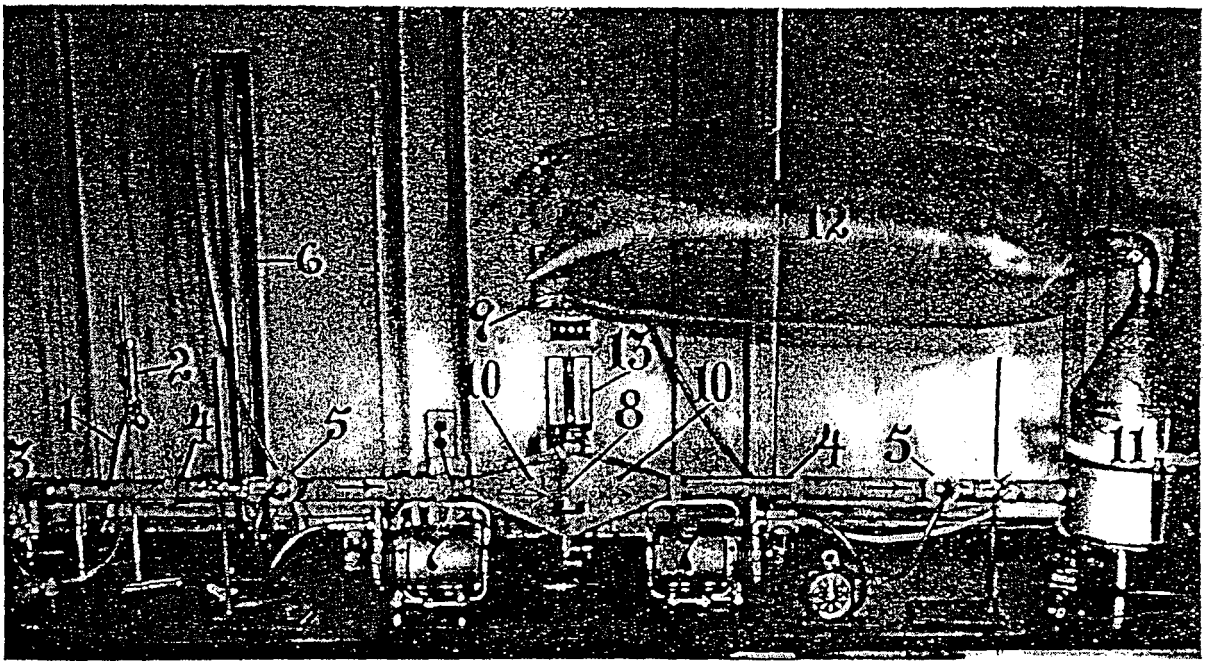

Fig. 1.—Filter-blower system: 1, nitrogen supply line; 2, flow regulator; 3, DeVilbiss 40 nebulizer; 4, location of dispersion disk; 5, sampling point (MF holder); 6, mercury manometer; 7, vacuum pumps; 8, filter medium in holder; 9, water gauge manometer; 10, filter holder; 11, fan; 12, calibrated bag (not used during tests); 13, wet and dry bulb thermometers.

Ventilating air is cleaned by passage through devices which operate on one of the following principles: (1) impingement on mediums coated with viscous material, (2) impaction on fine fibers of dry porous mediums, (3) electrostatic precipitation, or (4) washing or scrubbing by passage through wet cells or fine sprays.[6]

The antibacterial efficiency of viscous and wet cell filters is too low to warrant their use in critical hospital areas. Electronic air cleaners have been reported [7] to possess high efficiency against airborne bacteria and viruses but will not be discussed in this paper. Fibrous filters may be made of fabric-like mediums of wool felt or cotton batting or cloth; deep-bed mats composed of glass fibers averaging between 0.8 and 3.0μ in diameter, which

particles 10μ in diameter may be extremely inefficient against particles 1μ in diameter. A case in point is the poor performance of viscous filters against atmospheric dust.

Deep-bed mats composed of glass fibers averaging between 0.8 and 3.0μ in diameter are rated by the National Bureau of Standards (NBS) discoloration test with atmospheric dust used as the test material; that is, against particles averaging 0.5μ in diameter. Their efficiency increases with the useful life of the filter as particles build up on the filter face. Efficiencies from 35 to 95% over the life of different grades of filters are achieved at the rated velocity. The initial resistances of the various mediums range from 0.14 to 0.48 in. water gauge at the rated velocity.

Paper filters are rated by the NBS discoloration test or in terms of their efficiency against dioctyl phthalate (DOP) smoke, an aerosol of particles uniformly 0.3μ in diameter. Absolute filters achieve a minimum guaranteed arrest of 99.95% against DOP smoke. Their retention of bacteria approaches 100%. This high efficiency is obtained at the cost of increased resistance to air flow.

Experimental Studies

There are few studies of the efficiency of fibrous mediums against micro-organisms. Decker and coworkers [8] tested the efficiency of three grades of glass-fiber pads and of two types of mineral papers against freshly atomized aerosols of Serratia indica and Escherichia coli T-3 bacteriophage. A single-thickness pad possessing the characteristics of Filterdown 50-FG retained 99% of the bacteria and 98% of the bacteriophage. Penetration of the glass-asbestos paper was 2.8 to 14 per 10 million organisms; of type E glass paper, 1 to 2 per 100 million organisms.

The downstream section of the filter holder incorporated a fine, stiff stainless steel screen to provide backing for the filter medium being tested. The screen was spot-soldered to the flange, and the interstices of the meshwork were filled with aluminum powder in a plastic base so as to present a flush, smooth border 1.25 in. wide around the periphery of the filtering surface. A gasket of spun glass fiber was cemented to the downstream flange and one of 0.12-in. foam rubber to the upstream flange. Clamps were used to maintain firm pressure through the opposed flanges on the filter medium between the gaskets.

The ducts were equipped with dispersion disks located five duct diameters upstream from each sampling point to provide thorough mixing of the aerosol before sampling. The sampling points were located 20 in. downstream from the intake and from the filter holder respectively. All joints were made airtight with sealing tape.

Air samples were taken through right-angle glass tubes, 6 to 8 mm. in diameter, inserted through the

TABLE 1.—*Characteristics of Fibrous Filter Materials*

Code	Trade Name	Material	Diameter of Glass Fiber, μ	Efficiency, %*	Rating Test	Rated Velocity, Ft. per Min.	Pressure Drop, In. H_2O§	Efficiency vs. Bacterial Droplet Nuclei, %	Efficiency vs. Dustborne Bacteria, %
H 93...	CM 114	Glass-fiber paper	<1.0	99.97	DOP†	5.5	0.90	99.97	100
H 98 B.	Micretain	Glass-asbestos paper	<1.0	95	DOP	5.0	0.40	96.7-98.1	100
Ceramic....	Fiberfrax	Aluminum silicate paper	2.4	83	DOP	5.0	0.18	97-98	>99
50-FG..	Filterdown	Glass-fiber mat	1.25	90-95	NBS‡	21.0	0.48	87-99	>99
C 95....	Aerosolve 95	Glass-fiber mat	1.0-1.1	90-95	NBS	23.0	0.35	89-98	>99
C 85....	Aerosolve 85	Glass-fiber mat	0.8-0.9	80-85	NBS	25.0	0.22	54-69	...

* During useful life of filter.
† Dioctyl phthalate 0.3 μ smoke.
‡ National Bureau of Standards discoloration test.
§ At rated velocity.

Because the bacterial species used by these workers is particularly vulnerable to drying,[9] and because neither it nor the bacteriophage is likely to be encountered in environmental air, it seemed desirable to confirm these studies and to extend them to a pathogenic species more resistant to drying, to bacteria attached to dust particles, and to other filter materials. At the same time an opportunity was afforded to compare two sampling techniques in the light of newer knowledge regarding one of them.[10] With these purposes in mind the following test situation was established.

Materials.—A filter-blower system was adapted for bacterial sampling of air upstream and downstream from the filter medium. The assembly (fig. 1) consisted of several feet of round, galvanized, sheet metal duct 2 in. in diameter, a filter holder composed of two four-sided funnels with flanges by means of which the funnels could be clamped base to base, and a fan at the downstream end of the system. The filtration surface was 6.5 in. on a side, with an area of 0.29 sq. ft.

duct wall and pointing upstream in the center of the duct. The air was sampled for bacterial content either by filtration through cellulose ester gel membranes (Millipore filters [MF]) or by bubbling through critical orifice liquid impingers containing 200 cc. of 3.2% brain-heart infusion with 0.2% gelatin solution,[10] the stem being 4 cm. from the bottom of the container. The pH of the impinger fluid was 7.2. A loopful of a silicon antifoaming agent (Antifoam A) was added to each impinger. Sampling rates were 2.0 to 4.5 liters per minute, a pressure drop of 24 in. Hg being maintained across the critical orifices during operation. The dimensions of the sampling tubes were selected to make the sampling velocity approximately isokinetic with the central duct velocity.

Fresh aerosols were produced by atomization of bacterial suspensions from a DeVilbiss 40 nebulizer activated by nitrogen from a commercial cylinder at a flow rate of 6.4 liters per minute; 12-to-24-hour broth cultures of Staphylococcus aureus (Food and Drug Administration strain 209, American Type Culture Collection 6538) were diluted with sterile

distilled water to a degree suitable for sampling after nebulization. The organisms were less than 1μ in diameter and were highly dispersed.[11]

Dry aerosols were produced by insufflating fine dust obtained from the filter cones of ward vacuum cleaners into the duct from a powder blower. These dust-coated cones retain almost 100% of airborne bacteria contacting them.[11] The principal species recovered from this dust were represented by strains of yellow and white staphylococci, hay bacilli, sarcinae, and assorted molds. It is probable that the bacterial particles were not in a state of high dispersion in these aerosols.

The properties of the several filter materials tested are shown in table 1. At least three samples from one or more lots of each medium were tested, and at least three trials were made with each sample.

Operation.—The humidity of the room air was adjusted to the desired level by allowing steam to flow from the chamber of an autoclave into the room. The rate of air flow through the system was adjusted by controlling the fan speed to produce the desired velocity at the filter face. Flow rates

TABLE 2.—*Retention of Nebulized Staphylococci by a Single Pad of Filterdown 50-FG*[*]

Sampler	Colonies per Liter† Upstream	Downstream	Efficiency, %
Millipore filter	257	3.4	98.68
Impinger	920	9.4	98.98
Impinger: Millipore filter	3.57	2.75	

* Temperature 23 C, relative humidity 34%.
† Sampling rate, 2 liters per minute.

were measured directly by timing the inflation of a calibrated bag of light-weight polyethylene, capacity 5.5 cu. ft. (fig. 1).

With air flowing through the system at the desired rate, fresh or dry aerosols were introduced at the intake and allowed to flow for from 1 to 30 minutes before sampling was begun. Sampling was carried on simultaneously at the upstream and downstream sampling points, usually for 60 seconds.

At the end of each run, the filter membranes were transferred to the surface of trypticase soy agar plate or aliquots of the impinger fluid were filtered through Millipore filters (HA type) which were incubated on the same solid medium. After incubation of the plates at 37 C for 24 hours and 22 C for 12 hours colonies were counted under magnification, using the ophthalmic biomicroscope and slit lamp (Zeiss Opton).

Conditions and Controls.—The temperature during these experiments varied from 21 to 24 C; the relative humidity was adjusted between 31 and 71%. The construction of the system insured that no room air was drawn into it or the samplers other than that which was introduced at the intake. Organisms present in the room air were not of the test species and were numerically insignificant in proportion to those in the artificial aerosols, and their occasional presence appeared to have no effect on the results.

In a representative number of trials, but not in all, the filters and the downstream sections of the filter holder and ducts were sterilized by hot air between tests. Failure to sterilize them in other trials appeared to make no difference in the results of these tests, presumably because the test organisms were not present on, or were not liberated by blow-off from, the filter pads or the interior surfaces of the ducts in significant quantities. The sampling membranes were sterilized by autoclaving.

The experimental techniques used in this study are described more fully in the first paper of this series.[11] At the relatively low filtration velocities and the relatively small sampling volumes used in the present study there was no evidence that variation of the relative humidity within the range recorded above had any effect on either the efficiency of filtration by the glass-fiber materials or the recovery of organisms on the sampling membranes (MF). In contrast to conditions in the former study [11] there was no warming or drying of air during its passage through the filter-blower system. Humidification of sampled air by passing it through 18-in. by ¾-in. tubes containing rolled moist filter paper failed to increase the yield of organisms on the MF in comparative tests with air of 39% relative humidity at a sampling rate of 2 liters per minute.

There was no evidence of increasing penetration of the fibrous materials with time. Rather, it was clear that accumulation of dust on the filters increased their retention of bacteria. Filterless trials indicated an expected recovery rate of 90% or better at the downstream sampling point. No correction for this factor was made in calculating efficiency of filtration.

Results.—The findings recorded in table 1 refer to retention of bacterial droplet nuclei by new, unused filter materials in terms of the dry (aerosol assay) Millipore filter sampling technique. When parallel sampling by this method and by liquid impingers operated at an identical rate (2 liters per minute) was conducted simultaneously at both the upstream and the downstream sampling points, impinger counts were 3.3 to 3.57 times those on the MF at the upstream point and 2.75 to 2.9 times those on the MF at the downstream point. In spite of the threefold disparity in absolute values filtration by the glass-fiber medium demonstrated by both methods was of the same order of efficiency. It is presumed that the larger number of organisms recorded by the impinger represents both break-up of bacterial aggregates by it and decay of organisms after contacting the MF surface. The former factor could account for the slightly higher efficiencies demonstrated by the impinger technique, since aggregates

which would produce only a single colony on the MF would presumably be arrested by the glass-fiber filters more readily than single cells. The fact that the efficiency of the more retentive materials appeared nearly the same by both methods is consistent with monodispersion of the particles in the aerosol. A typical trial is shown in table 2.

Of the deep-bed materials, clean single-thickness pads of Filterdown 50-FG ordinarily retained 98.5 to 98.7% of freshly nebulized bacterial aerosols. Impinger samples confirmed the 99% retention reported by Decker and his group for the same medium. However, one substandard lot was received which passed up to 15% of droplet nuclei. This was returned to the manufacturer, who confirmed the poor performance of the sample and stated that steps had been taken to prevent release of substandard lots in the future. Single-thickness pads of Aerosolve 95, a deep-bed medium of considerably lower resistance to air flow than Filterdown 50-FG, showed an average retention of 95% with a range from 89 to 98.5% in different runs. Retention of droplet nuclei by dust-laden filters was higher than by clean filters. Both mediums retained essentially 100% of bacteria-bearing dust particles produced by the powder blower. It is reasonable to assume that any medium retaining 90% or more of an aerosol of droplet nuclei would retain essentially 100% of bacteria attached to atmospheric dust particles.

Unlike absolute filters deep-bed filters are not individually guaranteed as to their efficiency by the manufacturer. This fact suggests the need for testing the performance of individual filters used in critical situations, especially in view of the variation we have observed in different lots of deep-bed material.

Penetration of the glass and glass-asbestos papers by droplet nuclei was roughly in proportion to their DOP ratings. The high retention of these mediums was achieved only at a resistance to air flow significantly greater than that offered by the deep-bed mediums. A cotton surgical face mask retained less than 20% of staphylococcic droplet nuclei.

Field Studies

Because of abnormally high bacterial counts in the operating rooms, a survey of the two operating suites was undertaken. With use of titanium tetrachloride as an indicator it was determined that air from the corridor was being drawn into each of the four eye operating rooms and exhausted through ceiling ports in the scrub rooms and anesthesia rooms. When the doors to the corridor were closed a brisk flow of air under them into the operating rooms was apparent. The air flow at either end of the main corridor of the operating suite was then tested, and it was found that air was being drawn under and between the double doors which opened into the main stair well of the hospital at one end of the corridor and into the ear, nose, and throat outpatient clinic at the other. A similar situation was encountered in the ear, nose, and throat operating suite on the floor above.

A survey by ventilating engineers confirmed these findings. It was brought out that the air-supply fans had been slowed in order to reduce the intake of outdoor dust through viscous panel filters. At the same time exhaust fans in the anterooms continued to operate at their original speed, so that a negative air pressure was created in the operating rooms. The parallel between this situation and that reported by Blowers and co-workers [12] is striking.

In accordance with the consultants' recommendations the exhaust ports were sealed off and fan speeds increased to the maximum, 1,700 revolutions per minute, creating a positive pressure in the operating rooms. Air escaped by exfiltration under doors and through louvers into surrounding areas. The total air flow thus provided was between 500 and 600 cu. ft. per minute for each operating room, with 100% outside air, providing about 12 air changes per hour. Viscous filter panels in the intake ducts for outside air were supplemented by banks of deep-bed glass-fiber filters (Aerosolve 95) in the distribution ducts to each operating room.

TABLE 3.—*Performance of New Filters to Operating Rooms Against Nebulized Staphylococci*[*]

Room	Colonies per Cu. Ft.		Efficiency, %
	Upstream	Downstream	
1	5,400	160	97
2	3,600	170	95
3	2,400	170	93
4	8,000	228	97

[*] Pressure drop: 0.24-in. water gauge; 15-min. trials at 2 liters per minute.

In order to test the efficiency of the completed installations, samples were taken from the ducts at suitable locations upstream and downstream from the banks of filters while freshly nebulized and dry dust aerosols were being introduced through openings in the duct wall into the air stream from the supply air fan. The first tests showed penetration of the order of 50%. The fault was traced to defective installation and token calking of the cadmium-plated filter frames in the ducts and to omission of the tie-rods used to seat the filter cartridges firmly against the felt gaskets in the frame. This omission was contrary to the manufacturer's specifications. In one instance the metal-tapping screws used to fasten the water gauge manometer to the duct wall had forced the filter frame inward away from the duct. After correction of these deficiencies, retention of the order of 95% was found for droplet nuclei (table 3). The effect of ventilation on the concentration of droplet nuclei (Staph. albus) nebulized into an operating room is shown in figure 2.

Comment

Selection of a filter for a given purpose represents a compromise between high efficiency and low pressure drop (inversely reflecting power cost) and service life.[13] For air supplied to hospital operating rooms, delivery rooms, and nurseries, this compromise must be resolved in terms of the expected microbiological and particulate challenge to the filter and the efficiency of cleaning required of the filter against the expected challenge.

The state of bacteria and molds in outside atmospheric air is not entirely clear. Colebrook and Cawston[14] found a preponderance of nonpathogenic bacteria and molds with occasional colonies

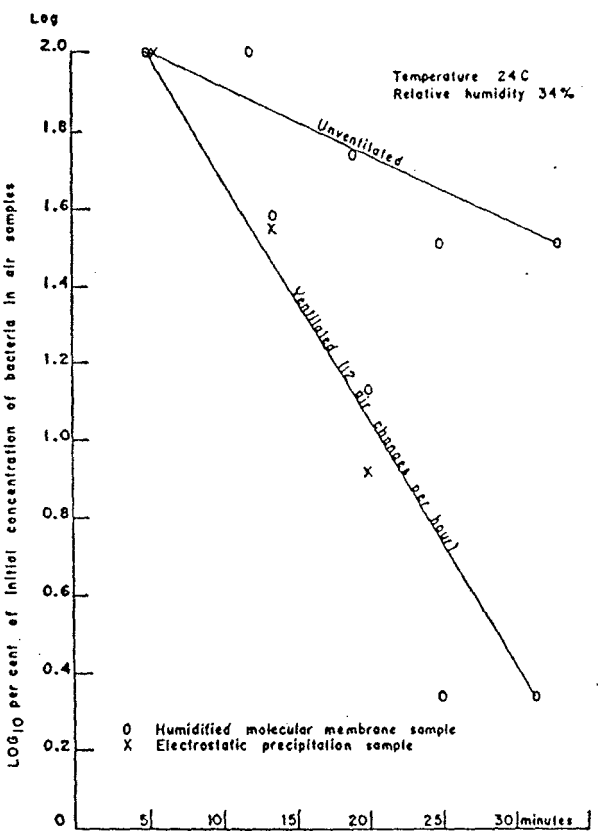

Fig. 2.—Rate of disappearance of Staphylococcus albus from ventilated and unventilated rooms.

of Staph. aureus in air sampled on the roof of their hospital. There was no way of telling whether these organisms were free-floating or attached to dust particles. The infrequency of the common human respiratory pathogens in their samples suggested that few bacteria existing as droplet nuclei survive drying and exposure to atmospheric conditions out of doors.

The efficiency of the deep-bed mediums Filterdown 50-FG and Aerosolve 95, together with a high rate of flow at a low pressure drop across the filters, renders them acceptable for filtration of ordinary atmospheric air supplied to critical hospital areas. The high pressure drop across the absolute and semiabsolute mediums would make their use appear uneconomical for air supplied to spaces in which human beings are continuously liberating organisms from their persons.

No filter medium can be better than the tightness of its installation. As air seeks the path of least resistance, the volume of air bypassing a loosely installed filter bank will increase with the build-up of dust in the filter bed. At the same time, low manometer readings may give the erroneous impression that the filter bed is operating well below its maximum permissible pressure drop, when actually the reverse is the case.

Unlike a plumbing installation a faulty air filter assembly shows no immediate sign of leakage. Because the load of particles entering the air intake during any short period of time is small, dust and bacteria may accumulate before spilling over into a channel. If alternate moisture and drying exist at an upstream location, bacteria which have proliferated during the moist phase may strike the filter face en masse during the dry phase. Detection of leakage would thus depend on prolonged sampling, fortuitous sampling during a period of spillage, or performance tests using a standard challenge of dust or bacteria.

Neither the contractor nor the consulting engineer carried out a performance test of the filters installed in the ducts leading to our operating rooms. Moreover, the consultant failed to detect the contractor's failure to meet the manufacturer's specifications for installing the filters. No hospital should accept an installation which has not been found to retain at least 85% of atmospheric dust or its equivalent. Ventilating engineers should be prepared to certify the initial performance of any high-efficiency filter system and to spot-check any sample of fibrous medium for substandard efficiency.

A correctly installed bank of deep-bed glass-fiber filters protected by suitable viscous or electronic prefilters requires remarkably little maintenance. After six months of continuous (24-hour) operation, the pressure drop across the filters for our operating rooms had risen from 0.25 to 0.42 in. of water (maximum allowable dirty drop is 0.8 in. of water). Other advantages include disposability, ease of replacement, and retention of dust during filter changes. Heavy particles on the duct floor should be removed by vacuum cleaning at the time of filter changes.

The ceramic paper is intended for high-temperature dust filtration and would not normally find an application in hospital ventilating systems. The absolute mediums, because of their higher resistance to flow, are not ordinarily used in air supply systems for hospitals.

The glass-asbestos paper (Micretain) is stated by the manufacturer to be suitable for use in supply systems to operating rooms. A cartridge presents 200 sq. ft. of pleated filtering surface and permits an

air flow of 1,000 cu. ft. per minute at a clean rated pressure drop of 0.4 in. water gauge. Because of its higher efficiency, greater uniformity, and longer service life (4,000 hours with adequate prefiltration) the manufacturer believes that this will be an economical filter for critical hospital air supply situations.

The excellent retention rate of several fibrous filters suggests the desirability of designing ventilating systems to permit partial recirculation of air. The advantages of recirculation in permitting easier and cheaper control of temperature and humidity are obvious, especially where explosive vapors are not in use. Even when volatile agents are being used Thomas [15] feels that the present requirement of 100% outside air is unreasonable and that 50% recirculation would be perfectly safe at the same relative humidity.

In ordinary ventilating situations the need to sterilize fibrous filters in place does not arise. If it became necessary to sterilize a heavily contaminated exhaust filter this could be done with beta-propiolactone in the vapor phase [16] or with ethylene oxide in suitable combination with an inert gas.

The high efficiency of Filterdown 50-FG permits other applications in the field of air filtration. At the suggestion of Snow [17] this material has been employed as a tertiary filter in an industrial vacuum cleaner (Kent Quiet Junior) which is suitable for use in hospitals. At a volume output of 135 cu. ft. per minute and at an air velocity of 210 ft. per minute through the medium, a single-thickness pad of Filterdown 50-FG placed upstream from the twin motor intakes retained 99.8±0.2% of nebulized staphylococci either alone or in conjunction with the normal primary (paper bag) and secondary (cloth bag) filters of the machines. The higher efficiency observed at the higher velocity is consistent with arrest by inertial impaction.

The low resistance to air flow of Aerosolve 95 and 85 suggests a possible application in surgical masks. We are currently exploring the use of these materials as a better means of checking bacteria of respiratory tract origin at their source.

Conclusions

A supply of clean air cannot by itself eliminate infection, but a supply of unclean air cannot be tolerated in a hospital. Adequate cleaning of air by filtration through efficient fibrous mediums or by electrostatic precipitation is mandatory for operating rooms, delivery rooms, and nurseries. Performance testing of any installation for high-efficiency fine filtration is essential. If an electronic air cleaner is used, incorporation of an efficient fibrous filter between it and the space being ventilated is essential. Two deep-bed glass-fiber materials were found to provide absolute filtration of bacteria on dust particles and high retention of bacterial droplet nuclei. A glass-asbestos paper intended for hospital use offered retention in the same range.

200 Beacon St. (16).

This study was supported, in part, by the Massachusetts Eye and Ear Infirmary through its Bacteriology Research Fund.

Mr. Werner Mueller Jr. supplied parts of the mechanical equipment, and Mr. David Feigenbaum supplied figure 1.

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