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THE NUMBERS AND THE SITES OF ORIGIN OF THE DROPLETS EXPELLED DURING EXPIRATORY ACTIVITIES

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INTRODUCTION

THE respiratory tract diseases, presumably spread by air-borne infection, occupy a place of predominant importance among the causes of ill-health in civilised communities. Their control remains one of the greatest of public health problems ; this has been emphasised by Wells and Wells (1936) and, more recently, by Mudd (1944), with reference to the sickness figures of the United States Public Health Service. Various measures, such as the treatment of carriers, dust-suppression and air-disinfection, have been advocated for the prevention of infective respiratory disease, but no practicable method has yet emerged which could be applied on a sufficiently large scale to ensure " safe air " for the general public. The problems of control are the more difficult because the mechanisms of air-borne infection are not yet fully understood, nor the extent known to which infection normally takes place by each of the different possible routes. For instance, the findings of some workers suggest that droplet-spray produces a heavy infection of the air which may persist for a considerable time and travel long distances (indoors), while the findings of other workers indicate that droplet-spray contains relatively few pathogenic organisms, that these are carried only in the large droplets which fall at once to the floor, and that aerial infection is caused mainly by the raising of dust which has been infected by these droplets or by more massive discharges.

Since Flugge (1897 and 1899) pointed out that a spray of small droplets may be emitted from the mouth during certain expiratory activities, much attention has been paid to droplet-spray as a means of infection. The expiratory activities which have been considered productive of droplet-spray, are sneezing, coughing, speaking, laughing and normal breathing. The significance of the part played in the spread of infection by each of these activities may be gauged according to the number of droplets which it produces and according to the frequency of its performance. Generally, it has been found that sneezing and

coughing produce many droplets, while speaking, laughing and breathing produce few. These latter activities may, however, be of considerable importance, for their performance is frequent and, moreover, they afford the only means of droplet-spray production in the case of healthy carriers, who normally neither cough nor sneeze (see Hamburger, 1944).

Various techniques have been employed for counting droplets, but no one technique is adequate to demonstrate droplets of every size, some demonstrating only the large and some only the small. Wells (1934) showed that the large droplets and the small droplets have a different ætiological significance. Droplets larger than 100 microns in diameter fall to the ground within a few seconds; droplets initially smaller than 100 microns evaporate before falling to the ground and so form residues, or "droplet-nuclei," which are small enough to remain air-borne for many hours, or even days. Thus, while the large droplets may be responsible for dust-borne infection, it is the small droplets which produce directly true air-borne infection. For this reason, counts of the large droplets and counts of the small droplets are both required for a comprehensive account of droplet-spray.

The large respiratory droplets are readily counted after collection on a slide, or on a culture plate, exposed directly in front of the mouth. The stain-marks left on the slide after evaporation of the droplets, are counted under the low power of a microscope; the colonies of commensal mouth organisms, or of *B. prodigiosus* if the mouth has been artificially infected, are counted by examination of the culture plate after incubation. These methods have been used to estimate droplet numbers by many early investigators (see Jennison, 1942), and have also been used in the present investigation. The large droplets are adequately represented in counts made in this manner, for they retain sufficient momentum to carry them out of the deflected air-stream on to the surface of the slide or plate. The smaller droplets, on the other hand, are greatly underestimated by these methods; for, on account of their small size and rapid evaporation to an even smaller size, they have little momentum and are mostly carried in the deflected air-stream past the slide or plate. Those such as Strausz (1926) who have measured the droplets collected have found that it is only droplets larger than 10 or 20 microns in diameter which are recovered on directly exposed slides. The fullest counts are obtained when the plate or slide is held close to the mouth, say within a few inches, for fewest droplets are then missed because of evaporation and scatter. In the case of vigorous sneezing, unfortunately, the plate usually becomes flooded if held close to the mouth and, consequently, application of the method is limited.

Jennison (1942) has enumerated respiratory droplets by counting the droplet images on enlarged, high-speed, dark-field photographs which were taken at the time when most droplets were present in front of the mouth. This method, like the last, demonstrates mainly the larger

droplets; it was found that only droplets with diameters over 5 or 10 microns could be clearly resolved and photographed.

The numbers of small droplets which carry commensal bacteria, may be estimated by allowing droplet-spray to become evenly distributed throughout the air of a closed chamber and then sampling a known proportion of the air for bacteria-carrying droplet-nuclei. An efficient sampling device is required, which can recover from the air on to a culture medium even the smallest bacterial particles. The slit sampler (Bourdillon, Lidwell and Thomas, 1941) appears to be the most efficient and convenient of the modern air-samplers; the authors claim for their apparatus an efficiency of over 94 per cent. in sampling the smallest bacteria-carrying particles (perhaps of only one or two microns diameter). In the present investigation the slit sampler was used for enumeration of bacteria-carrying droplet-nuclei. This method fails to demonstrate the smallest droplets, which do not contain commensal bacteria, and the droplets larger than about 100 microns in diameter, which fall at once to the ground and do not form droplet-nuclei.

In order to enumerate all the respiratory droplets small enough to form droplet-nuclei, whether or not these contained commensal bacteria, a new method was evolved and used in the present study. Stain-containing droplet-nuclei were recovered from the air on to oiled slides exposed in the slit sampler and were counted under the microscope, using oil immersion. This method demonstrated the droplets with initial diameters between about 1 and 100 microns; it gave far larger counts than were obtained by any other method.

The physical possibility of droplet-spray giving rise to air-borne infection of great extent, persistence and spread has been clearly established by the demonstration that expiratory activities may produce many droplets which are small enough to remain air-borne as droplet-nuclei. It has been found, however, by those who have investigated the expulsion of pathogenic organisms by infected persons, that aerial infection is much more limited than is suggested by the purely physical studies of droplet-spray, and that pathogenic organisms carried in the respiratory tract are not expelled as readily, nor in as great numbers, as commensal organisms from a normal mouth or *B. prodigiosus* from an artificially infected mouth (Winslow and Robinson, 1910; Bloomfield and Felty, 1924; Hare, 1940). The reason for this appears to be that the pathogenic organisms tend to be confined to certain circumscribed localities, especially to the tonsil and to the pharynx, and are seldom present at the front of the mouth, the site from which most droplets seem to originate (Bloomfield, 1921 and 1922). Thus, to assess the chances of air infection being produced by droplet-spray, information is required concerning the localities from which droplets, especially small droplets, may originate during the various expiratory activities, and also concerning the numbers of droplets which may arise from each site. The likely sites of droplet

origin are suggested by a consideration of the mechanism of atomisation and of the mechanism of each of the expiratory activities. Atomisation results from the passage of an air-stream at a sufficiently high speed over the surface of a liquid; tongues of liquid are drawn out from the surface, pulled thin and broken into columns of droplets. Air velocities high enough for atomisation are produced when the breath is forced out through some part of the respiratory tract which has been greatly narrowed. The site of narrowing, and thus of atomisation, is usually at the front of the mouth, this being almost closed by approximation of the tongue, teeth and lips. Atomisation may also perhaps occur in the throat, nearly closed by approximation of the tongue, tonsils, and soft palate; in the glottis, nearly closed by the vocal folds; in a bronchus, obstructed by secretion; in the nasal cavity, obstructed by secretion; or in the anterior nares, the narrowest parts of the normal nasal passages. In the present study the direct origin of droplets from the nose and from the throat was investigated; the number of droplets expelled from each of these sites was estimated in tests with *B. prodigiosus* applied to the site as an indicator.

Experimental Methods

The following expiratory activities were tested:—(1) normal nose-breathing for one- and five-minute periods; (2) normal mouth-breathing for a one-minute period; (3) violent simulated laughing for a one-minute period; (4) speaking loudly 100 "K's," in words such as "cake," "cook" and "kick" which contain no other consonant; (5) counting softly from "one" to "a hundred"; (6) counting loudly from "one" to "a hundred"; (7) single "throat-only coughs," voluntarily produced with mouth well open and tongue depressed; (8) single "lip-coughs," voluntarily produced with the mouth at first closed by approximation of the lips and the air blast then forced suddenly out between these; (9) single "tongue-teeth coughs," voluntarily produced with the mouth at first closed by approximation of the tongue and upper teeth and the air blast then suddenly released between these; (10) single "natural sneezes," induced by snuff or by tickling the nasal mucosa with a throat swab; (11) single "simulated sneezes," voluntarily produced by forming explosively the sound "ttsch"; and (12) single strong nasal expirations of the type made normally to clear minor obstruction or irritation. On some occasions the coughs were tested in volleys of 5 to 50 at a time and the average count calculated. Most of the tests were carried out with one subject; some were carried out with five other subjects. Between 9 and 45, and usually about 20, tests were carried out by each of the different techniques of investigation on each type of expiratory activity; the range and the arithmetic means of the counts obtained in each set of tests are given in Tables I to VI.

A. *Counts of Colonies on Culture Plates Exposed Directly to Droplet-spray*

Blood agar plates, 12 sq. in. in area, were exposed 3 in. in front of the mouth and below the nose; at this short distance, the droplet-spray was found to be scattered only to a slight extent and to fall largely within the

TABLE I

Numbers of Expelled Droplets larger than about 20 *microns in Diameter Revealed by Colony Counts of* 12 *sq. in. Blood Agar Plates Exposed* 3 *in. in front of the Mouth*

15-45 Tests in Each Case.	Range.	Average.
Mouth breathing, 1 minute	0-0	0
Laughing loudly, 1 minute	0-6	1
Speaking loudly 100 " K's "	0-650	76
Counting softly " 1 "-" 100 "	0-30	8
Counting loudly " 1 "-" 100 "	1-284	110
" Throat-only cough "	0-1100	48
" Lip cough "	15-1344	490
" Tongue-teeth cough "	21-6500	1400
Strong nasal expiration	0-1200	280
Sneeze with mouth masked	3-185	28

TABLE II

Numbers of Expelled Droplets larger than about 20 *microns in Diameter Computed from Counts of Stain-marks on Slides Exposed* 6 *in. in front of the Mouth*

12 Tests in Each Case.	Range.	Average.
Counting loudly " 1 "-" 100 "	40-550	260
" Throat-only cough "	0-1,100	120
" Lip cough "	360-5,800	2,000
" Tongue-teeth cough "	30-7,100	1,800
Natural sneeze	3,700-46,000	24,000
Simulated sneeze (weak)	5,000-52,000	26,000

TABLE III

Numbers of Bacteria-carrying Droplets initially smaller than about 100 *microns in Diameter Computed from Colony Counts of Blood Agar Plates Exposed in the Slit Sampler between Half and One and a Half Minutes after Droplet-Spray Production*

9-23 Tests in Each Case.	Range.	Average.
Strong nasal expiration	0-65	16
Speaking loudly 100 " K's "	0-30	7
Counting softly " 1 "-" 100 "	0-35	13
Counting loudly " 1 "-" 100 "	5-210	71
" Throat-only cough "	0-80	8
" Lip cough "	5-3,500	720
" Tongue-teeth cough "	80-1,500	730
Natural sneeze	4,500-150,000	39,000
Simulated sneeze (strong)	120,000-1,000,000	310,000

TABLE IV

Numbers of Expelled Droplets with Initial Diameters between about 1 *and* 100 *Microns Computed from Counts of Stain-containing Droplet-nuclei on Oiled Slides Exposed in the Slit Sampler between Half and One and a Half Minutes after Droplet-spray Production*

16-20 Tests in Each Case.	Range.	Average.
Counting softly " 1 "-" 100 " . . .	0-160	63
Counting loudly " 1 "-" 100 " . . .	50-770	250
" Lip cough "	490-16,000	4,800
" Tongue-teeth cough "	1,500-52,000	8,200
Natural sneeze	65,000-3,100,000	1,100,000
Simulated sneeze (strong) . . .	1,500,000-30,000,000	9,300,000

TABLE V

Numbers of Expelled Droplets larger than about 20 *Microns in Diameter originating from* (1) *the Throat and* (2) *the Nose, as Revealed by Counts of* B. prodigiosus *Colonies on* 12 *sq. in. Plates Exposed* 3 *in. in front of Mouth and Nose*

	15-30 Tests in each case.	Range.	Average.
From throat	Laughing loudly, 1 minute . . .	0-12	2
	Speaking loudly 100 " K's " . .	0-1100	92
	" Throat-only cough "	0-279	31
	Natural sneeze	0-2300	360
From nose	Nose breathing, 5 minutes . . .	0-6	2
	Natural sneeze	0-5600	250

TABLE VI

Numbers of Expelled Droplets initially smaller than about 100 *Microns in Diameter originating from* (1) *the Throat and* (2) *the Nose, as Computed from Counts of* B. prodigiosus *Colonies on Plates Exposed in the Slit Sampler between Half and One and a half Minutes after Droplet-spray Production*

	10 Tests in Each Case.	Range.	Average.
From throat	Speaking loudly 100 " K's " . .	0-33	7
	" Throat-only cough "	0·2-5·3	2
	Natural sneeze	0-390	110
From nose	Nose breathing, 5 minutes . . .	0-5	2
	Natural sneeze	5-360	56

area covered by the plate. After aerobic incubation for forty-eight hours the colonies were counted with the aid of a plate microscope. When the culture plate had been exposed only momentarily, as in the test of a cough, it was assumed that all the colonies found had resulted from the impingement of droplets. When, however, the plate had been exposed for a longer period, as in tests of speaking or breathing for one minute, there was the possibility

that some of the colonies had resulted from the deposition on the plate of air-borne dust organisms. The number of such contaminants found on control plates exposed behind the head for a one-minute period varied between 5 and 20. The contaminants were mostly staphylococci and sarcinæ, and never *Str. viridans*. In contrast, the majority (50 to 80 per cent.) of the colonies resulting from mouth-spray contained *Str. viridans*. Accordingly, in tests where the culture plate was exposed for a one-minute period, only the *Str. viridans* colonies were counted, this organism being taken as evidence of mouth-spray origin. In tests of nose-breathing no such procedure was possible, for the nose-spray organisms usually resembled the aerial flora. In Table I are summarised the results obtained by this method.

B. *Counts with the Microscope of Droplet Marks on Slides Exposed Directly to Mouth-spray*

To ensure that even the smallest droplet marks would show distinctly, a little powdered congo red, eosin or fluorescein was applied with a throat swab to the surfaces of the mouth and fauces, especially to the lips, front teeth and tip of tongue. After the dye had dissolved in the oral secretions, droplet-spray was directed towards slides held 6 in. in front of the mouth. The number of droplet marks in 1 sq. in. of the slide was counted under the low power of the microscope. In other tests the area of cross-section of the droplet-spray at 6 in. in front of the mouth was ascertained approximately from measurements of the area of intense staining on paper grids held in place of the slides. The average area for 6 sneezes was 20 sq. in., and for 12 coughs was 10 sq. in. The number of sneeze droplets found per square inch was therefore multiplied by 20, and the number of cough droplets per square inch by 10. The results obtained by this method are summarised in Table II. A large number of the droplet stain-marks were measured under the microscope with a micrometer eyepiece and the sizes of the parent droplets were calculated by making allowance for the flattening which took place on impingement upon the slide; some droplets of only 5 microns in diameter, and many of 10 microns, were found to have impinged; it appeared, however, that only droplets larger than about 20 microns in diameter were adequately represented in counts by this method.

C. *Counts of Colonies on Culture Plates Exposed in the Slit Sampler*

Tests were carried out by the same general method as employed by Bourdillon, Lidwell and Lovelock (1942). Three closed chambers were used, of 1700 cub. ft., 70 cub. ft., and $2\frac{1}{2}$ cub. ft. respectively. In the case of the two larger chambers, an electric fan was run at half speed to ensure thorough distribution of the droplet-nuclei; droplet-spray was directed forwards into the air-stream from standing height (5 ft.); the air was sampled through an intake 3 ft. 4 in. above the floor. In the case of the $2\frac{1}{2}$ cub. ft. box, droplet-spray was introduced horizontally through a face-hole $1\frac{1}{2}$ ft. above the floor of the box; air was sampled through an intake at the level of the floor. In tests of sneezing it was most convenient to use the larger chambers and so obtain considerable dilution of the very numerous droplets; in tests of coughing and speaking it was most convenient to use the small chambers and so maintain as high a concentration as possible of the less

numerous droplets. Because of the shorter falling distance, some droplets which would have had time to evaporate in the larger chambers must have failed to become droplet-nuclei in the 2½ cub. ft. box. These, however, were apparently but a small proportion of the whole, for the average counts obtained in the different chambers were very similar; no distinction has been drawn between the different chambers in recording the results in this paper. After the production of the droplet-spray, half a minute was allowed for the formation and distribution of the droplet-nuclei; during the minute following this, 1 cub. ft. of air was sampled on to a blood agar plate exposed in the slit sampler. The plate was incubated aerobically for forty-eight hours, the colonies were counted with the aid of a plate microscope, and the total number of droplet-nuclei was computed from this count minus the "control count" of air-borne dust organisms. The "control counts" were obtained from samples taken just before droplet-spray production; usually from 5 to 10 colonies of staphylococci and sarcinæ were found on 1 cub. ft. control plates, while *Str. viridans* was very seldom found. In tests of speaking and coughing the "test count" was often very little greater than the "control count"; when the "test count" was less than 40, only the number of *Str. viridans* colonies was recorded, the presence of this organism being taken as evidence of mouth-spray origin. In Table III are summarised the results obtained by this method.

D. *Counts with the Microscope of Stain-containing Droplet-nuclei on Oiled Slides Exposed in the Slit Sampler*

If the droplet-nuclei, especially the smaller ones, are to be readily recognised amid other particles of air-borne dust, it is necessary that they should be brightly coloured by some dye previously taken into the mouth. Just prior to each test a little powdered congo red was applied with a throat swab to the surfaces of the mouth and fauces, especially to the front teeth, lips and tip of tongue. Sometimes the dye induced excessive salivation; if so, the extra saliva was swallowed. Mouth-spray was produced in one or other of the three chambers described above. Half a minute was allowed for the formation and distribution of the droplet-nuclei. During the minute following this, 1 cub. ft. of air was sampled with the slit sampler; if the droplet-nuclei were very numerous, only ½ cub. ft., or even less, was sampled. Instead of using a culture plate in the slit sampler, a microscope slide, previously spread thinly with a 5 per cent. solution of boiled linseed oil in chloroform, was placed on the platform 2 mm. below the "slit." The platform was not rotated; accordingly, the air-dust and droplet-nuclei were deposited on the slide in a thin, easily visible line. This line, the "dust-line," was 29 mm. long; its width was indefinite, for although most of the particles were concentrated in a central strip ½ mm. wide, a few were scattered for distances up to 1 mm on either side. A drop of immersion oil was placed directly on the dust-line and this was examined with a microscope, using a mechanical stage, a $\frac{1}{12}$ in. objective and a (×8) eyepiece with a micrometer scale set in it. The scale, which had 10 major and 100 minor divisions, represented in all a length of 170 microns on the dust-line. In the search for droplet-nuclei the dust-line was scanned in transverse bands, each of which was 170 microns of its length. This was conveniently done by setting the micrometer scale parallel to the dust-line and moving the slide so that the dust-line passed under the scale from side to side; all the droplet-nuclei in the band were counted as they

passed the scale (see Fig.). The search was continued in transverse bands selected at intervals along the length of the dust-line until an adequate number of nuclei had been counted, usually from 300 to 500. If the nuclei were scanty, the whole dust-line might have to be searched before the count of even a few dozen could be obtained. If the nuclei were numerous, only 10, 20 or 30 transverse bands of 170 microns width were scanned. If the nuclei were very numerous, narrow transverse bands were examined; these occupied only 34 microns of the length of the dust-line and were covered by the two central major divisions of the scale. By appropriate multiplication, the number of nuclei in the whole dust-line (*i.e.* in ½ or 1 cub. ft. of air) and then the number in the total volume of the chamber, was calculated. As the initial counts were subject to the standard error of random sampling and as the computation usually involved a big multiplication (*e.g.* by 3500 in the computation for a sneeze and by 10 in the computation for a cough in the 70 cub. ft. chamber), the accuracy of the final figures obtained is not high; it is, however, the approximate number of the expelled droplets, rather than

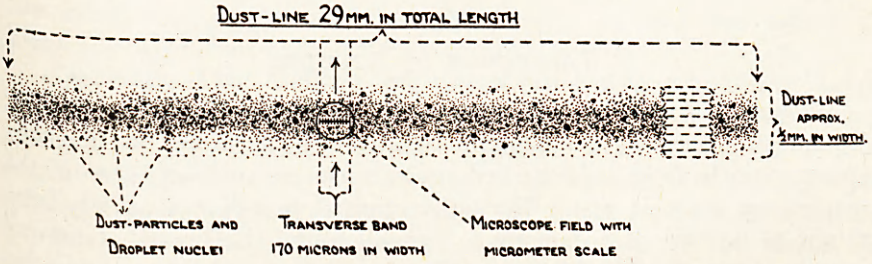

FIG.—Showing how the dust-line is scanned from side to side in transverse bands as these are passed under the micrometer scale.

the exact number, which is of interest. In recording the results, the counts are given corrected to two significant figures; this is not to be taken as an indication of the degree of their accuracy (Table IV).

The droplet-nuclei were readily distinguished from the black-green dust particles by their bright red colour. Most were spherical in shape, sometimes regular but more often irregular with indentations and ridges; a considerable number were disc-shaped or spindle-shaped. The nuclei recovered in the tests in the larger chambers were mostly between 0·25 and 25 microns in diameter; those recovered in the tests in the 2½ cub. ft. box were mostly between 0·25 and 15 microns in diameter; the commonest diameter in each case was between 1 and 2 microns. It was uncertain whether or not there was any considerable number of small nuclei which, on account of their smallness, were not recovered by the slit sampler or not recognised under the microscope. It was found by microscopic observation of the evaporation of large droplets of stain-containing saliva that a droplet-nucleus had a diameter about one quarter that of its parent droplet. It appears, therefore, that the counts obtained by this technique represent the expelled droplets with initial diameters between about 1 and 100 microns. These counts (Table IV) were much higher than the counts obtained for bacteria-carrying droplets small enough to form droplet-nuclei (Table III). The probable reason for this is that many of the smaller droplets do not contain bacteria and are thus not

demonstrated by the culture method. The preponderance was greatest in the case of the most violent expiratory activities; it was, on average, about thirty-fold for sneezing, ten-fold for coughing and five-fold for speaking.

E. *Counts of Droplets Originating from the Throat and from the Nose*

A throat swab was rubbed in a surface growth of *B. prodigiosus* and was applied, just before the test, to the throat or to the nose. For investigation of throat origin, only the tonsillar region, the free edge of the soft palate and the back of the tongue were inoculated; the anterior mouth was then proved free of *B. prodigiosus* by a swab taken from the front teeth, lips and tip of tongue. For investigation of nasal origin, the anterior nares and forward parts of the nasal cavities were inoculated. The numbers of *B. prodigiosus*-containing droplets which were expelled during the different expiratory activities, were assessed both by the method of counting colonies on directly exposed culture plates and by counting colonies on plates exposed in the slit sampler. The results obtained are summarised in Tables V and VI.

Discussion of Results

Normal Breathing.—It was early realised (Tyndall; Nageli; Buchner; Werrich; see Chapin, 1912) that bacteria are not liberated spontaneously from undisturbed moist surfaces, such as those of the respiratory tract at rest. Normally expired breath has usually been found to be free of organisms; Tyndall found the breath of normal persons to be devoid of germs; Flugge, Cadeac and others could not demonstrate tubercle bacilli in the normally expired breath of consumptives. Koelzer (see Wood, 1905), on the other hand, suggested that atomisation might occur within a tuberculous lung during normal respiration and that the breath might contain a few infected droplets. Meleney (1927) suggested that organisms might be expelled from the nose during normal expiration, perhaps being blown off hairs in the nostrils. The personnel of Naval Laboratory Research Unit No. 1 (1943), in a recent review of air-borne infection, included normal breathing among the air-infecting mechanisms.

In the present investigation no droplets were found to be expelled by *normal mouth-breathing for a one-minute period* in any of 15 tests with directly exposed culture plates. *Normal nose-breathing for a five-minute period* was, on the other hand, found usually to result in the expulsion of a few droplets, which originated from the nose; "large" droplets of over about 20 microns diameter, numbering from 1 to 6, were found to be expelled in 19 out of 30 tests with directly exposed plates; bacteria-carrying droplet-nuclei, numbering from 1 to 5, were found to be expelled in 7 out of 10 tests with the slit sampler. It appears then that infected droplets may be introduced into the air by breathing. The number of these droplets is small; yet, if two droplets are expelled every five minutes, the daily total of about 500 is not negligible.

If nasal expiration is somewhat more forceful, as in the effort to clear minor obstruction or irritation, many more droplets may be expelled. In 15 tests with directly exposed plates the number of "large" droplets found to be expelled by a *strong nasal expiration* varied from 0 to 1200 (on average, 280). In 9 tests with the slit sampler, the number of bacteria-carrying droplet-nuclei found to be produced by a *strong nasal expiration* varied from 0 to 65 (on average, 16).

Laughing.—Although seldom considered of importance, recent mention has been made of laughing, as a possible cause of droplet emission, by Hamburger (1944) and Mitman (1945). In the present investigation *violent simulated laughing for a one-minute period* was found to produce a few "large" droplets, numbering from 1 to 12, in 14 out of 30 tests with directly exposed plates. In 15 of the tests, *B. prodigiosus* was used as an indicator of throat origin, and in 8 out of these 15 tests the few droplets expelled were shown to have originated from the throat. Because of the few droplets produced and because of the infrequency of prolonged laughing, it is unlikely that laughing plays any significant part in the spread of infection.

Speaking.—The findings of the investigators who have used directly exposed plates for the enumeration of droplets, have been summarised by Jennison (1942); typically, from a few to a few hundred droplets were obtained from a few minutes' speaking. In photographic studies, Jennison (1942) found the number of droplets produced by each word or consonant to vary from a few dozen in normal conversation to a few hundred in loud talking.

In the present investigation the number of "large" droplets found to be expelled in *counting softly from "one" to "a hundred"* varied in 15 tests with directly exposed plates and slides from 0 to 30 (on average, 8); the number expelled in *counting loudly from "one" to "a hundred"* varied in 27 tests from 1 to 550 (on average, 180). The numbers of droplets small enough to remain air-borne as droplet-nuclei were found in tests with the slit sampler to be as great or greater. The number of bacteria-carrying droplet-nuclei produced by *counting softly* varied in 23 tests from 0 to 35 (on average, 13); the number produced by *counting loudly* varied in 23 tests from 5 to 210 (on average, 71). The number of microscopically visible droplet-nuclei produced by *counting softly* varied in 20 tests from 0 to 160 (on average, 63); the number produced by *counting loudly* varied in 20 tests from 50 to 770 (on average, 250).

In speaking, expiration is intermittently checked by the enunciation of consonants; these involve closures or narrowings of the air-way, thereby causing locally high air-speeds and atomisation. Koeniger (see Wood, 1905) found that most droplets were produced by the letters "P," "T," "F," and "K." Jennison (1942) found that most droplets were expelled in the enunciation of "P," "T," "F," and "S." In *counting from "one" to "a hundred,"* as in the present study, the most frequent droplet-producing consonants are "T," "F" and "S";

in the case of these, the closure, and thus atomisation, occur at the front of the mouth. For this reason, the numbers obtained in tests of counting must refer to droplets originating from the anterior mouth. On the other hand, it is probable that droplets emitted in the enunciation of words containing " K " as the sole consonant, originate from the throat where the closure and highest air-speeds presumably occur. The number of " large " droplets expelled by *speaking loudly* 100 " *K's* " was found in 30 tests with directly exposed plates to vary from 0 to 1100 (on average, 84), no droplets being expelled in 9 out of the 30 tests. The number of bacteria-carrying droplet-nuclei produced by *speaking loudly* 100 " *K's* " was found in 19 tests with the slit sampler to vary from 0 to 33 (on average, 7), no bacterial nuclei being produced in 7 out of the 19 tests. In 25 of the tests, *B. prodigiosus* was used as an indicator of throat origin and in 18 out of these 25 tests the droplets expelled were shown to have originated from the throat. In normal conversation, loudly enunciated " K's " are not very frequent ; most droplets expelled in speaking must originate from the anterior mouth and very few from the throat.

Coughing.—The findings of the investigators who used directly exposed plates to enumerate droplets, have been summarised by Jennison (1942) ; typically, a cough was found to produce from a few to a few hundred droplets. In photographic studies, Jennison (1942) obtained from a few dozen to a few hundred droplets for each cough.

In the present investigation it was found that when a cough was performed with the mouth kept well open and the tongue depressed (" *throat-only cough* "), few or no droplets were expelled ; when, on the other hand, the mouth was closed at the start of the cough, either by approximation of the lips (" *lip cough* ") or by approximation of the tongue and teeth (" *tongue-teeth cough* "), many droplets were expelled. The number of " large " droplets found in 57 tests with directly exposed plates and slides to be expelled by a single " *throat-only cough* " varied from 0 to 1100 (on average, 63), no droplets being expelled in 19 out of the 57 tests ; the number expelled by a single " *lip cough* " varied in 27 tests from 15 to 5800 (on average, 1200) ; the number expelled by a single " *tongue-teeth cough* " varied in 27 tests from 21 to 7100 (on average, 1600). In tests with the slit sampler, droplets small enough to remain air-borne as droplet-nuclei were demonstrated ; in the case of coughs performed with the mouth initially closed, these small droplets were found to be very numerous. The number of bacteria-carrying droplet-nuclei produced by a single cough varied in 21 tests of a " *throat-only cough* " from 0 to 80 (on average, 8), in 19 tests of a " *lip-cough* " from 5 to 3500 (on average, 720) and in 19 tests of a " *tongue-teeth cough* " from 80 to 1500 (on average, 730). The number of microscopically visible droplet-nuclei produced by a single cough varied in 16 tests of a " *lip cough* " from 490 to 16,000 (on average, 4800) and in 16 tests of a " *tongue-teeth cough* " from 1500 to 52,000 (on average, 8200).

Jennison (1942) suggested that, in coughing, the majority of the droplets may originate from the pharyngeal region instead of from the front of the mouth, as in speaking and sneezing; the mouth often remains well open during a cough and in such cases the highest air-speed, and probably also the zone of greatest droplet formation, must occur in the pharyngeal region. The findings of Bloomfield and Felty (1924) suggest that this is not the case; these workers inoculated the tonsils of three subjects with a culture of *B. coli* and subsequently exposed culture plates a few inches in front of the mouth during coughing; no droplets containing *B. coli* were expelled by any of the subjects. In the present investigation similar tests were carried out with *B. prodigiosus* applied to the tonsillar region of the subject; the expulsion of droplets containing this organism was demonstrated in 37 out of 40 tests of a single "*throat-only cough*." The number of "large" droplets expelled from the throat in a cough was found in 30 tests with directly exposed plates to vary from 0 to 279 (on average, 31). The number of bacteria-carrying droplet-nuclei originating from the throat in a cough was found in 10 tests with the slit sampler to vary from 0·2 to 5·3 (on average, 2). The difference between these results and the findings of Bloomfield and Felty may perhaps be due to more vigorous coughing in the present investigation or to more liberal and more widespread inoculation of the indicator organism, all regions of the posterior mouth and fauces being inoculated instead of the tonsillar area alone.

Ziesché (1907) examined microscopically the droplets caught on slides exposed to the coughing of subjects with open pulmonary tuberculosis. On the basis of morphological differences described by Heymann (1899), he distinguished droplets of bronchial origin, containing thick mucus, leucocytes and tubercle bacilli, from droplets of oral origin, containing thin mucus, epithelial cells, commensal mouth organisms, but no, or occasionally a few, tubercle bacilli. He found that the bronchial droplets were usually less numerous than the oral droplets and that they were less frequently produced. If a bronchus is obstructed by exudate, the air velocity presumably may become sufficiently raised to cause atomisation; in this way infection may be introduced directly into the air from a diseased lung. It seems likely, however, that most droplets originating in a bronchus will impinge upon the walls of the respiratory tract higher up and so fail to pass out of the mouth. The organisms of lung infections may more commonly be expelled in droplets of bronchial exudate which has been first coughed up into the throat or mouth and then atomised from one of these sites.

Sneezing.—Much larger numbers of droplets are produced in sneezing than in coughing and speaking. Wells (1935) found that a sneeze produced over 20,000 bacteria-carrying droplet-nuclei. Bourdillon and Lidwell (1941) obtained 19,000 colonies on a 60 sq. in. serum agar plate exposed 3 feet in front of the mouth during a sneeze.

Bourdillon, Lidwell and Lovelock (1942) found that snuff-induced sneezes each gave rise to about 100,000 bacteria-carrying droplets small enough to remain air-borne as droplet-nuclei for at least one minute. Jennison (1942), in photographic studies, found that the droplets expelled during a sneeze numbered in many cases about 20,000; he quoted 40,000 as a high count and 4500 as a low count.

In the present investigation the number of "large" droplets expelled by a single "*natural sneeze*" was found in 6 tests with directly exposed slides to vary from 3700 to 46,000 (on average, 24,000). Results similar to those of Bourdillon, Lidwell and Lovelock were obtained in tests carried out by their method using the slit sampler. The number of bacteria-carrying droplets small enough to remain air-borne for at least half a minute, which were produced by a single "*natural sneeze*," was found in 21 tests to vary from 4500 to 150,000 (on average 39,000). The numbers of droplet-nuclei found by microscopic examination of slides exposed in the slit sampler were much greater; they varied in 18 tests from 65,000 to 3,100,000 (on average, 1,100,000) per single "*natural sneeze*." "*Violent simulated sneezes*" were found to produce more droplets than "*natural sneezes*"; the number of bacteria-carrying droplet-nuclei produced by a "*violent simulated sneeze*" varied in 23 tests from 120,000 to 1,000,000 (on average, 310,000); the number of microscopically visible droplet-nuclei varied in 18 tests from 1,500,000 to 30,000,000 (on average, 9,300,000).

In the expiratory phase of a sneeze, some air passes out through the nose but most escapes through the mouth, rushing at maximum speed between the approximated teeth; it is chiefly the secretions of the anterior mouth about the front teeth which are atomised. In photographic studies, Jennison (1942) found that most sneeze droplets appeared to originate from the front of the mouth and that, in both stifled and unstifled sneezes, relatively few, if any, droplets issued from the nose; the nasal exudate was often expelled as large masses rather than as small droplets. Bourdillon and Lidwell (1941), also in photographic studies, found that although the majority of droplets usually came from the mouth, in some sneezes there was a purely nasal discharge, albeit slight, and in others a mixed oral and nasal discharge. In the present investigation the numbers of droplets emitted from the nose during sneezing were estimated in tests with the mouth efficiently masked with an impermeable shield and in tests with *B. prodigiosus* applied to the anterior nares and anterior nasal cavity. The number of "large" droplets expelled by a single "*natural sneeze*" was found in 40 tests with directly exposed plates to vary from 0 to 5600 (on average, 190), no droplets being expelled in 4 out of the 40 tests. The number of bacteria-carrying droplet-nuclei originating from the nose in a single "*natural sneeze*" was found in 10 tests with the slit sampler to vary from 5 to 360 (on average, 56). It appears then that sneezing may give rise to a small amount of air-borne infection with nose-carried organisms.

Bloomfield and Felty (1924) found that droplets were not readily expelled from the throat during sneezing; no droplets containing *B. coli* were expelled during sneezing by any of three subjects to whose tonsillar regions a culture of *B. coli* had been applied. In the present investigation droplets were found to be expelled from the throat by a single "*natural sneeze*" in 20 out of 25 tests with *B. prodigiosus* used as an indicator of throat origin. The number of "large" droplets originating from the throat was found in 15 tests with directly exposed plates to vary from 0 to 2300 (on average, 360) per sneeze. The number of bacteria-carrying droplet-nuclei originating from the throat was found in 10 tests with the slit sampler to vary from 0 to 390 (on average, 110) per sneeze. It appears then that sneezing may produce a small amount of air-borne infection with organisms carried only in the faucial region.

Conclusions

Speaking, coughing and sneezing produce very many droplets small enough to remain air-borne as droplet-nuclei. Nearly all of these small droplets originate from the front of the mouth; only relatively few, if any, originate from the nose, as in sneezing and breathing, or from the throat, as in sneezing, coughing, speaking and laughing. The extent of the air-borne infection which may be produced by the droplet-spray of infected persons must depend, therefore, largely upon the frequency with which pathogenic organisms, especially large numbers of these, are present in the secretions of the anterior mouth; this frequency, according to the little information available, does not appear to be great. The hazard of air infection with droplets originating from the nose or from the throat, sites in which pathogenic organisms are often carried and often numerous, is limited by the small amount of atomisation which takes place at these sites. To decide the part played by droplet-spray in the spread of infection, more information is needed about the occurrence in the anterior mouth secretions of the different pathogenic organisms and also about the numbers of expelled droplets, especially small droplets, which may contain these pathogenic organisms.

Summary

(1) The numbers of droplets expelled during normal breathing, strong nasal expiration, laughing, speaking, coughing and sneezing, have been estimated by four different methods: (i) counting colonies on culture plates exposed directly to droplet-spray: this gives the numbers of bacteria-carrying droplets larger than about 20 microns in diameter; (ii) counting droplet stain-marks on slides exposed directly to droplet-spray: this gives the numbers of all droplets larger than about 20 microns in diameter; (iii) counting colonies on culture plates exposed in the Bourdillon slit sampler: this gives the numbers

of bacteria-carrying droplets small enough, with initial diameters under about 100 microns, to remain air-borne as droplet-nuclei; (iv) counting all microscopically visible droplet-nuclei found on oiled slides exposed in the slit sampler, the nuclei being coloured by dye previously taken into the mouth; this is a new method and it gives the numbers of droplets with initial diameters between about 1 and 100 microns; these counts are considerably greater than the counts obtained by any other method.

(2) The numbers of droplets originating from the nose and from the throat were estimated in tests with *B. prodigious* inoculated as an indicator on to one of the sites.

(3) Normal breathing for a five-minute period sometimes did not produce any droplets and sometimes produced a few; these were found to originate from the nose. A single strong nasal expiration produced from a few to a few hundred droplets; some of these were small enough to form droplet-nuclei.

(4) Laughing for a one-minute period sometimes did not produce any droplets and sometimes produced a few; these were found to originate from the faucial region.

(5) Counting softly from "one" to "a hundred" produced from a few to a few dozen droplets; counting loudly from "one" to "a hundred" produced from a few dozen to a few hundred; these apparently originated from the front of the mouth and most were small enough to form droplet-nuclei. Enunciating loudly 100 "K's" sometimes did not produce any droplets and sometimes produced a few dozen or a few hundred; many of these droplets originated from the faucial region and a few of the faucial droplets were small enough to form droplet-nuclei.

(6) A single cough with the mouth kept well open sometimes did not produce any droplets and sometimes produced a few dozen or a few hundred; it was found that many of these droplets originated from the faucial region and that a few of the faucial droplets were small enough to form droplet-nuclei. A single cough with the mouth initially closed produced from a few hundred to many thousand droplets; these apparently originated from the front of the mouth and most were small enough to form droplet-nuclei.

(7) A single natural sneeze produced from a few hundred thousand to a few million droplets; these apparently originated from the front of the mouth and most were small enough to form droplet-nuclei. In most sneezes, between a few and a few thousand droplets were found to originate both from the nose and from the faucial region; some of these droplets arising from the nose and throat were small enough to form droplet-nuclei.

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