THE SIZE AND THE DURATION OF AIR-CARRIAGE OF RESPIRATORY DROPLETS AND DROPLET-NUCLEI

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INTRODUCTION

The opportunity for infection to be spread by air-carriage of the droplets expelled in speaking, coughing and sneezing, depends upon the time for which these droplets can remain airborne; this is determined mainly by their size. Lange & Keschischian (1925), observing droplets of an artificially atomized eosin solution, found that these remained airborne for only a few seconds if they were over 200 μ in diameter, but for as much as a few minutes or a few hours if they were under 20 μ in diameter. Wells (1934) showed that droplets larger than about 100 μ in diameter fall to the ground within 1 or 2 sec., while droplets initially smaller than 100 μ evaporate before falling to the ground and so form residues, or 'droplet-nuclei', which may remain airborne for some hours or even some days. This deduction of Wells was based upon falling and evaporation times which were calculated for droplets of *pure water*; droplets of saliva would evaporate a little more slowly, but, because of the predominant influence of size, the same general relationships would hold. The time for falling 2 m. in saturated air was calculated as 0·6 sec. for droplets with diameters over 1000 μ, 2 sec. for those of 200 μ, 6 sec. for those of 100 μ, 1 min. for those of 30 μ, 10 min. for those of 10 μ and 17 hr. for those of 1 μ; the time for complete evaporation in unsaturated air at 18° C. was calculated as 3 min. for droplets with a diameter of 1000 μ, 7 sec. for those of 200 μ, 1·7 sec. for those of 100 μ and 0·4 sec. for those of 50 μ. The length of time for which the droplet-nuclei will remain airborne, subsequent to their formation from the respiratory droplets, will similarly be determined by their size. The size of the droplet-nuclei is of further importance, for it determines the part of the respiratory tract on to which the nuclei will be deposited when they are inhaled. According to Hatch (1942), most particles larger than 5 μ in diameter are deposited by centrifugal force in the upper respiratory tract (nasal cavity), while many particles smaller than 5 μ are deposited by settlement in the alveoli of the lungs; this distinction may be of aetiological significance in the case of lung infection.

Several investigators have estimated the size of droplets by catching the droplets on a glass slide held a short distance in front of the mouth, and measuring the well-defined circular stain-marks which the droplets leave after evaporation; the droplets produced in speaking and coughing have been found by this method to vary in diameter from 20 to 2000 μ, the majority being between 100 and 500 μ (Jennison, 1942). Strausz (1926) found that the stain-marks left on glass slides were about three times greater in diameter than the original droplets; taking this into account, he calculated from measurements of droplet-marks on slides, which had been exposed 20 cm. in front of the mouth during the coughing of bronchitics and consumptives, that the expelled droplets ranged from 10 to 500 μ in diameter and that the most common diameters were between 70 and 85 μ. Studies of stain-marks on slides do not, however, give a complete account of the size distribution of the respiratory droplets; the smaller droplets usually fail to impinge upon the slides and are thus disproportionately underestimated. It appears that droplets produced by artificial air-stream atomization may have a mean diameter of as little as 10 μ (Castleman, 1931). Sauter (1928), by photometric measurement of the droplets produced on mechanical atomization of *water*, found that the mean droplet diameter decreased as the air-stream velocity increased, until a lower limit of 12 μ diameter was reached at air speeds of 100 m./sec. and higher; there was much variation in the size of the droplets produced at any one air speed. The extent of this size variation was studied by Phelps & Buchbinder (1941) in the case of a broth solution of uranine which was atomized mechanically at an air speed of 360 m./sec.; the sizes of the droplet-nuclei resulting from the spray were calculated from measurements of their settling rates; the variation in size was about 4-fold within the central 68 % of the material atomized and about 16-fold within the central 95 %. The applicability to mouth-spray droplets of these measurements made in the case of artificial sprays depends upon the similarity of the conditions of atomization, especially as regards the viscosity of the liquid and the velocity of the air stream. Jennison (1941) calculated that, if the maximum expiratory effort were made, an air-stream velocity of as much as 100 m./sec. might be produced. Strausz (1922) found air speeds of up to 16 m./sec. in loud speaking;

Chaussé & Magne (1916) found air speeds of up to 100 m./sec. in coughing. In motion pictures of sneezes, Jennison (1942) recorded droplet velocities of up to 46 m./sec.; the original air-stream velocities were probably greater than these droplet velocities. It appears then that expiratory air-stream velocities may be high enough for the production of droplets with a size distribution similar to that found in the investigations in which atomization was performed artificially; that is to say, the respiratory droplets might have a mean diameter of about 10 μ. The viscosity of the respiratory secretions is, however, greater than that of water; for this reason, Jennison (1942) has concluded that respiratory droplets initially as small as 10 μ are unlikely to be formed.

Little information is available about the size of the droplet-nuclei which are produced by mouth spray. Wells (1934) mentioned, as an indication of their probable size, that a droplet of normal saline would reduce on evaporation to a salt nucleus roughly one-fifth of the former diameter. Mitman (1945), saying that he could not find any statement as to the size of a droplet-nucleus, surmised that the diameter would be less than 5 μ. Jennison (1942) estimated the *final minimum diameters* of sneeze droplets from measurements of the images on photographs taken during the late stages of a sneeze; in one case the diameters ranged from 10 to 420 μ, with from 40 to 80 % under 100 μ and from 20 to 40 % under 50 μ. Particles smaller than about 10 μ in diameter could not be resolved by the photographic methods used, and it is probable that many of the droplet-nuclei were less than 10 μ in diameter, for a large number of droplets seemed to 'disappear' because of evaporation to sizes which were unresolvable; in a high-speed motion picture of a sneeze, most of the droplets had 'disappeared' within 0·25 sec. after the start of atomization. Phelps & Buchbinder (1941) found that most, 95 % by weight, of the droplet-nuclei which were produced by mechanical atomization of a broth solution of uranine ranged between 0·34 and 5·4 μ in diameter.

Flugge (1897, 1899) investigated, with directly exposed culture plates, the aerial infection produced by droplet-spray; he concluded that the respiratory droplets are relatively large and that they settle out of the air rapidly, within a few feet of their origin. Other early workers, in experiments with the mouth heavily inoculated with *B. prodigiosus* as an indicator, were able to demonstrate that some of the droplets produced in speaking and coughing could remain airborne for several minutes and could be distributed throughout the room of the experiment; for instance, Koeniger found that 40 % of mouth-spray droplets remained airborne for 10 min., 10 % for 20 min., 5·5 % for 30 min., 2·7 % for 45 min., 0·7 % for 60 min. and none for 90 min. (see Winslow & Robinson, 1910). When artificial sprays were used, even greater duration of air-carriage was demonstrated: Flugge found that some droplets remained airborne for as much as 5 hr.; Hutchison (1901) found that some droplets were able to travel 55 m. along a corridor and up the stairs of a building. However, until there became available an apparatus whereby very small particles might be recovered from the air with a fair degree of efficiency, the number of the respiratory droplets which were small enough to remain airborne was greatly underestimated, and the hygienic importance of these droplets was underrated. The 'air centrifuge' (Wells, 1933) was the first of the modern air-sampling devices to be used extensively; it was employed by Wells & Stone (1934) to estimate, at intervals after artificial atomization of cultures in a test tank, the numbers of bacteria-carrying droplet-nuclei which remained airborne. The most resistant organism tested was *B. subtilis*; this disappeared from the air at the rate of 90 % per day, some infected nuclei being still airborne after 1 week. Other organisms disappeared from the air more rapidly, apparently because of earlier death; viable *Str. pyogenes*, *Str. pneumoniae* and *C. diphtheriae* only remained present in the air for about 2 days. Phelps & Buchbinder (1941), using both the air centrifuge and directly exposed plates, studied the settlement from the air (in a 455 cu.ft. airtight chamber) of the infected nuclei produced by mechanical atomization of a *Str. viridans* culture; the nuclei were found to be deposited from the air at a rate which decreased geometrically with time, and those remaining airborne were found to be kept in uniform distribution throughout the chamber, presumably by the minor, naturally occurring convection currents. About 3 hr. were taken for deposition from the air of 50 % of the droplet-nuclei containing *Str. viridans*. Death of the *Str. viridans* contained in 50 % of the nuclei took about 26 hr. in the absence of light and about 50 min. in the presence of daylight (Buchbinder & Phelps, 1941). It appears from these findings that the duration of aerial infection in a daylit room will be determined to a significant extent both by the settling rate of the droplet-nuclei and by the death-rate of the contained organisms. The settling velocities of uranine-broth droplet-nuclei are given by Phelps & Buchbinder (1941) as 7·7 in./hr. for those of 1·35 μ diameter, 25 in./hr. for those of 2·4 μ and 125 in./hr. for those of 17 μ. The persistence of aerial infection following sneezing has been studied by Bourdillon, Lidwell & Lovelock (1942); after a few sneezes in quick succession were performed in a small room, the air was examined at intervals with a slit sampler (Bourdillon, Lidwell & Thomas, 1941), an instrument which is probably the most convenient and efficient of the modern air-sampling devices. The number of bacteria-

carrying droplet-nuclei which remained airborne after sneezing was found to decrease geometrically with time; only 4 % remained airborne after 30 min. and 2 % after 40 min.

In the present investigation, the droplet-nuclei produced in speaking, in coughing and in sneezing have been measured by a new technique, namely, by direct micrometry after their recovery from the air on to oiled slides. The sizes of the smaller respiratory droplets have been calculated from the sizes of these droplet-nuclei. The sizes of the larger respiratory droplets have been estimated from measurements made of stain-marks found on slides exposed directly to mouth-spray. By appropriate combination of these two sets of findings, the formulation of a comprehensive size distribution for the respiratory droplets has been attempted. The duration of aerial infection by droplet-nuclei has been observed by examination of the air at intervals after droplet-spray production, for the presence both of bacteria-carrying droplet-nuclei and of all microscopically visible droplet-nuclei.

THE MEASUREMENT OF DROPLETS AND DROPLET-NUCLEI

The following expiratory activities were tested: (1) *sneezes*, induced by snuff or by tickling the nasal mucosa with a throat swab; (2) *coughs with the mouth initially closed*, voluntarily performed with the lips, or with the tongue and the upper teeth, approximated at the start of expiration; (3) *coughs with the mouth open*, voluntarily performed with the mouth kept well open and the tongue depressed; (4) *speaking loudly one hundred words*, by counting from 'one' to 'a hundred'.

A. *The measurement of stain-marks on slides exposed directly to mouth-spray*

In order that even the smallest droplet-marks might be readily visible, some dye was introduced into the mouth just prior to each test. A little congo red, eosin or fluorescein powder was applied with a throat swab to the surfaces of the mouth and fauces; the heaviest application was made to the tip of the tongue, to the front teeth and to the lips, for droplet-spray originates largely from the secretions of the anterior mouth. Following solution of the dye, droplet-spray was produced by sneezing, by coughing or by speaking; it was directed at a celluloid-surfaced slide held 3 in. in front of the mouth in tests of speaking, and 6 in. in front of the mouth in tests of coughing and sneezing. The slide was examined under the microscope, and the diameters of the first few hundred droplet-marks encountered were measured with aid of a micrometer eyepiece. In the case of each type of expiratory activity, a number of tests, from 10 to 22, were carried out, involving the measurement of 3000 droplets.

In order to ascertain the relationship between the diameters of the droplets while in their original spherical state, and the diameters of the stain-marks which the droplets leave on evaporation after impinging and flattening upon a slide, the experiments of Strausz (1926) were repeated. With the low power of a microscope and a micrometer eyepiece, large drops of saliva (1–3 mm. in diameter) were measured, first while they hung from fine glass capillaries and then again after they had fallen, flattened and evaporated on a slide. When a glass slide was used, it was found, as it had been by Strausz, that the diameters of the original droplets were about one-third those of the stain-marks. When a celluloid-surfaced slide was used, the diameters of the original droplets were about half those of the stain-marks. Celluloid slides were used throughout the present investigation, so the original droplet diameters have been calculated as half the measured diameters of the stain-marks. The size distribution so found for the droplets expelled in the different expiratory activities, is shown in Table 1. It will be noted that few droplets were found of less than 10 μ in diameter and none of less than 5 μ. It is presumed that droplets smaller than this possessed such a small mass, or evaporated rapidly to such a small mass, that they were carried past the slide in the deflected air stream.

Table 1. *The size distribution of the larger droplets*

Showing for each type of expiratory activity the diameters of 3000 droplets calculated as half the measured diameters of the stain-marks found on celluloid slides exposed a few inches in front of the mouth.

Diameter in μ	Sneezes	Coughs with mouth 'closed'	Coughs with mouth open	Speaking loudly
0–5	0	0	0	0
5–10	36	24	8	20
10–15	94	119	39	84
15–20	267	337	127	200
20–25	312	346	189	224
25–50	807	767	577	597
50–75	593	468	593	531
75–100	260	285	341	352
100–125	144	160	231	260
125–150	105	125	202	214
150–200	115	115	253	179
200–250	82	96	165	99
250–500	118	113	213	197
500–1000	59	40	52	41
1000–2000	8	5	10	2

B. *The measurement of stain-containing droplet-nuclei recovered from the air on to oiled slides exposed in the slit sampler*

The larger droplet-nuclei are sometimes recognizable in their normal unstained state, but, in order that the small droplet-nuclei may be recognized amid the other dust particles recovered from the air, it is necessary that they should be brightly coloured by some dye contained within them. Congo-red powder was introduced into the mouth just prior to each test, in the manner described above (A). Droplet-spray was produced in one of three chambers, of 1700, of 70 and of 2½ cu.ft. capacity respectively. In the case of the two larger chambers, the droplet-spray was introduced at a height of 5 ft. above the floor and was directed into the blast of an electric fan running at half speed; air samples were withdrawn through an intake 3 ft. 4 in. above the floor. In the case of the 2½ cu.ft. box, droplet-spray was introduced 1½ ft. above the floor and air samples were withdrawn at floor level. Air sampling was carried out with the Bourdillon slit sampler during the minute beginning at half a minute after droplet-spray production. Instead of a culture plate, a slide, previously spread thinly with a 5% solution of boiled linseed oil in chloroform, was placed on the platform 2 mm. under the air-intake slit. The platform was not rotated during sampling; accordingly, the air dust and droplet-nuclei were deposited in a thin, easily visible line (the 'dust-line'). A drop of immersion oil was placed directly on the dust-line, and the latter was examined under a microscope, using a $\frac{1}{12}$ in. objective and a (×8) eyepiece with a micrometer scale. The dust-line was scanned in transverse bands and the diameter of each droplet-nucleus encountered was measured. Most of the droplet-nuclei were roughly spherical, although with indentations and ridges; some were spindle-shaped and some were disk-shaped. That they were solid and not flattened on the slide was shown by their depth of focus; when their margins were in focus, the background of dust particles on the slide surface was out of focus. In the case of each type of expiratory activity, a number of tests, from 19 to 28, were carried out, involving the measurement of several thousand droplet-nuclei; the size distribution of these droplet-nuclei is shown in Table 2. It will be noted that large nuclei were found more commonly in tests carried out in the larger chambers, where the potential falling height was 5 ft., than in tests carried out in the 2½ cu.ft. box, where the potential falling height was only 1½ ft.; presumably, those droplets which were large enough to form big droplet-nuclei (i.e. 16–25 μ in diameter) could evaporate before falling 5 ft., but not before falling 1½ ft. Half of the tests were, however, carried out in the 2½ cu.ft. box, for relatively more droplet-nuclei and fewer dust particles were obtained in the dust-line; this facilitated

Table 2. *The size distribution of droplet-nuclei*

Showing for each type of expiratory activity the diameters of some thousand stain-containing droplet-nuclei found on oiled slides exposed in the slit sampler.

Type of activity ...	Sneezes		Coughs with mouth initially closed		Coughs with mouth open	Speaking loudly
Falling height ...	1½ ft.	5 ft.	1½ ft.	5 ft.	1½ ft.	1½ ft.
Diam. in μ						
¼–½	215	49	68	8	0	10
½–1	904	729	380	55	43	115
1–2	1931	1586	1238	214	520	455
2–4	1270	1627	1713	726	849	677
4–6	420	574	921	386	362	351
6–8	153	227	404	231	143	213
8–10	64	112	204	155	55	110
10–12	25	52	54	78	20	49
12–14	10	23	15	54	7	16
14–16	5	12	2	37	1	3
16–18	3	6	0	22	0	1
18–20	0	3	1	19	0	0
20–25	0	0	0	11	0	0
25–	0	0	0	4*	0	0
Total	5000	5000	5000	2000	2000	2000

* 28, 32, 35 and 42 μ.

identification of the smallest droplet-nuclei, many of which appeared to be at the limit of microscopic resolution. These smallest droplet-nuclei have been classed as $\frac{1}{4}$–$\frac{1}{2}\,\mu$ in diameter, but, in the case of such small sizes, measurement could not be very accurate. It is possible that there were still smaller droplet-nuclei which, on account of their smallness, were not recovered by the slit sampler or were not recognized in the dust-line.

In order to derive, from these measurements of droplet-nuclei, the diameters possessed by the parent droplets before their evaporation, it was necessary to discover how much shrinkage occurred as a result of evaporation. Saliva usually contains between 0·3 and 1·5 % solid matter; accordingly, if all water were lost on evaporation, a salivary droplet-nucleus would have a diameter between one-seventh and one-quarter that of its parent droplet. In the experiments of this investigation, congo red was added to the saliva, and this increased its solid content. In four of the experiments a sample of saliva was collected after the congo red had been taken into the mouth; these samples were pooled and evaporated in a water-bath so that their solid content might be ascertained; this was found to be 1·8 %. In another six of the experiments a sample of dye-containing saliva was collected and the evaporation of several drops of each sample was observed and measured microscopically; the drops, about 1 mm. in diameter, were suspended from the ends of fine glass fibres and were observed with the low power of a horizontally placed microscope, using a micrometer eyepiece; in the case of twelve of the drops, the residue left after evaporation (this took about 30 min.) was sufficiently spherical for its mean diameter to be estimated; the diameters of these residues were found to vary between one-fifth and one-third of the diameters of the parent droplets. It was concluded from these findings that the stain-containing droplet-nuclei, recorded in Table 2, were formed from droplets which were originally *about* four times greater in diameter; it also appeared likely that the droplet-nuclei would have been smaller, about two-thirds of their diameter, if they had contained no congo red.

C. *Discussion of results*

The 21,000 droplet-nuclei measured in the present investigation varied in diameter from $\frac{1}{4}$ to $42\,\mu$; 97 % of the nuclei had diameters between $\frac{1}{2}$ and $12\,\mu$; the commonest diameter lay between 1 and $2\,\mu$ (Table 2). There was no great difference between the size distributions of the droplet-nuclei produced by the different types of expiratory activity; in general, more small nuclei were produced in the more violent activities, especially in sneezing.

The largest droplet to remain airborne as a droplet-nucleus was probably about $170\,\mu$ in diameter ($4 \times 42\,\mu$); most of the droplet-nuclei, however, were apparently formed from droplets with diameters between 2 and $50\,\mu$. Droplets of this small size, especially of under $25\,\mu$ in diameter, were found with disproportionate infrequency in the observations made of stain-marks found on directly exposed slides (Table 1). In order, therefore, to obtain a comprehensive size-distribution table for the respiratory droplets, the two series of measurements were combined (Table 3). The size distribution, calculated from the measurements of droplet stain-marks, was used only for the droplets *over* $50\,\mu$ in diameter; the size distribution, calculated from the measurements of droplet-nuclei (multiplied by four to give the sizes of their parent droplets), was used only for the droplets *under* $50\,\mu$ in diameter. The two series of figures were adapted to each other so that their size-distribution curves crossed at the $50\,\mu$ abscissa. The composite size distribution was calculated so that the total number of droplets given for each expiratory activity was

Table 3. *Composite size-distribution table for the droplets expelled during sneezing, coughing and speaking*

Showing the number of expelled droplets which were originally of each diameter; the distribution was calculated for diameters under $50\,\mu$ from observations of droplet-nuclei caught on oiled slides exposed in the slit sampler, and for diameters over $50\,\mu$ from observations of droplet-marks found on slides exposed directly to mouth-spray.

Droplet diameter in μ	One sneeze	One cough with mouth 'closed'	Counting loudly '1'–'100'
Remain airborne as droplet-nuclei			
1–2	26,000	50	1
2–4	160,000	290	13
4–8	350,000	970	52
8–16	280,000	1,600	78
16–24	97,000	870	40
24–32	37,000	420	24
32–40	17,000	240	12
40–50	9,000	110	6
50–75	10,000	140	7
75–100	4,500	85	5
Fall at once to ground			
100–125	2,500	48	4
125–150	1,800	38	3
150–200	2,000	35	2
200–250	1,400	29	1
250–500	2,100	34	3
500–1000	1,000	12	1
1000–2000	140	2	0
Approx. total	1,000,000	5,000	250

that which had been found previously by microscopic enumeration of the droplet-nuclei (Duguid, 1945) to be the average number expelled by that activity, namely, 1,000,000 by a sneeze, 5000 by a cough with the mouth initially closed and 250 by speaking loudly one hundred words. In view of the imperfections of the basic techniques of observation, and in view of the several approximations involved in the calculation of the composite size-distribution table, this table should not be taken as more than a rough indication of the composition of droplet-spray. The respiratory droplets, as shown in Table 3, vary in diameter from 1 to 2000 μ; 95 %, the calculation, it was assumed that, over each size range shown in the table, the droplets were distributed equally by diameter; the mean volume of the droplets in each such group was calculated as $\frac{1}{6}\pi \cdot \frac{1}{4}(b^4 - a^4)/(b-a)$, where a and b are the minimum and maximum diameters of the droplets in the group. The mean number of bacteria present in a droplet of this mean volume was then calculated for each of the different size ranges and for each of the different numbers of bacteria per millilitre of saliva. The percentage of droplets in each size range which would contain one or more bacteria was calculated as $100\,(1-e^{-m})$, where m is the mean

Table 4. *The calculated percentages of droplets in each size group which are likely to contain organisms when* 30,000,000, 1,000,000, 30,000 *and* 1000 *of these are present in each millilitre of the secretions atomized*

Droplet diameter in μ	30,000,000 commensals per ml. %	1,000,000 pathogens per ml. %	30,000 pathogens per ml. %	1000 pathogens per ml. %
		Remain airborne as droplet-nuclei		
1–2	0·0059	0·00020	0·0000059	0·00000020
2–4	0·047	0·0016	0·000047	0·0000016
4–8	0·38	0·013	0·00038	0·000013
8–16	3·0	0·10	0·0030	0·00010
16–24	12	0·44	0·013	0·00044
24–32	30	1·2	0·035	0·0012
32–40	51	2·4	0·072	0·0024
40–50	76	4·8	0·14	0·0048
50–75	98	12	0·40	0·013
75–100	100	30	1·1	0·036
		Fall at once to ground		
100–125	100	53	2·2	0·075
125–150	100	74	4·1	0·14
150–200	100	95	8·6	0·29
200–250	100	100	16	0·60
250–500	100	100	60	3·1
500–1000	100	100	100	22
1000–2000	100	100	100	86

or more, have diameters between 2 and 100 μ; the most common diameter lies between 4 and 8 μ.

Because most of the respiratory droplets are small enough (under 100 μ) to remain airborne as droplet-nuclei, it does not follow that those which contain pathogenic or commensal organisms will also, for the most part, be small enough. The chances of organisms being contained in a droplet are determined by, and may be calculated from, the volume of the droplet and the number of organisms, or small aggregates of organisms, present in the atomized secretions. The percentages of droplets of each different size, which were calculated as likely to contain organisms when 30,000,000, 1,000,000, 30,000 or 1000 of these are present in each millilitre of saliva, are shown in Table 4. For the purpose of number of bacteria per droplet and e is 2·718; this assumes a Poisson distribution of the bacteria among the droplets. The figure of 30,000,000 was chosen to represent the number of commensal bacteria per millilitre of saliva. Gordon (1904) examined twenty-five samples of saliva and found that *Str. viridans*, the commonest commensal, was present in numbers varying from 10,000,000 to 100,000,000 per millilitre. In the present study, two estimations were made of the total number of viable organisms in the saliva of the test-subject, by counting the colonies on aerobically incubated blood agar plates which had been inoculated with various dilutions of the saliva; on these two occasions, the numbers of organisms found per millilitre of saliva were 23,000,000 and 34,000,000. Assuming

30,000,000 per millilitre of saliva, the percentages of droplets of each size likely to contain commensal organisms would be as shown in the first column of Table 4; it should be noted how low these percentages are in the case of the smaller droplets. By taking these percentages of the numbers of droplets of each size shown in Table 3, an estimate was obtained of the actual number of bacteria-carrying droplets likely to be expelled by a sneeze, by a cough and by speaking loudly one hundred words (Table 5). Of the 1,000,000 droplets expelled on average by a vigorous sneeze, it was calculated that the mean expected number of those carrying commensal organisms was about 73,000, some 62,000 of these being small enough to remain airborne as droplet-nuclei. This latter figure is to be compared with figures which have been obtained by direct observation and enumeration of the bacteria-carrying droplet-nuclei produced by a sneeze, 1000 of these organisms per millilitre of saliva (Tables 4, 5). These calculations showed that pathogenic organisms will be carried by only a small proportion of the total number of droplets expelled and by only a very small proportion of the droplets small enough to form droplet-nuclei. Out of the 5000 droplets produced on average by a cough, the number calculated as likely to contain haemolytic streptococci ranged from 6 to 230 (i.e. from 0·1 to 4·6 %); the number of these small enough to form droplet-nuclei ranged from 0 to 64. These calculated figures accord well with the figures obtained by Hare (1940), in direct observations of the expulsion of haemolytic streptococci in the mouth-spray of throat carriers; haemolytic streptococci were found to be contained in only a small proportion, from 0·3 to 3·5 %, of the expelled droplets, and, apparently, in none of the droplets small enough to form droplet-nuclei.

Table 5. *The calculated numbers of the respiratory droplets which are likely to contain pathogenic or commensal organisms*

The calculations were based on the figures given in Tables 3 and 4.

Expiratory activity	30,000,000 commensals per ml.	1,000,000 pathogens per ml.	30,000 pathogens per ml.	1000 pathogens per ml.
One sneeze:				
Under 100 μ	62,000	4,600	150	5
All sizes	73,000	14,000	3,100	430
One cough:				
Under 100 μ	710	64	2	0
All sizes	910	230	47	6
Counting to '100'				
Under 100 μ	36	3	0	0
All sizes	50	14	3	0

namely, about 20,000 (Wells, 1935), about 100,000 (Bourdillon, *et al.* 1942), and from 4500 to 150,000, on average 39,000 (Duguid, 1945). For a cough with the mouth initially closed, the calculated number of bacteria-carrying droplet-nuclei was 710; for speaking loudly one hundred words, it was 36. For comparison, the numbers found by direct observation (Duguid, 1945) were, on average, 700 for a cough and 70 for speaking loudly. This similarity between the observed and the calculated numbers may to some extent be taken as confirming the validity of the size distributions proposed and justifying the application of these to the case of pathogenic organisms. Hamburger (1944) found the number of *Str. pyogenes* present in the saliva of persons with infected throats to vary from 1000 to 1,000,000 per millilitre. In the case of other pathogenic organisms, little information is available about the numbers which may be present in the saliva. Accordingly, the number of droplets of each size likely to contain pathogenic organisms was calculated for the presence of 1,000,000, 30,000 and

It appears that the extent to which droplet-spray may result in direct aerial infection must depend largely upon the numbers of pathogenic organisms present in the saliva at the front of the mouth; danger will only be appreciable when the saliva is heavily infected.

THE DURATION OF AIR-CARRIAGE OF DROPLET-NUCLEI

Most of the observations made of the persistence of aerial infection were carried out in experiments with sneezing, for the greatest numbers of droplet-nuclei were produced by this activity. In one series of tests, the disappearance from the air was observed of differently sized, *microscopically visible droplet-nuclei.* Congo red was taken into the mouth before sneezing. Five tests were carried out in the 1700 cu.ft. room and nine tests in the 70 cu.ft. chamber; the electric fan was run throughout three of the tests in the 70 cu.ft. chamber, but only during the first minute of the other tests. The air

was sampled, at intervals after the sneeze, on to oiled slides exposed in the slit sampler; usually about 12 samples, of $\frac{1}{4}$, $\frac{1}{2}$ or 1 cu.ft. amounts of air, were taken during the 24 hr. following the sneeze. The dust-line on each slide was scanned in transverse bands; all droplet-nuclei which were encountered in a portion of the dust-line corresponding to $\frac{1}{50}$ cu.ft. of air, were counted and measured. The results of a typical experiment are shown in Table 6. As regards the disappearance of droplet-nuclei during the first hour or two following sneezing, similar results were obtained in all the experiments in which the fan was not used throughout. As would be expected, the larger nuclei were first to disappear; those over 8 μ in diameter disappeared from the air usually within 20 min., and those over 4 μ within 90 min. In the tests with the electric fan run throughout, the rate of disappearance of the nuclei was much faster; those over 4 μ disappeared from the air within 10–20 min. The results obtained for periods at more than an hour or so after sneezing showed considerable variation; the probable reason for this was that the congo red contained in the nuclei became black with the passage of time, and the small nuclei could not then be distinguished with certainty from the dust particles. It is quite possible that large numbers of the smallest droplet-nuclei remained airborne for longer than was found in any of the present experiments; the greatest duration of air-carriage demonstrated was for 30 hr. (Table 6).

Table 6. *The disappearance from the air in a 70 cu.ft. chamber of the differently sized droplet-nuclei produced by a single sneeze*

Showing the number of nuclei found in 1/50 cu.ft. of air at various intervals after sneezing.

Minutes after sneeze	Diameter of droplet-nuclei in μ										Total of all sizes	Average no. carrying bacteria
	$\frac{1}{2}$–1	1–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18		
Control	0	0	0	0	0	0	0	0	0	0	0	0·22*
$\frac{1}{2}$–1	89	228	129	37	20	9	5	2	1	1	521	16·08
9$\frac{1}{2}$–10	79	181	107	23	6	1	0	0	0	0	397	6·60
19–20	56	130	68	14	2	0	0	0	0	0	270	3·04
29–30	52	124	33	12	1	0	0	0	0	0	222	1·54
59–60	42	100	32	5	0	0	0	0	0	0	179	0·68
74–75	29	64	16	1	0	0	0	0	0	0	110	0·56
89–90	27	60	15	0	0	0	0	0	0	0	102	0·34
119–120	32	65	12	0	0	0	0	0	0	0	109	0·34*
149–150	27	44	13	0	0	0	0	0	0	0	84	—
359–360	23	21	2	0	0	0	0	0	0	0	46	0·32*
599–600	8	2	0	0	0	0	0	0	0	0	10	—
1799–1800	4	1	0	0	0	0	0	0	0	0	5	—

* Included no *Str. viridans*, therefore probably no bacteria-carrying droplet-nuclei present.

A second series of experiments was carried out, in which the disappearance from the air of *bacteria-carrying droplet-nuclei* was observed. The slit sampler was used in the normal way, with blood agar plates; 1 or 2 cu.ft. amounts of air were sampled at each time. After aerobic incubation for 48 hr., counts were made of all the colonies present on each plate, and also of the *Str. viridans* colonies alone. Sixteen experiments were carried out without congo red being taken into the mouth, eight in the 1700 cu.ft. chamber and eight in the 70 cu.ft. chamber. During three of the tests in each chamber, the electric fan was kept running throughout; the fan was run only during the first minute of the other tests. All the tests were carried out in the absence of daylight. The results obtained in the differently sized chambers were similar. The results were, however, considerably affected by the use of the fan: the bacteria-carrying droplet-nuclei disappeared from the air more rapidly in tests with, than in tests without, the fan run throughout; the time taken for 90 % of the bacteria-carrying nuclei to disappear from the air varied from 10 to 30 min. when the fan was run throughout, and from 30 to 60 min. when it was not; some nuclei carrying *Str. viridans* were found present in the air for between 5 and 45 min. after sneezing when the fan was used, and for between 60 and 120 min. when it was not used.

Sampling for bacteria-carrying nuclei, using blood agar plates in the slit sampler, was also carried out during most of the experiments in which congo red was taken into the mouth to allow microscopic observation of the droplet-nuclei. The presence of congo red in the nuclei did not appear to interfere with the viability of the commensal organisms, for the persistence in the air of nuclei carrying viable bacteria was found to be as great when congo red

was used as when it was not used. The last column of Table 6 shows the numbers of bacteria-carrying nuclei which were found, at various times after sneezing, to be contained, on average, in $\frac{1}{50}$ cu.ft. of air. The findings illustrated in this table show that the nuclei which carried bacteria formed only a small proportion of all the microscopically visible nuclei; the bacteria-carrying nuclei disappeared from the air more rapidly than the small, microscopically visible nuclei, being absent from the air after 90 min., at which time many of the latter were still present in the air. There were, apparently, few nuclei of less than 4 μ in diameter which carried commensal organisms (see also Tables 3 and 4).

A few experiments were carried out in which the persistence of droplet-nuclei in the air following coughing was observed. The results of these experiments were similar to those obtained in the case of sneezing.

SUMMARY

1. The sizes of the droplets and droplet-nuclei produced by sneezing, by coughing and by speaking, were studied by the microscopic measurement of 12,000 droplet stain-marks found on slides exposed directly to mouth-spray, and of 21,000 stain-containing droplet-nuclei recovered from the air on to oiled slides exposed in the slit sampler.

2. From these measurements it was calculated that the original diameters of the respiratory droplets ranged from 1 to 2000 μ, that 95 % were between 2 and 100 μ and that the most common were between 4 and 8 μ. Similar size distributions were exhibited by the droplets produced in sneezing, in coughing and in speaking, except that, in the case of sneezing, the smaller droplets were relatively more numerous.

3. The respiratory droplet-nuclei were found to range in diameter from $\frac{1}{4}$ to 42 μ; 97 % had diameters between $\frac{1}{2}$ and 12 μ; the commonest diameter was between 1 and 2 μ.

4. The proportion of droplets of each size which will contain bacteria, whether commensal or pathogenic, is determined by the size of the droplets and by the numbers of bacteria in the secretions atomized. Calculations made on the basis of the size distributions obtained in this investigation indicated that few of the smaller droplets, and thus few of the droplet-nuclei, are likely to contain pathogenic organisms. Droplet-spray is unlikely to give rise directly to true airborne infection unless very large numbers of pathogenic organisms are present in the secretions of the anterior mouth.

5. The persistence of droplet-nuclei in the air of a 1700 cu.ft. room and of a 70 cu.ft. chamber was investigated by sampling the air with the slit sampler at intervals following sneezing.

6. When the air was not artificially disturbed by a fan, the time taken for the disappearance from the air of 90 % of the bacteria-carrying droplet-nuclei varied from 30 to 60 min.; the nuclei larger than 8 μ in diameter usually disappeared within 20 min., and the nuclei larger than 4 μ within 90 min.; the smaller nuclei, few of which contained bacteria, remained airborne for much longer periods, on one occasion for at least 30 hr. When a fan was run throughout the experiment, the nuclei disappeared from the air much more rapidly.

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