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ON AIR-BORNE INFECTION.*

STUDY II. DROPLETS AND DROPLET NUCLEI.

By

W. F. WELLS.†

(Received for publication June 14, 1934.)

The infective range of droplets expelled from the nose or mouth depends primarily upon the time interval spent in the atmosphere. The unresisted falling time from mouth to ground can be readily shown by Newton's Law to be less than a second. Air resistance becomes a negligible factor in determining the time of fall of droplets larger than a tenth millimeter through the height of a man. As droplets decrease in diameter the volume and weight, or gravitational pull, decrease more rapidly than the surface area which determines the resistance to fall through air. Particles smaller than a tenth millimeter diameter soon reach a velocity which remains constant. This fact is expressed by Stokes' Law ‡ which says that the velocity is proportional to the surface area of the droplet or to the square of its diameter. In moisture-saturated air all but very small

* In 1931 an instrument for the bacterial examination of air was developed by the Department of Public Health Administration of the Harvard School of Public Health. The application of this instrument in the present studies has been made possible through the facilities and assistance of several Departments of Harvard University. The technical assistance of Mr. Stone, graduate student in the Department of Sanitary Engineering of the Harvard Engineering School, the use of the experimental chamber of the Department of Industrial Hygiene of the School of Public Health and the advice and cooperation of the Departments of Bacteriology and Preventive Medicine of the Harvard Medical School are here gratefully acknowledged.

No claim is made that the results presented are final in character. They are presented as found in order that they may stimulate wider and more thorough studies into this important subject of air-borne infection. The experiments were conducted during the spring and summer of 1933 and were presented to the Medical Section of the American Association for the Advancement of Science on December 27, 1933, under the title, "Viability of Bacteria in Air."

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‡ Stokes' Mathematical and Physical Papers, 1901, vol. 3, page 60.

droplets would reach the ground in less than ten seconds (table 1). Whether droplets falling two meters obey Stokes' law or Newton's law, therefore, the time they spend in the air would be small, and their radius of spread would be limited to a few feet. Infection caused by such droplets would therefore appear to be limited both in time and space to the immediate vicinity of the source.

TABLE 1.

Settling of water droplets in saturated air.

Diameter of droplet Millimeters	Falling velocity Centimeters per second	Time in seconds of falling two meters
>1.0	981 × time in seconds	.6
.1	30.	6.
.01	.3	600. = 10 minutes
.001.....	.003	60,000. = 16.6 hours

It would be incorrect to conclude merely from this, however, that air receiving infected droplets cannot convey such infection long distances. To do so would be to neglect a most important characteristic of liquid droplets, namely their tendency to evaporate. Evaporation causes the volume of water droplets to change, and this change becomes more rapid as the droplet decreases in size. Careful determination of the rate of evaporation has proved that at constant temperature and humidity the rate of change of surface is constant. The life of droplets in unsaturated air is therefore proportional to the square of their diameter. It becomes quite short for small droplets, in fact much shorter than their time of fall if they settled without evaporation. Approximate evaporation times for droplets of different sizes are tabulated below.

We find, therefore, that minute droplets settle slowly and evapo-

TABLE 2.

*Evaporation time of water droplets in unsaturated air at 18° C.**

Diameter of droplet Millimeters	Evaporation time Seconds
2.	660.
1.	165.
.5	41.
.2	6.6
.1	1.7
.05.....	.4

* Computed from data given in chapt. 15, "Evaporation of Droplets." Smoke: A Study of Aerial Disperse Systems; R. Whytlaw-Gray and H. S. Patterson, page 176 Edward Arnold & Co., London, 1932.

rate almost immediately, whereas large drops settle rapidly and reach the ground without appreciable loss by evaporation. This is an important difference since it produces a complete change in state of small droplets in comparison with large drops. On chart 1 the curves of evaporation time and falling time (to fall two meters in saturated air) are seen to be almost similar in shape but opposite in direction. The point of intersection gives the size of droplets which would evapo-

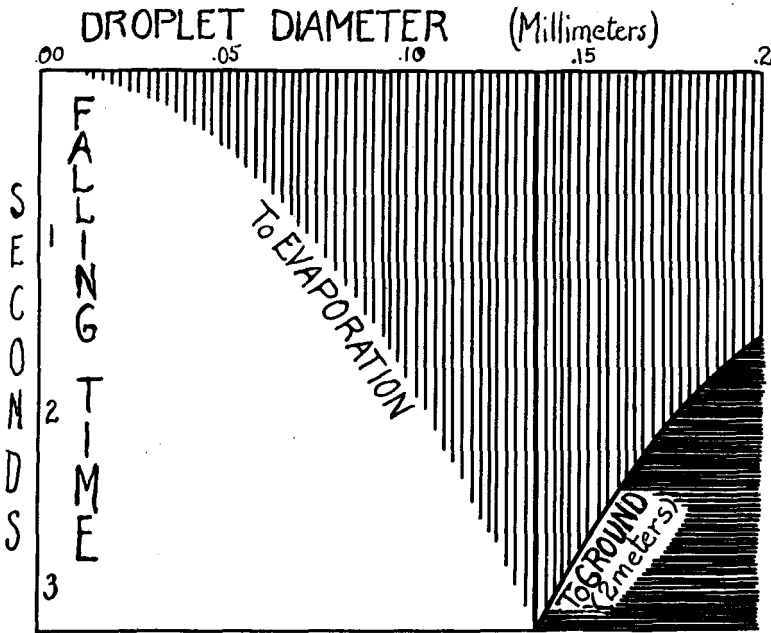


CHART 1. Falling times and evaporation times of droplets of varying diameter.

rate and particles which would fall two meters in the same time. Somewhere between .1 and .2 mm. lies the droplet size which identifies droplets of mouth spray that reach the ground within the life of the droplet as against droplets that evaporate and remain in the air as droplet nuclei with attached infection.

The falling times given in table 1, as shown in chart 1, assume droplets fixed in size. These times must be corrected when evaporation creates droplets of diminishing size, which may become droplet nuclei. The distance a droplet will fall before it evaporates can be readily deduced from the assumptions that the rate of fall is proportional to the surface and that the rate of change of surface is con-

stant. If thus h = height, S = surface, t = time, D = diameter, and c and k = constants for given atmospheric and droplet conditions,

$$\text{Velocity of fall} = \frac{dh}{dt} = kS,$$

$$\text{Rate of evaporation} \frac{dS}{dt} = c.$$

$$\text{Hence } \frac{dh}{dS} = \frac{k}{c} S.$$

$$\text{By integration } h = 1/2 \frac{k}{c} S^2.$$

$$\text{Letting } \frac{k}{2c} = K, \quad h = KS^2 = K^1 D^4.$$

The distance a droplet will fall before ceasing to be a droplet is therefore proportional to the square of the surface or the fourth power of the diameter.

On the basis of this reasoning, a raindrop two millimeters in diameter can fall miles without completely evaporating under conditions which would cause a two-tenths millimeter droplet to evaporate before it had fallen the height of a man. Difference in size, therefore, explains why rain can fall from the clouds and yet spray drying can be practiced in industry.

Other factors, principally temperature and humidity of the atmosphere, also enter into the problem. The distance of fall depends, however, upon the first power of these factors, while it varies with the fourth power of the diameter. A minor change in size of droplet, therefore, is more important than a major change in atmospheric conditions. Chart 2 illustrates the effect of changing rate of evaporation on the height a droplet will fall. Thus a droplet .17 mm. in diameter would evaporate in falling two meters in dry air, and a tenth millimeter droplet would evaporate in humid air. It follows that under ordinary atmospheric conditions, droplets less than .1 mm. diameter projected from the mouth may be assumed to dry before reaching the ground.

Droplets derived from body secretions contain dissolved substances which alter the rate of evaporation. Hence relations deduced for droplets of pure water will not strictly apply. The predominating importance of droplet size in determining the height of fall remains unimpaired, however, and for practical considerations the effect of dissolved or suspended matters should not alter the force of the argument. The fact, however, that evaporation of infected droplets leaves

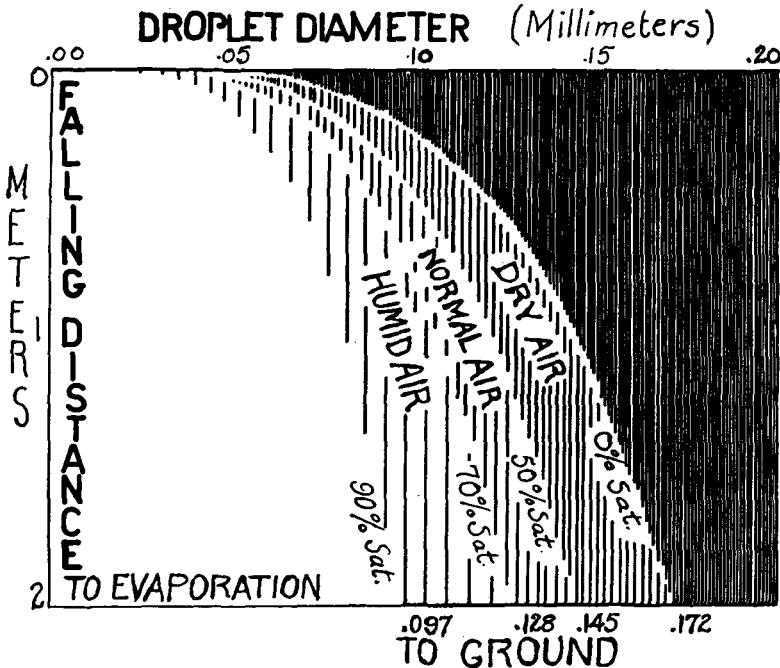


CHART 2. Falling distances to evaporation of droplets of varying diameter in air of different humidities.

residues or nuclei physically comparable with particles of fine dust may be of considerable hygienic importance.

The size of droplet nuclei depends upon the amount of solid matter contained in the evaporating droplet. Because of the high percentage of water in body fluids, nuclei will be small in proportion to the size of the original droplet. Yet they will remain large in comparison to the mass of a bacterium. Normal saline droplets would reduce to salt nuclei roughly one-fifth of the former diameter, having a volume of some ten thousand bacteria. The nuclei of such droplets would settle slowly and be carried long distances by light air currents.

Tyndall's classic experiments on atmospheric dust suggest a simple method for demonstrating the realness of droplet nuclei. To make use of this method, the author employed a tight cylindrical tank seven feet long and of the same diameter to enclose a controlled atmosphere. A powerful beam of light was projected through this experimental chamber. Ports in the side of the tank gave a perpendicular sight on the beam, revealing suspended particles entering

its path. Tyndall clearly described how such a beam becomes indistinguishable from its dark background after the chamber has remained undisturbed for several days. Water atomized into this beam appears like a jet of steam in cold air, which vanishes when the spray ceases, proving that the droplets have evaporated.

In striking contrast is the dense fog of droplet nuclei remaining after normal saline solution or culture broth has been atomized into the chamber. A beam of diminishing intensity can then be observed for three or four days. Chemical identification of the nuclei by the yellow flame of sodium can be made as late as the second day by drawing the air through a Bunsen burner.

That salt from ocean spray is carried many miles inland is clearly indicated by the map of normal chloride in the inland waters of Massachusetts. The lines of equal chloride content almost parallel the shore line at distances roughly indicated in table 3.

TABLE 3.
Chloride approximation in Massachusetts waters.

Distance from coast Miles	Chloride Parts per million
5	4.0
10	3.0
15	2.5
25	2.0
45	1.5
65	1.0
Cape Cod	greater than 10.0
Provincetown	24.2

An atomized suspension of bacteria in distilled water leaves in the path of a Tyndall beam a delicate pale blue smoke band cutting the blackness. The presence of bacteria in this atmosphere can be demonstrated after the beam ceases to be perceptible. Using the author's air centrifuge to collect the bacteria on suitable culture media, resistant bacteria have been recovered from the still air of the tank a week after inoculation. The results of quantitative experiments to determine the rate of disappearance of *B. subtilis* given in table 4 show a decrease of about 90 per cent each day.

It appears, therefore, that transmission of infection through air may take one of two forms depending upon the size of the infected droplet. The form first recognized and most obvious is droplet infection proper. It applies to droplets larger than a tenth milli-

TABLE 4.

Recovery of B. subtilis from quiet air of experimental chamber.

Days	Bacteria per 10 cu. ft. of air from	
	Broth culture	Suspension in distilled water
0.....	20,000	200,000
1.....	3,600	
2.....	220	
3.....	150	2,000
4.....	10	1,530
5.....	2.6	50
6.....	—	30
7.....	—	10

meter in diameter, which are rapidly removed from the air by gravity, before they can dry, and within a short distance of the source. The second form may be called air-borne infection, and deals with dried infected droplet nuclei, derived directly from droplets less than a tenth millimeter diameter, depending primarily upon air for the buoyancy which keeps them suspended for long times and carries them long distances. Droplet infection may change into air-borne infection when larger drops settle, evaporate and are lifted into the air as dust.

The important hygienic distinction between droplets and droplet nuclei and with it of droplet infection and air-borne infection appears to have escaped attention in the past. Experimental data based on exposure of Petri dishes to mouth spray, inoculated with *B. prodigiosus*, have been employed to define the limits of droplet spread. The fact, however, that colonies seldom are observed on plates exposed more than a few feet from the source does not necessarily indicate that considerable numbers of droplet nuclei have not been widely dispersed in large volumes of air. Nor is it necessary to conclude that tubercle bacilli expelled in droplets larger than 15 microns cannot according to Stokes' law remain in the air long enough to travel considerable distances. Observations that droplets penetrate filters and into the lungs more readily than dust particles of the same size receive a simple explanation in the light of the droplet nuclei concept. Obviously, the smaller nucleus of the shrinking droplet, recovered in the experiment, penetrates more readily than the unchanged solid dust particle.

The epidemiological characteristics of droplet infection and droplet nuclei infection are by nature opposite. Droplet infection is essentially localized and concentrated while infection broadcast by droplet

nuclei is dispersed and dilute. Thus it readily escapes detection by the instruments previously devised for atmospheric exploration. Failure to discover air-borne infection bacteriologically no more proves its absence, therefore, than failure to isolate *B. typhosus* from a sewage polluted water proves that typhoid fever cannot be conveyed by drinking water. The epidemiologist has long ceased to regard all dispersed cases of intestinal disease as of local origin, but considers carefully any bacteriological evidence of pollution of the water supply. Better comprehension of the bacterial behavior of air may likewise help to elucidate the epidemiology of diseases conveyed through the naso-pharynx.