Virus Transfer from Surf to Wind

Surf bubbles adsorb and carry virus to the surface where bursting bubbles propel virus into the wind.

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Summary. Bubbles in the sea surf adsorb and carry viruses to the surface where they are propelled into the air on tiny jets of seawater when the bubble bursts. The ejected jets become tiny drops of aerosol. The bubble adsorption and virus concentration in the surf is analagous to industrial bubble levitation processes that concentrate metallic ores, enzymes, and finely divided organic crystals. Bubble levitation of viruses deliberately injected into the surf produced 200 times more virus per milliliter in the aerosol than were present in samples from the surf. Some aerosol drops created by the surf and carried by the wind fall out on the beach. The frequency of virus-bearing drops, that is, the number of plaques on seeded plates exposed on the beach, decreased exponentially with the distance downwind from the surf.

Early in this century, Horrocks (*1*) reported that bacteria could be injected into the air by bursting bubbles. He seeded identifiable bacteria (*Bacillus prodigiosus*, now called *Serratia marcescens*) into waste waters of the sewers of Gibraltar and recovered the seeding organisms on agar settling plates in ventillation risers upstream of the seeding point. In 1970, Blanchard and Syzdek (*2*) found that the concentration of bacteria in the drops produced by the bubbles was far higher than that in the water when the bubbles burst. Morrow (*3*) concentrated foot-and-mouth disease viruses tenfold by foaming but he ignored the probably higher concentrations of viruses in the aerosols produced by the foaming process. Blanchard and Syzdek (*2*) suggested that aerosols from rivers and lakes could account for the airborne spread of foot-and-mouth disease. Aerosols formed from waste water, whether this water is from a treatment plant subjected to aeration and agitation, or from the spray irrigation of agricultural fields, contain bacteria (*4, 5*).

Field studies of airborne viruses have not been undertaken according to Clark and Kabler, although these authors have abundantly documented the presence of viruses in waste water (*6*). The transfer of viruses from waste water to aerosol was first suggested by Woodcock (*7*), and later by Sorber *et al.* (*8*), and was demonstrated by Katzenelson *et al.* (*5*) who showed a high correlation between the incidence of disease and the use of waste water for spray irrigation in certain Israeli agricultural communities.

To make use of the aerosol generating properties of the sea surf, Dimmick (*9*) injected *Bacillus subtilis* spores into the ocean and recovered the spores 3 kilometers downwind of the injection site. The public health aspect of aerosol-carried microbial agents from the sea has been widely neglected, although Gruft *et al.* (*10*) recently demonstrated that *Mycobacterium intracellulare*, the causative organism of Battey infection, can become airborne from the sea.

The purpose of this article is to demonstrate that viruses in seawater become absorbed on air bubbles which, on bursting, eject concentrated virus particles into the air in the form of jet droplets in the manner described for bacteria (*2, 11*). The virus-containing droplets may be carried for considerable distances by the wind. This distance depends on, among other things, wind speed and the survival time of the airborne virus. Viruses with appropriately short survival times were used in this study. Our work suggests that viruses are carried by the aerosol created by the surf as well as the open ocean, and suggests that seawater in which raw sewage is present may produce an airborne health hazard.

Sampling Virus Fallout on the Beach

A network of sampling stations on the beach was designed to provide the following information: (i) whether aerosol drops falling on the beach contained the virus we had injected into the surf, (ii) whether the concentration of virus was greater in the aerosol than it was in the surf, and (iii) a rough estimate of the survival time of and distance traveled by the airborne virus.

Aerosol samples were collected by allowing the droplets to fall on settling plates that were arranged in a Latin square of three or more columns parallel to the wind direction and three or more rows parallel to the water's edge. Each row or column was 10 meters from its nearest neighbor and the bottom row was 2 m above the swash zone.

Each sampling station within the network had three different kinds of settling plates: (i) a clean disposable plastic petri dish for size measurements of fallen drops, (ii) an agar plate seeded with the appropriate host cells for counting the number of virus-bearing drops per unit area, and (iii) a liquid surface for estimating the total number of virus particles contained in the drops falling on each unit area. Each of these plates was placed in the bottom of a bucket 15 centimeters in diameter and 22 cm high to prevent contamination with blowing sand. At the time of dye and virus release in the surf, the plates were uncovered. They were covered again and collected either after the dye patch injected with the virus was carried away by the alongshore currents, or after some specified time if no alongshore currents existed. When the wind blew at an angle to the shoreline and currents flowed alongshore at 0.2 to 1.0 m per second, we released the dye and virus 100 m upstream in the surf. Under these circumstances, the water mass containing the dye and virus moved past the sampling network within 3 to 10 minutes.

At each injection, 2 liters of lysate containing 10^{12} viruses per milliliter and

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Table 1. Plating characteristics of phages MS-2, T2, and T4 on different strains of *E. coli*. Symbols: +, clear plaques; −, no plaques; ±, turbid plaques (implies that only one of two host cell strains was lysed); B + B/2 → B/4 means velvet transfer from B + B/2 to B/4.

Phage	Host cell strain					
	P4X6	B	B/2	B/4	B + B/2	B + B/2 → B/4
MS-2	+	−	−	−	−	−
T2	+	+	−	+	±	+
T4	+	+	+	−	+	−
T2 + T4	+	+	+	+	+	+

1 liter of fluorescein (200 grams per liter) were carried into the breaking surf to a wave-trough depth of 1.5 m and were released simultaneously. Mixing occurred rapidly in a surf of 2-m waves, but the dye was visible in all instances for 30 minutes or longer.

Seawater in the surf was sampled before and during the experiments by opening sterile culture tubes under water. Sand and foam samples were put into sterile culture tubes with a sterile spatula. Five milliliters of 0.1*M* acetate buffer, *p*H 5.6 (routinely used to protect and preserve high titers of virus) were added to the sand and foam samples and the fluid was assayed by the standard plate method.

We chose relatively unpopulated beaches that had a surf as well as a breeze blowing from the sea to the shore. Kismet Beach, Fire Island, New York, where most of our experiments were conducted, had a 2-m surf on the days we worked. For a low surf beach (0.5-m waves) with slow mixing, long residence time of the dye and virus, and a greatly reduced rate of aerosol production, we chose Orient Point Park Beach.

Because of the currents flowing parallel and perpendicular to the shoreline (*12*), we chose our beach location by dropping small quantities of dye into the surf to observe the direction and speed of the current. After we determined that we were not in the area of a rip current that would carry dye and viruses away from the surf, we set out the network of sampling stations. Since these were downstream of the dye and virus injection point, all the dye- and virus-laden water eventually moved past and upwind of the network of sampling stations. Bubbles in the surf created the aerosol droplets that we tested for the presence of virus.

Bacteria and Bacteriophages Used

Strain B of the common colon bacillus, *Escherichia coli*, which is sensitive to and, therefore, lysed by the coliphages T2 Hershey and T4 Doerman, was used both to assay and to grow high-titer stocks of these phages. The use of both strains of phage simultaneously in our experiments required us to be able to distinguish between them. For this purpose, we used two additional strains of *E. coli* (see Table 1). The bacterial strain B/2 is resistant to (not lysed by) phage T2 Hershey, and the bacterial strain B/4 is resistant to phage T4 Doerman. Thus, when aerosol drops that contained only T4 fell upon a settling plate seeded with a mixture of the bacterial strains B and B/2, then, T4 lysed both B and B/2 and gave clear plaques. By contrast, aerosol drops that contained only T2 produced turbid plaques because the T2 lysed the B strain of bacteria but left the B/2 untouched. On the other hand, aerosol drops that contained both T2 and T4 gave clear plaques upon the mixture of B and B/2. Thus the presence of T2 phages in the drop would go undetected unless the clear plaque were transferred to a test plate containing only the bacterial strain B/4. In practice (*13*) all plaques were transferred simultaneously by successively pressing upon a piece of clean sterile velvet, first the plate bearing the plaques to be tested and, second, the plate bearing the sheet of B/4 upon which T4 does not grow and T2 forms clear plaques. The use of fiducial marks upon the velvet and upon both plates permitted exact identification of all plaques by their location. Thus the number of clear plaques that transferred is the number of drops that contained both T2 and T4. The use of two or more strains of phage simultaneously in experiments provides checks for internal consistency of data and permits the use of Poisson statistical techniques (*14*).

In addition to the DNA phages T2 and T4, we used an RNA phage called MS-2 that was grown on and assayed with the male strain of *E. coli* designated P4X6. This RNA phage was used alone in a single experiment. The relations between all the strains of phages and bacteria used in our experiments are shown in Table 1. High-titer stocks of MS-2 were grown on P4X6 in 500 milliliters of tryptone broth (Difco) containing 0.5 percent NaCl at 37°C in shaker baths. The titers of the lysates reached 1×10^{12} to 5×10^{12} phages per milliliter.

The DNA phages T2 and T4 were grown to titers of 10^{12} per milliliter on *E. coli* strain B in M9 synthetic medium (*14*). All phages were assayed by dilution and plated on the proper host cell on agar plates (1.1 percent agar, 0.5 percent NaCl, 1 percent tryptone, and 0.5 percent glucose) (*15*).

Plates for detecting the presence of virus in aerosol were prepared in the laboratory before departure to the field. Prepoured agar plates were overlaid with soft (0.7 percent) agar containing 0.2 ml of appropriate host cells from an overnight culture in 2 ml of agar. Such plates, held at ambient temperature and exposed to virus containing aerosol fallout up to 5 hours after preparation gave countable plaques.

Control Measurements

Control samples of seawater and beach sand that were obtained from Kismet Beach before the phages were released in the surf contained no phage. Control samples from a public bathing beach 1 km east of Kismet contained RNA and DNA phages (approximately 10^3 per milliliter) genetically distinct from the phages used in our experiments.

To determine the persistence of phage in the environment, we sampled water and sand at Orient Park Beach 1 day after the release of 3 liters of T4 phages containing 10^{12} phages per milliliter. On the day after release, the phage concentration in the water was about 10^2 per milliliter and about 10^4 per milliliter in the wet sand. Two days after release, no phages were found. The low surf characteristic of Orient Point Park Beach produced aerosol very slowly so that some virus persisted the following day. By contrast, the high surf of Kismet Beach left no phages after the dye had disappeared.

Settling Plates

Our experiments showed that viruses present in the surf were incorporated into aerosol drops created by the surf and that these drops were carried by the wind for distances of greater than 30 m. Plaque-forming units in the aerosol droplets were cultured and identified as T2 and T4 by their plating characteristics on the B/2 and B/4 strains of *E. coli*.

Representative results are shown in Fig. 1. The number of virus-containing

aerosol drops found on the settling plates decreased as a function of the logarithm of the distance from the surf. The absolute quantities of virus-containing drops, as well as their decrement rates within the sampling network, were consistent for any one day. The conspicuous day-to-day variation in virus fallout was primarily related to the speed of the alongshore current which controlled how long the virus and dye remained downwind of the collecting network on the beach.

In addition to releasing the DNA phages, in one experiment, we released the RNA phage MS-2 in the surf. Although MS-2 was abundant in the seawater we nevertheless found few MS-2 plaques on the settling plates. The conspicuous shift from a high ratio of MS-2 to T2 in the seawater to a low ratio on the settling plates probably indicates poor adsorption of MS-2 to air bubbles. We do not believe that this apparent loss of MS-2 was due to ultraviolet inactivation because plates held normal to the wind direction at the water's edge failed to show MS-2. On some occasions the host cell used to detect MS-2 did not grow well under field conditions. MS-2 is an interesting virus because it closely resembles pathogenic viruses of animals, but it remains to be seen whether it is adaptable to field experimentation. Because of the poor results with MS-2, we experimented chiefly with T2 and T4.

Dye and Phage Dispersion in the Surf

The dispersion and sampling accessibility of the dye and phage in the surf depended on the wave height and direction of the surf and the wind speed and wind direction relative to the beach. In the quiet waters of Orient Point Park, in the shelter of Peconic Bay, the diffusing and mixing dye patch elongated parallel to the beach and by 30 minutes after its release had expanded to an area more than 100 m long and 3 to 4 m wide with clearly visible fluorescence. Phage sampled from the most concentrated dye area in the water showed a dilution factor of approximately 10^4, and that from the trailing edge of the moving dye patch showed a dilution of approximately 10^6. Contrasted with this was the rapid initial dispersion of dye and virus in the 2-m-high surf on Kismet Beach facing the Atlantic Ocean. Moreover, the motion of the dye patch away from the shore, although maintaining the dye in the breaking waves, nevertheless made sampling difficult and occasionally hazardous. Depending on the wave height and the wind, the dye spot spread out parallel to the beach and maintained its color longer than 1 hour, although most often the dye patches migrated downwind. On several occasions the dye patch was seen and reported to us by beach strollers after it had moved more than 1.5 km down the beach. That the dye and phage remained together is clearly shown where seeded plates held normal to the wind direction and downwind of the injection site collected phage only when downwind of the visible patch of dye. Separation of the phage from the dye is achieved only by foaming action of the surf.

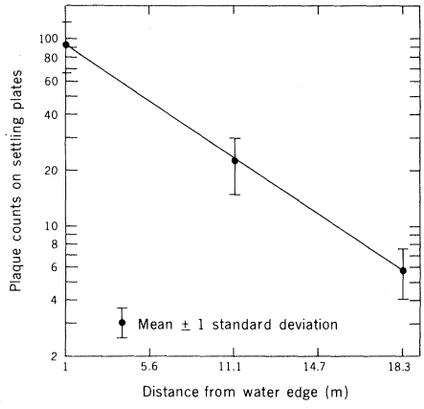

Fig. 1. Decrement of phage fallout in aerosol drops expressed as percentage of fallout at water's edge plotted against distance from water's edge. These data show the means and standard deviations for three rows of collecting sites in a 3 by 5 matrix sampling array.

Aerosol Drop Diameter

Filar micrometer measurements of the size of dried drops on clean settling plates had a range of 9 to 400 micrometers with a mean of 60 ± 80 μm standard deviation (S.D.) when the settling plates were near the water's edge. Ten meters from the shore, at the location of the Andersen sampler, the mean drop diameter was 21 ± 22 μm S.D. The means of the droplet sizes are not significantly different. Data on the diameter of droplets from the settling plates near the water's edge contain some spuriously large numbers that confer a distinct bimodal distribution on the data. When the spuriously large numbers are removed the mean is 35 ± 27 μm S.D. According to Blanchard and Syzdek (*2*), the ejected droplets from bursting bubbles are approximately 0.1 of the diameter of the bubble. Hence, the mean size of the bubbles in the surf was 350 μm, in good agreement with the data of Blanchard and Woodcock (*16*).

The performance of the Andersen sampler (*17*) was less reliable than that of the horizontal settling plates. On some days we obtained less than 20 plaques on all six plates, while settling plates collecting at the same time showed many hundreds of plaques. On two occasions we obtained 300 and 700 plaques, respectively, on the Andersen plates. These data, when plotted on log normal probability paper, fell on straight lines, with

Table 2. Data from the Andersen viable sampler. The sampler, with all six stages loaded with seeded agar plates, was turned on when the settling plates were uncovered and turned off when the plates were covered again.

Injection number	Date during 1976	Median diameter of particles captured on each of six stages of sampler (μm)						Distance from water (m)	Time sampled (minutes)
		7	4.7	3.3	2.1	1.1	0.65		
1	9 June*	19	4	0	6	0	0	50	45
2	9 June*	6	17	2	2	8	1	50	45
1	10 June*	14	6	11	34	8	3	50	45
2	10 June*	7	3	8	3	3	0	50	45
1	2 July†	14	1	3	0	0	0	8	15
1	8 July†	23	0	0	0	0	0	8	15
2	8 July†	2	0	0	0	0	0	8	15
1	15 July‡	459	182	27	39	16	5	8	15
2	15 July‡	318	119	4	13	4	0	8	15
1	22 July	10	3	7	2	0	0	8	15
2	22 July	4	1	2	1	0	0	8	15

*Other types of sampling not used. †Plates were seeded with the cell P4X6 which grew very poorly so that plaques were detected only by velvet transfer to new plates. The results were considered positive but not quantitative. ‡Each hole of the top plate of the Andersen sampler had one or more plaques beneath it.

the exception of the first stage data where the drops of all sizes greater than 7 μm impacted and skewed the otherwise logarithmic density of the frequency of drop diameters. Particle diameter data obtained with the Andersen sampler showed a range of 1 μm to greater than 7 μm as shown in Table 2. The data of Table 2 have an uneven quality and an unusual number of zeros. The uneven quality reflects the fact that we collected the data on many different days and had no control over such variables as wind speed and alongshore current speed. The number of zeros reflects the decreasing probability of one phage per drop when the drop size decreases. In addition, the number of zeros must result from the dilution of the phage-bearing aerosol as it moves from the surf to the sampler.

When the volume of the aerosol drop decreases, the number of phages expected in a drop decreases and the number of drops containing no phage increases. If, for example, each drop that was 35 μm in diameter contained two phages, then a drop that was 3 to 4 μm in diameter would be expected to carry 0.004 phage and 99.6 percent of the drops would carry no phage. In a 30-minute collection of the Andersen sampler, 1 cubic meter of air passed through the sampler. The number of drops having a diameter of 3 to 4 μm in this volume of marine aerosal is 5×10^5 per cubic meter according to Blanchard and Woodcock (*16*). If there were no mixing of the phage-bearing aerosol with uncontaminated marine aerosal, then we would expect $4 \times 10^{-3} \times 5 \times 10^5$ or 2×10^3 plaques per 30-minute sampling on the third stage of the Andersen sampler. When we correct for the dilution and mixing that occurred between the surf and the sampler we expect about 1/20 of the original concentration of viruses emitted by the surf, or approximately 100 plaques. Because the alongshore currents carried the virus-dye patch rapidly past our sampling array we never found the expected number of plaques but, instead, found as many as 27 and frequently found none at all, as Table 2 shows. It is clear in retrospect that not only the Andersen sampler but the entire sampling array should have been moved along the beach to remain continuously downwind of the virus-dye patch.

Concentration Factor

The T2 and T4 phages become adsorbed on bubbles and appeared in the drops formed from bursting bubbles (*18*).

Table 3. Analysis of the data from release No. 2 of 15 July 1976. Data show the windborne aerosol fallout from a mixed injection of T2 and T4 in the surf, and are expressed as numbers of plaque-forming units. A single column of the collecting matrix was analyzed for the relative numbers of pure and mixed plaques present in rows 1, 2, and 3 at 1, 11, and 22 m, respectively, from the water's edge.

Phage type	Row number			Row total
	1	2	3	
T4	135	171	184	490
T2	36	68	27	131
T2 + T4	24	52	33	109
Total number of plaques counted				730

The virus concentration was enhanced in the same manner as was observed by Blanchard and Syzdek (*11*) for bacteria and other organic substances. The concentration of virus on such drops was 50 times greater than in the bulk fluid from which the drops were ejected. Our results confirm that the same phenomenon occurs in the ocean.

The concentration factor is the ratio of virus concentration in the drop formed from a bubble to the concentration of virus in the seawater. The concentration of virus in the surf (number per milliliter) was sampled directly from the most concentrated dye spot whenever possible. The concentration of virus in the drops was determined from the settling plates, where we measured the number of virus particles per unit area of collecting liquid surface, the number of drops per unit area of the seeded plates, and the volume of drops on the clean plates. We assumed in these calculations that the several measurements made on different drops sampled about a half a meter apart were made on identical samples.

A critically important number in calculating the concentration factor is the total number of phages per drop. There are two ways to find this number. In the first method, the number of phages per square centimeter of impact area on the liquid settling plates is divided by the volume of drops falling per square centimeter of surface on seeded plates. This method gave satisfactory results only when iced tryptone broth was used as the liquid impact surface. The second method involves the simultaneous injection of both T2 and T4. The distribution of the two strains in the drops after a simultaneous injection of T2 and T4 permitted us to determine the total number of phages per drop by Poisson statistics. Analysis of the data in Table 3 is based on the following assumptions: (i) pure plaques of T2 are zero counts of T4; (ii) pure plaques of T4 are zero counts of T2; and (iii) plaques of T2 plus T4 contain at least one or more than one of each type of phage. Table 3 shows that the number of plaques containing no T2 was 490 which, divided by the total number, 730, gives 0.67. If we substituted this number in the zeroth term of the Poisson expansion, we see that the expression reduces to $e^{-x} = 0.67$, from which we see that $x = 0.4$ T2 phages per drop. Similarly, for zero counts of T4, we have 131/730 = 0.18 and, again, substituting we find the probability of zero counts of T4 is $e^{-x} = 0.18$, from which we see that $x = 1.7$ T4 phages per drop. The sum of the T2 per drop and the T4 per drop is 2.1 phages per drop, the combined dosage of phage per drop.

The total number of plaques counted on the same day as that shown in Table 3 was 3922, of which 722 were pure T2. Using these additional data, we find the number of T4 per drop is 1.78, which is in agreement with the 1.7 per drop determined from the subset that was analyzed for mixed drops. Extension of the Poisson analysis to include more than one, more than two, and so on, phages per drop shows good internal consistency of the data and excellent agreement of calculated with observed numbers per drop. For example, the Poisson calculation predicts that 45 percent of the plaques containing a T2 particle should also contain a T4 particle. The observed number, in excellent agreement with the predicted number, was 45.2 percent.

To facilitate the calculation of the concentration factor, we shall assume there are two phages per drop and that the volume of each drop is 2×10^4 μm^3, thus giving a phage concentration of 1×10^8 per milliliter. For phage concentration in the surf we are assuming 10^6 per milliliter and this gives us a calculated concentration factor of 100. As we shall see, this concentration factor is extremely conservative. The actual measurements of phage concentration in the surf were 2×10^4 and 2×10^5 phages per milliliter of seawater. We do not use these lower concentrations of phage in the surf for the concentration factor calculation because we cannot be certain that we have measured the surf phage concentration at the most concentrated location. Locating and sampling the area of highest dye concentration is difficult without levitation.

Estimates of the concentration factor made from aerosol fallout into iced tryptone broth on these different releases on one day gave average phage concentrations per drop of 500. Again, assuming a drop volume of 2×10^4 μm^3 we find a phage concentration of 2.5×10^{10} per milliliter. The concentration of phage in

the surf again suffers from the same uncertainty that we have not measured the most concentrated area. On the day of this experiment, the wind speed was 25 to 35 km per hour. The sampling began 2 minutes after injection before the dye patch had dispersed and continued at 30-second intervals for the 2 minutes that the dye was in line with the sampling network on the beach. The phage concentration in the surf was 10^8 per milliliter which gives a concentration factor of 250. We believe that the concentration factors of 100 to 250 found in our beach experiments are probably low, certainly conservative, and show beyond doubt that viruses are concentrated in the drops propelled into the air by breaking bubbles.

Discussion

Sampling the fallout of virus-containing aerosols confirmed and extended earlier observations on the wide range of sizes of drops generated by the surf (*16*).

We did not corroborate the particle fallout rates found by Perkins and Vaughn (*19*). These authors have given a calculation for the gravitational fallout of aerosol drops moving in a 16 km/hour breeze. Terminal velocities calculated from their equation are slow and make it unlikely in our experiments that such particles would fall within the confines of our sampling array. Yet, they did fall within it and the only explanation we can offer is that aerosol drops trapped inside the buckets of the sampling array were not carried away by the wind and fell freely to the sample collecting surface. The sharply decreasing rates of fallout shown by the data in Fig. 1 are probably due to the dilution of virus-containing aerosol with uncontaminated aerosol in the turbulent vertical mixing created by the sea breeze. The observed loss rates of virus-containing aerosol drops cannot be ascribed to drying or the effects of ultraviolet light because the exposure times of 3 to 6 seconds are too short.

Indeed, viruses caught in sea-foam survive more than 3 hours of drying and sunlight. Bacteria, viruses, and algae (*20*) are not alone when they are adsorbed to bubbles in seawater. Naturally occurring surface active materials in seawater also adsorb to bubbles (*21*). These materials may confer protection to the living entities against drying and inactivation caused by ultraviolet light.

Field experiments frequently suffer from a lack of control of some of the experimental variables. Ours are no exception. The least predictable and most vexing environmental variable of these experiments was the direction and speed of the alongshore current. The direction often changed between two consecutive virus injections, and in several cases we were forced to move the entire sampling array in an effort to maintain it downwind of the virus-emitting area in the surf. When the wind speed exceeded 27 km/hour, it was impossible to keep the sampling array in the airflow downwind from the virus sufficiently long to complete the desired sampling. Under these circumstances, the Andersen samples gave few or no plaques even when settling plates gave good results. Clearly, the sampling rate of the Andersen sampler is too low for the rates encountered in our experiments.

Another uncertainty in our experiments was the virus concentration in the surf which differed greatly between experiments depending on wind speed, water turbulence, and wave height. Because we could not control these variables, and could not be certain we were sampling virus concentration from the area of most intense fluorescence, we used our most conservative data for calculating the concentration factor. The real number doubtlessly exceeds the 100-fold enrichment we calculated. Whether or not we have been overcautious in calculating the concentration factor, it is in good agreement with concentration factors for phages (*18*) and bacteria (*2*) found in laboratory experiments. The significance of the concentration factor is that aerosol drops from low virus concentrations in natural waters may carry not one but many infective particles and thereby greatly increase the exposure of people or animals breathing the aerosol.

It remains to be seen whether all viruses and bacteria will show similarly high concentration factors. Some, such as the tubercle bacillus with its waxy coat, will probably have greater concentration factors. Others, such as the bacterial virus MS-2 used in some of our preliminary experiments, will have concentration factors of less than 100.

In considering the implications of our data to public health problems, we are able to make certain predictions. People living near large population centers on the seashore have been exposed to aerosol-carried infections for as long as the surf has been contaminated by sewage. Although we know of no epidemics in which marine aerosol has been a proven vector, nevertheless, the potential problem remains and increasing populations on the seaboard means increasing sewage and increasing exposure to airborne organisms. Fortunately, exposure to airborne viruses or other microorganisms may not be harmful if they occur normally and benignly, or if they occur repeatedly at very low levels so that immunity is built up without a full-blown clinical infection developing. It seems likely that people resident on the seacoast already have some immunities from repeated low-level exposures to the ambient microbial population in aerosols from sewage-contaminated surf. The pattern of built-up immunities along the seashore is of great interest and has been demonstrated by the work of Gruft *et al.* (*10*) relating marine aerosols and skin sensitivity to *Mycobacterium intracellulare* (Battey infection) in U.S. Naval recruits born and raised on the southeastern seaboard. The real danger to people inhabiting a coastline comes in the case of epidemics for which no previous immunity has been developed.

Occasionally, a coastline is subjected to a sudden intrusion of untreated sewage, as, for example, when several days of southwesterly winds blow the Hudson River plume 100 km east along the shore of Fire Island. When this happens, many human cultural artifacts commonly associated with sewage litter the beaches but, surprisingly enough, few coliform bacteria are found in the surf. This apparent paradox may be explained partly by mixing and partly by the bacteria adsorbing to bubbles from whitecaps and being ejected from the water into the wind. The surf alone produces 3×10^5 bubbles per square meter per second (*16*) and if we assume that the surf is 25 m wide and 100 km long we have 2.5×10^6 m^2 emitting 7.5×10^{11} bubbles per second. If each bubble ejects a single bacterium from the water there will be 7.5×10^{11} bacteria lofted into the wind every second. That is an impressive removal rate, especially when compared with the input of the Hudson River. The average summer flow of the Hudson is approximately 5×10^2 m^3 per second according to Bowman (*22*), and the average bacterial count of New York Harbor water at The Narrows is approximately 10^{12} per cubic meter according to Cassin (*23*). Hence, there are 5×10^{14} bacteria per second flowing along the south shore. If this outflowing water were evenly distributed along the 100 km of surf, then at a rate of removal of 7.5×10^{11} bacteria per second, the surf would be clean in less than 12 minutes.

Conclusions

Not only can virus be transferred from the sea to the atmosphere, but its concentration in the aerosol can be many

times higher than that in the main body of seawater. This is caused by the adsorption of virus to air bubbles as they rise through the water. When they burst at the surface the bubble skin strips the virus-rich layer of water from the bubble surface and ejects it into the air as small droplets. This mechanism of virus enrichment in the aerosol is, no doubt, the same as that which has been found for bacteria (*11*).

This work has implications for the field of public health, especially because viruses have been found in sewage (*6*), and because the dumping of sewage into the coastal regions of the sea is commonplace.

References and Notes

1. H. W. Horrocks, *Proc. R. Soc. London, Ser. B* **79**, 255 (1907).
2. D. C. Blanchard and L. Syzdek, *Science* **170**, 626 (1970).
3. A. W. Morrow, *Nature (London)* **22**, 489 (1969).
4. L. S. Hickey and C. Reist, *J. Water Pollut. Control Fed.* **47**, 2758 (1975).
5. E. Katzenelson, I. Buium, H. I. Shuval, *Science* **194**, 944 (1976).
6. N. A. Clark and P. W. Kabler, *Health Lab. Sci.* **1**, 1 (1964).
7. A. H. Woodcock, *Sewage Ind. Wastes* **27**, 1189 (1955).
8. C. A. Sorber, S. A. Schaub, H. T. Bausam, in *Virus Survival in Water and Wastewater Systems*, J. F. Malina, Jr., and B. P. Sagik, Eds. (Center for Research in Water Resources, University of Texas, Austin, 1974), p. 251.
9. R. Dimmick, unpublished data.
10. H. Gruft, J. Katz, D. C. Blanchard, *Am. J. Epidemiol.* **102**, 311 (1975).
11. D. C. Blanchard and L. D. Syzdek, *J. Res. Atmospheriques* **8**, 529 (1974).
12. D. L. Inman and W. H. Quinn, *Proceedings of the Second Conference on Coastal Engineering*, J. W. Johnson, Ed. (American Society of Civil Engineers, New York, 1951), p. 24.
13. M. B. Baylor *et al.*, *Genetics* **42**, 104 (1957).
14. G. S. Stent, *Molecular Biology of Bacterial Viruses* (Freeman, San Francisco, 1963).
15. M. H. Adam, *Bacteriophages* (Interscience, New York, 1959).
16. D. C. Blanchard and A. H. Woodcock. *Tellus* **9**, 145 (1957).
17. A. A. Andersen, *J. Bacteriol.* **76**, 471 (1958).
18. E. R. Baylor, V. B. Peters, M. B. Baylor, *Science* **197**, 763 (1977).
19. W. A. Perkins and L. M. Vaughan, *Bacteriol. Rev.* **25**, 347 (1961).
20. D. C. Blanchard, *Proceedings of the International Conference on Cloud Physics, 26 to 30 August, Toronto* (1968), pp. 25-29.
21. N. G. Maynard, *Z. Allg. Mikrobiol.* **8** (No. 2), 119 (1968); E. R. Baylor and W. H. Sutcliff, *Limnol. Oceanogr.* **8**, 369 (1963); G. A. Riley, *ibid.*, p. 372; B. D. Johnson, *ibid.* **21** (No. 3), 444 (1976).
22. M. Bowman, personal communication.
23. J. Cassin, personal communication.

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Humanity in Science: A Perspective and a Plea

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Summary. The phrase "humanity in science" encompasses several problems of various dimensions, which have been present for a long period. Their particular force can be most clearly appreciated by seeing the historical circumstances in which they arose and by examining the changing nature of the social contract between the scientific profession and society. The new ethical imperatives presently operating within society call for new responses. In addition, new ways must be found of mirroring scientific activity so as to more faithfully reflect its real nature to and incorporate it into our culture.

It is an honor and a pleasure to be asked to give the Phi Beta Kappa lecture to the American Association for the Advancement of Science, and after nearly a century and a half of a remarkable tradition in both America and England, it is a good opportunity to take stock. Here in Denver, representatives of the scientific profession, the media, and the enlightened citizenry of the town meet in an atmosphere if not of complacency, at least one that shows a tendency toward mutual admiration. We are the heirs of a very worthy tradition, which in England goes back some 146 years to 1831, when the British Association for the Advancement of Science held its first meeting in York, and thus started these annual celebrations of worthy endeavor and high purpose.

Now if we look around, both at this present gathering and retrospectively at history, we are tempted to deduce that all is indeed well with the relationship of science and society, and that 146 years earlier all, indeed, was well; that from the beginning the public and the scientific profession together have enjoyed a persistently happy partnership. Both deductions are quite wrong. All is not well with the present relationship between science and society, and in the early years too, when the scientific profession was born in Europe, all was not well. The golden days for the mutual involvement of science and society came much later. At the beginning there were, in fact, great tensions as the profession emerged, and equally there are some now. And I want to argue that at least one problem which lies at the root of some of our present troubles was a specter at these feasts from the very start and has haunted the profession ever since. If I may change my metaphor; it has been like the Cheshire cat, taking on firm outlines at one period, fading at another, and then returning to sneer at us once more. This problem is the theme of my article and it is the problem of humanity in science.

Now this phrase can have several meanings. Marie Curie once said, "Science deals with things not people." The problem arises if, and when, scientists and technologists are tempted to deal with people as things. One of the problems in and around science arises through the inevitable stance of detached objectivity whereby a scientist must approach the natural world. It can be no problem—but as recent work in the biomedical sciences or genetic engineering demonstrates, it can be a serious problem. And at a time when the social contract between this profession and society is in the process of being renegotiated, as it is now, humanity in science considered in these terms becomes deeply significant.

The second interpretation of this phrase means a consideration of the human beings who do science; those remarkable people who come to us in an assemblage infinitely varied. It is difficult to reach out and touch the humanity, or the humaneness, in the people who do

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