

Respirable Droplets from Whirlpools: Measurements of Size Distribution and Estimation of Disease Potential

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Droplets generated from water surfaces have been implicated in a number of diseases such as Legionnaires' disease and Pontiac fever. These droplets can be inhaled by people and can deposit in the respiratory system. The physical size of the droplets is critical in determining whether the droplets can contain the bacteria, reach the breathing zone of the subject, and deposit in the respiratory tract. The present study establishes the presence of water droplets above the surface of health club whirlpools. These droplets are of the appropriate size for causing respiratory disease. Several factors including pool temperature, bubbling action during operation, and height above the water surface have been investigated. The results are related to the deposition of the droplets, and hence bacteria, in the various regions of the respiratory tract. © 1986 Academic Press, Inc.

INTRODUCTION

Bacterial respiratory infections have been associated with a variety of water sources. The transmission of the bacteria from the water to the air and then to the human respiratory system requires the generation of water droplets small enough to reach and be deposited in the respiratory tract yet large enough to contain the bacteria and keep them in a viable condition. A number of outbreaks of disease have been studied in which a transmission mechanism of this type has been hypothesized. In recent years the most noted disease of this type has been Legionnaires' disease and its variant, Pontiac fever (Jones and Hebert, 1979; Glick *et al.*, 1978). Since the widely publicized outbreak at the Legionnaires' convention in Philadelphia in 1976, several serogroups of *Legionella pneumophila* have been identified from outbreaks in locations as diverse as power plant cooling towers (Tyndall, 1983), air-conditioning cooling towers (Dondero *et al.*, 1980), hospital shower heads (Cordes *et al.*, 1981), steam turbine condensers (Fraser *et al.*, 1979; Lauderdale and Johnson, 1983), and respiratory therapeutic nebulizers (Arnow *et al.*, 1982).

Other respiratory ailments have been found in power plant cooling towers and steam turbine condensers as well. Outbreaks also have been attributed to aerosolized water droplets from water treatment plants and from oceans ("red tide")

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microorganisms (Blanchard, 1972)). Respiratory ailments are frequently referred to as “fevers,” such as “bath water fever” (Muttari *et al.*, 1980), “humidifier fever” (Rylander *et al.*, 1978), etc.

It appears that little attempt has been made so far to measure the sizes of liquid aerosols that have disease potential. Measurements of the sizes and concentrations of liquid droplets equal in size or larger than the suspected bacteria would confirm that a source-receptor relationship exists for the disease-carrying bacteria in these outbreaks. It is assumed that a liquid environment is necessary for the bacteria to remain viable while airborne. Since liquid aerosols such as water droplets cannot be collected on a filter for subsequent size analysis, the transitory nature of these droplets and their presence in low concentrations renders such measurements technically difficult. In addition, the episodic nature of most of the outbreaks has generally prevented direct measurement of the airborne pathogens.

The generation of droplets from bubbles bursting at the water surface is a very common occurrence. For example, the presence of salt nuclei in the atmosphere even hundreds of miles away from the ocean has been postulated to result from the bursting of bubbles in the salt-containing ocean water and the subsequent wind transport of the dried residues of the aerosolized water (Blanchard and Woodcock, 1972). Bubbles are present in liquids as trapped air due to wave motion in natural bodies of water, or they are injected into the liquid by aeration in health club whirlpools and in sewage treatment plants. They may also result from evolution of gases from liquids undergoing pressure change, particularly prominent in carbonated drinks. The bubbles move upward and burst when breaking through the surface layer of the liquid (see Fig. 1). When the surface film of the air bubble bursts, “film droplets” are created. In addition, when the top of the bubble bursts, part of the film is pulled back into the surface of the water depression by water tension and a pencil-like water jet is formed at the center of the depression. It shoots up at high velocity and breaks up into several droplets. These “jet droplets” tend to be larger than the film droplets. Both types of droplets are formed in most bubbles. However, it appears that jet droplets are

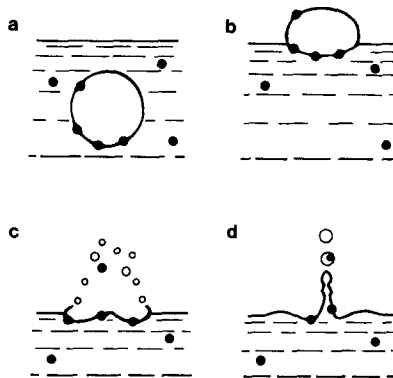


FIG. 1. Bubble motion and disintegration: (a) contaminant enrichment of rising bubble film; (b) bubble at surface; (c) film droplet formation; (d) jet droplet formation.

principally formed by small bubbles (approx. less than 1 cm in diameter) (Tommaides and Whitby, 1975; Blanchard and Syzdek, 1982).

As the bubble rises through the water, it collects particles such as bacteria on its surface by interception. This can result in an enrichment of bacterial concentration in the bubble surface relative to the bulk concentration in the liquid. Both the film droplets and the jet droplets that are formed from the bubble surface can have an enrichment of bacterial concentration ranging from unity to several hundred (Blanchard and Syzdek, 1982; Weber *et al.*, 1983). The enrichment is greater for the jet droplets, although enrichment factors of 10 to 50 have been found for film droplets. The bacterial enrichment depends on the distance the bubble rises through the water and on water contaminants such as surfactants and oils (Blanchard and Hoffman, 1978).

The size distribution of airborne liquid droplets is critical for delivering viable bacteria to the respiratory system. Legionella bacteria have been measured by electron microscopy to be 0.3 to 0.9 μm in diameter and more than 2 μm long (Chandler *et al.*, 1979). We assume for the present discussion that the minimum droplet diameter to contain such bacteria is 2 μm . In order to reach the alveolar region of the respiratory system, the droplet diameter must be less than 10 μm . Droplets depositing in the tracheobronchial region can be as large as 20 μm . Deposition in the extrathoracic region can occur for larger droplets up to 200 μm (Ogden, 1983). A specific size range of droplets is therefore required to deliver the bacteria to the sensitive sites.

The stability of the droplets in the air is highly dependent on the temperature and humidity conditions in the environment. Droplets present in air that is supersaturated with water vapor will generally increase in size. If the relative humidity is close to 100% the droplets will remain about the same diameter. If the relative humidity is less than 100%, the droplets will evaporate. For instance, water evaporated from a heated pool will produce a supersaturated condition when it meets relatively cool and dry surrounding air. The water vapor will condense on particles and droplets already present in the air increasing their size. If there is further mixing with cool, dry air, then the droplets will begin to evaporate. On the other hand if the air around the pool is enclosed and the temperature and humidity levels are in equilibrium with those near the water surface, the droplet size will stabilize.

Another factor that must be considered is the droplets' settling velocity; that is, the rate at which the individual droplets would fall due to gravity in still air. For instance, a 5- μm water droplet has a gravitational settling velocity of 0.08 cm/sec, while a 10- μm droplet has one of 0.3 cm/sec. If the air above the water surface is rising due to the water temperature, then the droplets smaller than 5 μm may rise with the vapor while droplets larger than 10 μm will generally settle back to the water surface. However, if the air above the surface is stirred, such as by the motion of people in the water, then larger droplets will also be carried up into the air.

The investigation of a Pontiac fever outbreak at a whirlpool in a health spa in Rochester, Michigan, provided an opportunity to use a newly developed instrument, the aerodynamic particle sizer (Baron, 1983; Remiarz *et al.*, 1983), to make *in situ* measurements of the water droplet size distribution. Measurements were

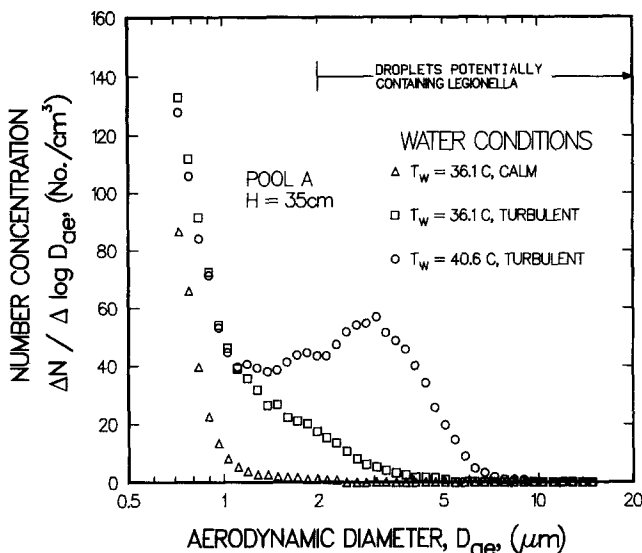


FIG. 2. Number distributions as a function of particle size above a heated therapeutic whirlpool as measured with the aerodynamic particle sizer. The curves indicate the effect of water temperature and surface turbulence.

made at this whirlpool and at another one of a different type in an attempt to elucidate the conditions under which droplets are emitted and are likely to transmit bacteria.

METHODS AND MATERIALS

The water droplet size distribution was measured with an aerodynamic particle sizer (Model 3300, TSI, Inc., St. Paul, Minn.)². This instrument consists of a separate sensor unit (size $43 \times 43 \times 27$ cm, mass 15 kg), a microcomputer for control, data manipulation, and display, and a printer for hard-copy output. The aerodynamic particle sizer (APS) operates by drawing aerosols into a nozzle which accelerates the particles through a laser velocimeter. The velocity of the particles is directly related to their aerodynamic size, because the larger particles accelerate less than the smaller ones. The aerodynamic diameter is the diameter of a unit density sphere having the same settling velocity in air as the particle in question. The APS is calibrated with reference latex spheres. An independent check was carried out to ascertain that the water droplet shape was not distorted by the high acceleration field. Larger particles with lower surface tension than the ones considered here were found to distort significantly. The APS gives a rapid display of the particle size distribution in the range of 0.7 to 15 μm . The ability to measure water droplets is aided by the short path to the sensing volume and the rapid measurement process. The relative humidity is kept unchanged so that the droplets' sizes will not be altered. Since water droplets are spherical and have unit density, the aerodynamic diameter is the same as the physical diameter. Both the physical size and the aerodynamic size are generally of interest because

² The mention of trade names or commercial products does not constitute endorsement by the National Institute for Occupational Safety and Health.

the physical size determines whether bacteria can be contained by the aerosolized droplet and the aerodynamic size determines the site and extent of deposition in the respiratory tract.

During the measurement of the water droplet size distribution, the APS was suspended over the pool by a scaffolding constructed of light structural steel beams. The APS was inverted with the inlet nozzle pointing down so that the instrument body did not interfere with the upward motion of the aerosols emitted from the water surface. Since the instrument was powered by 115 VAC, a ground fault interrupter was used to reduce the shock hazard. Outside ambient air was ducted to the internal volume of the APS to prevent water condensation on the electronic components. Size distribution measurement times ranged from 2 to 5 min. Air velocity measurements were made with a hot film anemometer and the temperature measurements were made with a laboratory thermometer.

Whirlpools at two different locations were investigated. The first was at a Cincinnati, Ohio, health club. This whirlpool (Pool A) was located in an open atrium in the center of the club. The pool was round and measured approximately 3 m in diameter. During use an air injection system caused increased jet action in the pool. The jets were aimed up toward the surface and this increased the turbulence and bubbling at the surface. The bubbles were up to several centimeters in diameter. This whirlpool was allowed to cool before starting the measurements and was then heated by adding hot water to observe the effect of the whirlpool temperature on droplet size and concentration. These measurements were taken in the region above the whirlpool where people might inhale the droplets. Since the whirlpool was in an open area, good ventilation of the air above the whirlpool took place. An aerosol was visible above the whirlpool, but disappeared about 1 to 1.5 meters above the pool surface.

The second whirlpool (Pool B) was at the health club in Rochester, Michigan, where the outbreak of Pontiac fever had taken place. This pool was square (approximately 2×2 m) and was enclosed in a small room only slightly larger than the whirlpool. During operation of the whirlpool, water was injected as horizontal jets about 0.5 m below the surface. No air injection was used and the only indication of bubbling was a small amount of foam visible on the surface after the pool was turned on. The bubbles were noticeably smaller than at Pool A. Air ventilation in this room was almost nonexistent. The air velocity at the exhaust vent in the ceiling and at the door to the room was less than 25 cm/sec.

RESULTS

The size distributions by number of the water droplets obtained with the APS above the whirlpools are shown in Figs. 2 to 4. The figures indicate aerodynamic diameter which, for unit density spheres such as water droplets, is the same as physical diameter. Figure 2 shows the effect of turbulence and water temperature on the number concentration of water droplets above the surface of Pool A. The initial measurement was made after the pool heater had been turned off for several hours. At that time the temperature was 36.1°C. The second measurement shown was taken with the water jets and aeration turned on. The pool was then partially drained and hot tap water was added, raising the whirlpool temperature to 40.6°C.

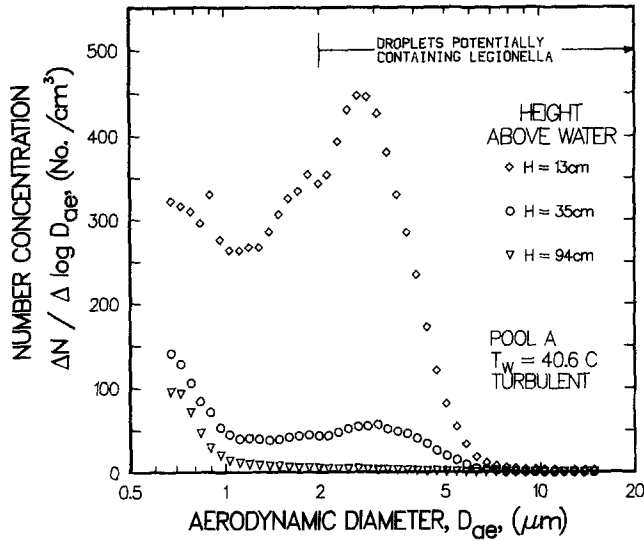


FIG. 3. Number distributions as a function of particle size above a whirlpool. The curves indicate the effect of distance above the water surface when the rising vapor and droplets mix with cooler, drier surrounding air.

Figure 3 shows the size distribution above Pool A at three different heights. These heights were chosen to approximately cover the range of people's breathing zones when in or at the edge of a whirlpool. Figure 4 shows a comparison of size distributions above Pools A and B. While the measurements at different heights at Pool A indicate varying size distributions, similar measurements at Pool B all gave the distribution shown in Fig. 4 within 20%.

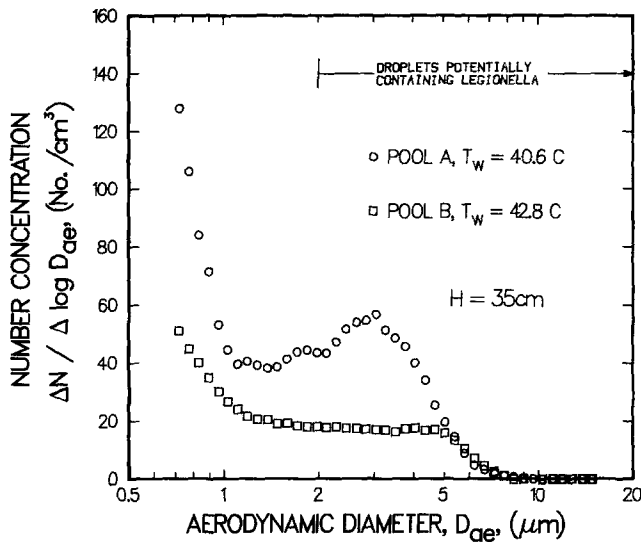


FIG. 4. Number distributions as a function of particle size above two different whirlpools. The curves indicate the effect of different pool conditions, primarily those of turbulence and relative humidity.

DISCUSSION

The process of droplet generation, growth, and evaporation is dependent on the water surface conditions and the relative humidity in the air surrounding the water surface. One variable that was available for our control was the whirlpool temperature. By raising the water temperature, both the rate of water evaporation and the difference in water and air temperatures were increased. These increases contributed to higher saturation of water vapor in the air above the surface. Figure 2 shows (a) the droplet size distributions for the initial condition in Pool A with no massage jets turned on, (b) the distribution in the same pool at the same temperature with the jets and aeration on, and (c) the distribution in the same pool with jets and aeration on at a higher temperature. Since the jets in Pool A angled up, the surface of the whirlpool was quite turbulent. With no surface turbulence, it can be seen that the droplet concentration above $1\ \mu\text{m}$ is relatively low. The particle concentration indicated between 0.8 and $1\ \mu\text{m}$ is representative of number concentrations found in ambient air environments (Willeke and Whitby, 1975). As illustrated below, the high number concentration in this size range corresponds to very little mass. With the water jets and aeration on, Fig. 2 shows that water droplets are generated. For instance, at $1\ \mu\text{m}$, the increase is fivefold; at $2\ \mu\text{m}$, 36-fold; and at $5\ \mu\text{m}$, over 100-fold. At the higher temperature of 40.6°C , there is a dramatic jump in the concentration of droplets in the 1 - to $7\text{-}\mu\text{m}$ range. The low concentration of droplets larger than $7\ \mu\text{m}$ is largely due to their increased settling rate. It should be noted that the normal operating range of the whirlpool was indicated to be about 39 to 43°C . Thus, the latter measurement condition is within the normal operating range of the pool and indicates a typical aerosol distribution. Assuming that *Legionella* bacteria are present in the whirlpool and that the droplets need to be $2\ \mu\text{m}$ in diameter or larger to potentially contain these bacteria, this typical aerosol size distribution shows that bacteria may be present in the air above the whirlpool.

Droplets being generated from the surface of the water are affected by the relative humidity conditions above the surface. The instantaneous relative humidity as the droplets travel upward with the heated vapor determines the droplets' growth, evaporation, or stability. In Pool A, the open air arrangement allows cooler, drier air to mix with the rising droplets and causes their evaporation. This is seen clearly in Fig. 3 which depicts the distribution above Pool A at 13 , 35 , and 94 cm above the surface. This observation contrasts sharply with measurements at Pool B, where the distributions were quite similar at several heights above the water surface. Pool B was in an enclosed room that prevented mixing of the aerosol with drier air and hence a stable size distribution was produced.

Another variable affecting the concentration and size distribution of droplets is the degree of bubbling at the surface. Figure 4 compares the distributions above Pools A and B at similar height and temperature conditions. The amount of bubbling produced at Pool B was not great. The pressure variation within the jet under the water surface apparently caused some bubbles (generally less than 1 cm diameter) to be formed. The bubbling due to the aeration in Pool A significantly increases the number of droplet generated into the air.

The APS software allows the calculation of the aerosol mass distribution from the number distribution. The data in Fig. 2 are transformed in this manner and presented in Fig. 5. Since larger particles, although fewer in number, have larger mass, the peaks of the mass distribution shift to larger diameters when compared to the peaks in the number distribution. The increase in mass of aerosol with increasing temperature and surface turbulence is even more dramatic than indicated in the number distribution. The number of bacteria generated from the surface is probably more closely related to the volume or mass of water droplets rather than to the number of droplets ejected into the air. This relationship may be modified by the enrichment of bacteria on the bubble surface and by other mechanisms in the droplet generation process. Figure 5 indicates that the mass of droplets above 7 μm is significant. These larger droplets were found to be few in number because their increased settling velocity tended to prevent their rise beyond a few centimeters above the surface. However, with the presence of people in the whirlpool disturbing the air, the number and mass of these larger droplets being carried up to the people's breathing zones could increase greatly.

The data above have shown the presence of particles in the air above the whirlpools. Some of these particles are normally present in the ambient air. However there are relatively few of these particles. Most of the particles observed must be water droplets, since no other material from which the particles can form is present. The droplets seem to be formed primarily by the bursting of bubbles, since the droplet concentration is significantly greater when the bubbles are present. The next link in the source-receptor chain is the deposition of droplets containing bacteria in the respiratory tracts of people using the whirlpools. Note that these droplets must be of sufficient size to contain bacteria, assumed to be 2 μm in diameter for *Legionella* bacteria. The size dependence of aerosol deposition in the various regions of the human respiratory tract has been well studied

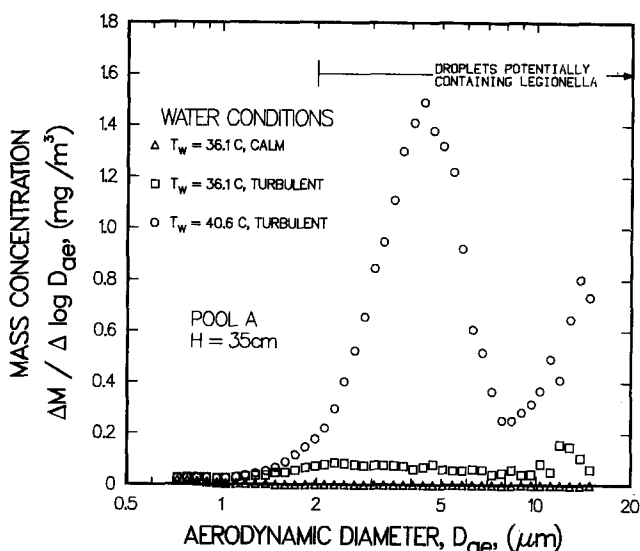


FIG. 5. Mass distributions as a function of particle size as calculated from the data in Fig. 2.

(Lippmann *et al.*, 1983). There are a number of empirically determined or calculated size-dependent deposition and sampling curves that can be applied to the droplet size data. As an example of the calculation of aerosol distributions reaching specific sites in the respiratory tract, we have used the definitions produced by the International Standards Organization (ISO) Technical Committee 146 (Ogden, 1983).

The ISO definitions divide the respiratory tract into components, as indicated in Fig. 6. As particle size increases, the fraction that enters the nose and mouth drops from 100 to 0% for submicrometer particles at about 200 μm . The fractions reaching each of the aforementioned regions according to the ISO definitions have been determined for the highest concentration mass distribution measured at Pool A and are displayed in Fig. 6. It is apparent that, in the example given, droplets potentially containing *Legionella* reach all the respiratory regions. The greatest mass of droplets is available to the tracheobronchial region, with significant amounts also available to the alveolar and extrathoracic surfaces. Thus, it is possible to obtain quantitative estimates of exposure of the various target regions to droplets potentially containing hazardous bacteria.

CONCLUSIONS

The water droplet size distributions have been measured in the air above two different whirlpools using the newly developed aerodynamic particle sizer. The size distributions have been shown to contain fractions that are of the appropriate size to transport *Legionella* bacteria to the alveolar and tracheobronchial regions as well as to the extrathoracic regions of the respiratory tract. The size distribution and concentration of droplets are complex functions of the pool temper-

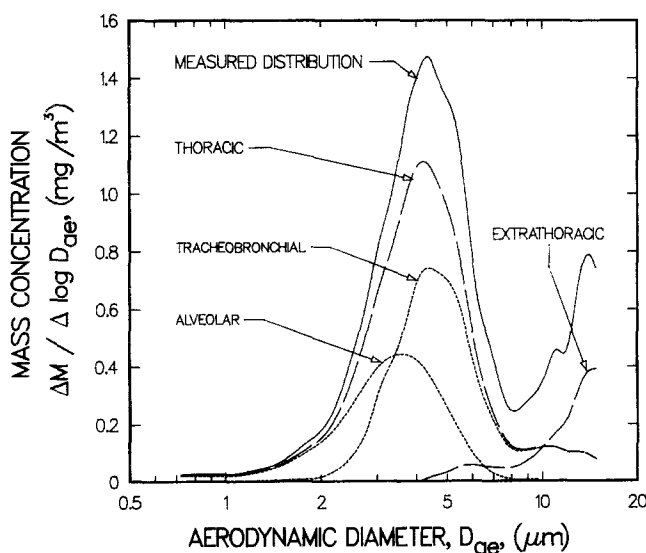


FIG. 6. The fractions of droplets reaching specific regions of the respiratory tract are shown for the measured aerosol size distribution at the higher temperature condition in Fig. 4. The alveolar definition used here is that produced by the American Conference of Governmental Industrial Hygienists.

ature and agitation conditions as well as of the room temperature and humidity. Bubbling or agitation of the surface is required to generate water droplets containing bacteria. As the pool temperature increases relative to the air temperature, the size and concentration of droplets increases. As the degree of bubbling and agitation of the surface increases, the droplet concentration increases. As the stirring of the air above the surface of the whirlpool increases there is probably an increase in the number of particles larger than 10 μm being delivered to the breathing zone. Unknown variables at this time are the degree of bacterial enrichment in the bubble-generated water droplets and the apportionment of bacteria in droplets as a function of droplet size.

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