PRODUCING SAFE DRINKING WATER IS NOT EASY

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Introduction

Production of water that is safe to drink is the foremost goal of the water treatment industry. Safe drinking water, as defined by the Safe Drinking Water Act (SDWA) of 1974,[1] is water which causes no adverse effects on human health. The SDWA and its amendments of 1986[2] led to U. S. Environmental Protection Agency (EPA) regulations designed to protect the public's health. These regulations are directed against chemical and microbial contaminants in drinking water. Currently 83 contaminants, mostly specific chemical compounds, are regulated and more regulations will be added each year.[3]

Public concern for the presence in water of chemicals which might cause adverse health effects after long-term exposure appears to be greater than the concern for the presence of microbial agents which can cause illness within two weeks of exposure. Yet the practice of treating water to make it safe for drinking began because of the need to control the transmission, by water, of microorganisms which cause disease. Production of drinking water that is safe microbiologically is still the primary public health concern of the drinking water industry. However, despite remarkable progress in the improvement of water treatment, outbreaks of waterborne disease still occur with disturbing frequency.[4]

Data-Reporting System for Outbreaks

Before the data on waterborne disease outbreaks is interpreted, it is appropriate to note how it is collected. From 1920 to 1971, information on waterborne illness, together with information on illnesses spread by contaminated food and milk, was submitted voluntarily to the U. S. Public Health Service (USPHS) by state agencies concerned with intestinal illness. The reporting procedure was changed in 1971 when EPA joined with the Center for Disease Control (CDC) in a collaborative effort to improve reporting of waterborne illnesses[5] which now are reported separately. Under the current system,[6] EPA contacts all state water-supply regulatory agencies to obtain information about waterborne-disease outbreaks. Additionally, state health departments report water-related disease outbreaks to CDC on a standard reporting form. The statistics include information from both sources. Representatives from CDC and EPA review and summarize outbreak data and work together to investigate and evaluate waterborne-disease outbreaks. Also, on request by state health departments, CDC and EPA offer epidemiologic assistance, provide consultation in the engineering and environmental aspects of water treatment, and, when indicated, collect large-volume water samples to identify viruses, parasites, and bacterial pathogens.

Since this is a voluntary system, there are limitations to the data. Some investigators think the increase in outbreaks, especially since 1971, reflects increased reporting rather than increased occurrence. In the opinions of both CDC and EPA, the number of waterborne- disease outbreaks reported represents a fraction of the total number that occur.

Few states have an active outbreak-surveillance program, and disease outbreaks often are not recognized in a community or, if recognized, are not traced to the drinking-water source. One EPA-funded study in Colorado found that only about one-fourth of waterborne-disease outbreaks were being recognized and reported. Other studies suggest that under-reporting may be much greater.[7]

A major factor in the failure to recognize waterborne disease outbreaks is that most people who experience gastroenteritis, some of which may be waterborne in origin, do not seek medical attention. When medical attention is sought, physicians generally cannot attribute gastroenteritis to any specific source. Physician-treated illnesses are seldom reported to state public health agencies even when a causative agent has been identified. Following reporting, if it occurs, there still must be investigation and effective communication between agencies responsible for public health and water supply. Thus, EPA believes the number of cases of illness caused by waterborne agents is ten-fold to several-hundred-fold higher than actually is recorded and reported.[7] Therefore, it is difficult to draw firm conclusions about the true incidence of waterborne-disease outbreaks or about the relative incidence of waterborne diseases of various etiologies.[6]

Statistics for Waterborne Disease Outbreaks

Statistics show that the number of waterborne disease outbreaks has been increasing since 1946.[5] During the 15-year period including 1971 through 1985, 502 outbreaks caused 111,228 cases of illness.[8] The number of outbreaks occurring during this period was more than had occurred in any 15-year period since 1920.[8]

The outbreaks occurred in all types of water systems. Eighty-five percent of the outbreaks, causing 99% of the illnesses, occurred in public water systems.[8] Although individual water systems were associated with 15% of the outbreaks, these systems produced only 1% of the illnesses.

Water supply systems are defined in the SDWA. A public water supply system normally consists of: (1) a water supply from a surface source such as a river, lake, or reservoir, or from a ground source such as a well or spring, or a mixture of the two; (2) treatment facilities; and (3) a distribution network of mains and pipes that deliver water to the consuming public. There are two types of public water systems: community and noncommunity. A community water system serves year-round residents; a noncommunity water system serves the traveling public at places like institutions, camps, parks, or motels. Where public water systems are not available, people develop their own household water supplies, individual systems, usually wells. There are about 215,000 public water systems in the United States.[5] Of these, 65,000 are community systems and 150,000 are noncommunity systems. There are about 10 million individual systems, most of which serve individual households.

Community water systems generally serve larger populations than the other systems. Thus, an outbreak in a community water system can affect many people as shown by these systems accounting for 42% of the outbreaks and 68% of the illnesses.[8]

Etiology of Waterborne Disease in the U.S.

Etiology is the cause or origin of a disease or abnormal condition. The etiologic agents identified in waterborne-disease outbreaks include bacteria (13%), protozoans (19%), viruses (8%), and chemicals (10%).[8] Bacteria, protozoans, and viruses collectively are called microorganisms, or microbes. In 50% of the outbreaks, a causative agent was never identified so the illnesses were reported simply as acute gastrointestinal illness (AGI).

Outbreaks and illness caused by chemicals probably are better recognized and reported than are those caused by microbial agents.[9] Chemical contaminants usually impart unusual taste, odor, or discoloration to the water or cause immediate irritation of skin or eyes, leading to complaints that prompt investigation.

Bacteria: Bacteria are microscopic, single-celled plants. Most bacteria in the world perform valuable services for mankind, but a few are pathogenic (disease causing). The pathogenic bacteria identified in the outbreaks include *Shigella, Salmonella, Campylobacter*, enteropathogenic *Escherichia coli, Pasteurella*, and *Yersinia*.[9] All these cause gastroenteritis that varies in severity from mild to fatal. Their presence in water indicates fecal contamination of the water.

The laboratory isolation and identification of pathogenic enteric bacteria involves the use of selective culture media developed to isolate known species. In other words, failure to culture (grow) a pathogenic bacterium does not mean that none are present. It only means none were cultured using the prescribed procedures. Fairly simple and relatively inexpensive procedures exist for isolating from the feces of infected persons those bacteria known to be pathogenic. Even in feces of infected persons the numbers of pathogenic bacteria are relatively low compared to the numbers of bacteria which represent the normal flora of the intestinal tract. Isolating them from water in which their numbers are markedly reduced and their survival is threatened by being out of their natural habitat is much more difficult.

The only bacteria for which water routinely is cultured are the coliform bacteria. Originally, it was thought that coliforms consistently were found only in feces of warm-blooded animals. Thus, their presence in water signaled the presence of fecal material and, hence, the potential presence of enteric pathogens. However, the "coliform" classification is based on certain cultural characteristics which are shared by other bacteria widely distributed in nature and not associated with the intestinal tract of warm-blooded animals. When the simple, routine screening for total coliforms is positive, further definitive tests are necessary to identity fecal coliforms, a subgroup of the total coliform group, or to identify *Escherichia coli*, an unquestionable inhabitant of the gastrointestinal tract of man and other warm-blooded animals. In this fuller sense, coliform testing is used as an indication of fecal contamination and is a water-quality parameter both for drinking water and the raw-water source from which the drinking water is produced.

Viruses: Although only 8% of the outbreaks occurring from 1971 to 1985 were shown to be caused by viruses, it is suspected that many of the outbreaks of unknown etiology also were caused by viruses.[9] Viruses are sub-microscopic in size and are obligate intracellular parasites. Thus, their recovery from water and from infected persons is extremely difficult. Water never is tested routinely for viruses.

Laboratory culture of viruses requires dividing cells for culture media. Cell cultures to support the growth of viruses exist for only some of the known viruses. In fact, Hepatitis A Virus (HAV), which has been responsible for many viral disease outbreaks, has very recently been adapted to culture in a cell line.[10] Thus, for more than two decades, questions about the effectiveness of water treatment practices to remove HAV remained unanswered.

Other enteric viruses associated with waterborne-disease outbreaks include Rotavirus, Norwalk virus, and Polio virus.[9]

The virus getting most public attention currently is Human Immunodeficiency Virus (HIV), the causative agent of Acquired Immunodeficiency Syndrome, AIDS. The American Water Works Association (AWWA) Research Foundation commissioned an assessment of the potential for transmission of HIV by water.[11] The assessment was that the risk is essentially zero. The modes of transmission for HIV are well-known. No environmentally-mediated mode has ever been shown. Also, HIV is extremely sensitive to disinfection. A 0.1% solution of household bleach can inactivate the virus in 10-20 seconds.

Protozoa: Pathogenic protozoans enter water supplies as eggs or cysts deposited in the environment with feces from infected humans and animals. Protozoans of most concern in water supplies include *Entamoeba histolytica*, which causes the severe disease amoebic dysentery, and *Giardia lamblia* and *Cryptosporidium*, which cause less severe gastrointestinal illness.[8]

Giardia lamblia is the most prevalent cause of waterborne disease in the U. S.[8] The infective stage of *Giardia*, the cyst form, has been found in more than 25% of the surface water sources in the U.S.[7] It has been found in pristine streams and in finished drinking- water supplies.[12]

Giardia cysts are carried by infected humans and by animals such as dogs, cats, and beavers. The cysts are very hardy, surviving in cool waters for up to two months, and are very resistant to disinfection.[13]

Recovery of cysts from feces is by flotation methods based on specific gravities. Recovery from water requires membrane filtration of large volumes of water. Identification of *Giardia* cysts is by direct microscopic examination or by immunofluorescent assay.[14]

Cryptosporidium as a cause for waterborne disease was unknown before 1985.[14] The infective stage is a cyst form, called an oocyst, which appears to be much more resistant to disinfection than *Giardia*.[14] It is present in infected humans and in many wild and domestic animals. Cross-species infectivity has been demonstrated.[14]

Cryptosporidium oocysts have been found in 55% to 92% of the raw-water sources in the U. S. and in at least 17% of the treated-water supplies examined for its presence.[3] Presence of the parasite does not lead inevitably to outbreaks.[3]

Only two U. S. outbreaks have been linked to *Cryptosporidium*. In one, the raw-water source was groundwater which had been contaminated with sewage.[14] Treated surface water caused the second outbreak which occurred in Carrollton, Georgia, in 1987. With 13,000 reported cases of illness, this outbreak is the largest one reported to CDC since 1971.[6]

Recovery and detection methods for *Cryptosporidium* oocysts are similar to those used for *Giardia*.

Water never is tested routinely for the presence of protozoan cysts since the methods are too complicated and expensive for routine use.

Control of Waterborne Disease Outbreaks

Multiple Barrier Concept: The multiple barrier concept for control of waterborne disease focuses on three barriers:

1. Protection of the raw-water source
2. Properly designed and operated water-treatment processes, and
3. Adequate and continuous disinfection of drinking water

If one barrier fails, the magnitude of the consequence is reduced if the others are intact. Protection of the raw-water source includes proper sewage disposal, locations of water intakes upstream from wastewater discharges, sanitary construction of wells, and possible restriction of human activity on watershed areas.

Disinfection: Disinfection, the final barrier, still is considered the most important. Currently, not all public water supplies in the U. S. are disinfected, but that soon will change as required by the 1986 amendments to the SDWA. The Surface Water Treatment Rule (SWTR) which became effective December 31, 1990, requires disinfection for all public water supplies from surface-water sources.[7] Regulations requiring disinfection of drinking water from groundwater sources are being developed.

Disinfection kills some microorganisms and inactivates others. It does not sterilize the water. Microorganisms vary in their degree of sensitivity to disinfectants. Generally, bacteria are most sensitive, viruses have intermediate sensitivity, and protozoan cysts are most resistant.[9] The effectiveness of any disinfectant is lowered when high concentrations of microorganisms or other particulate matter are present in the water. Thus, it is desirable to remove as many microorganisms and as much other matter as possible prior to disinfection.

Effective Treatment Processes: Treatment processes effective for removal of microorganisms from water include: (1) conventional treatment, (2) direct filtration, (3) slow sand filtration, and (4) diatomaceous earth filtration. Other processes such as ultrafiltration and reverse osmosis are being evaluated for practical application to the treatment of drinking water.

Conventional treatment, employed in many large treatment plants which use surface water as the source water, includes coagulation, flocculation, sedimentation, and filtration prior to disinfection.

Coagulation is the process of destabilization of the charge, predominantly negative, on suspended particulates and colloids. The purpose of destabilization is to lessen the repelling character of the particles and allow them to become attached to other particles so that they may be removed in subsequent processes. Destabilization is accomplished by the addition of coagulant chemicals such as alum, ferric sulfate, lime, and cationic polymers.

Flocculation is the agglomeration of destabilized particles and colloids toward settleable (or filterable) particles called flocs. Incidental flocculation begins immediately after destabilization and may be adequate in some circumstances. Normally, flocculation involves an intentional and defined process of gentle stirring to enhance contact of destabilized particles and to build floc particles of optimum size, density, and strength to be removed by settling or filtration.

Sedimentation is the removal of flocculated matter from suspension by gravity.

The particulates in water contribute to an optical property called turbidity, which is the scattering of light rays as they pass through the water. The common measurement of turbidity uses a photoelectric detector that makes use of nephelometry to measure the intensity of scattered light. Measurements are expressed in nephelometric turbidity units (ntu). Current regulations require that the turbidity of drinking water be no more than 0.5 ntu in 95% of the measurements, which must be taken at least as frequently as every four hours.[7] Many plants have turbidimeters installed to give continuous measurements of the water as it leaves the filter or prior to distribution.

Filtration is the passage of water through a porous medium to remove suspended solids. In conventional treatment, filtration is at a rapid rate through sand or mixed media containing sand and anthracite coal. Rapid rate filtration must be preceded by effective coagulation.

With direct filtration, the sedimentation step is eliminated. Occasionally, the deliberate flocculation stage is eliminated also. Decisions to eliminate stages of treatment are based on raw-water quality and the ability to achieve the regulatory standards for finished drinking water. Direct filtration is rapid-rate; therefore, it also must be preceded by effective coagulation.

Historically, slow sand filtration was the first water-treatment process and still is used effectively. It requires more land area for the filters and is suitable for small systems where the demand for water is low. In recent years, this process has been overshadowed by the rapid-rate process but currently is receiving renewed interest. Many small systems will be required to install filtration under the new SWTR and the slow-sand process will be used by most.[7]

With slow-sand filtration, no pretreatment of water is necessary. A combination of biological, biochemical, and physical processes occur in the filter to remove microorganisms effectively.

Straining is the mechanism for microbial removal by diatomaceous earth filtration. The filter consists of a pressure vessel containing a septum on which diatomite is supported. The medium, diatomite, has much smaller pore sizes than the sand used in the other filters. The configuration of the attached diatomite particles further enhances the physical straining process.

These treatment processes, when properly designed and well-operated, are effective in the removal of microorganisms. Studies show that 90 to 99.9 percent of the microbes can be removed, leaving few to be inactivated by disinfection.[7] Overall, the most effective treatment is conventional treatment which achieves 99% removal of viruses and bacteria and more than 99% removal of *Giardia* cysts.[7] Slow sand filtration achieves 99% removal of all microbes.[7]

Concepts Developed from Outbreak Investigations

Concepts developed from the investigation of waterborne disease outbreaks and from pilot plant studies of treatment processes to remove and/or inactivate pathogenic microorganisms in drinking water have focused design and treatment processes.

Some of these concepts follow:

1. As a parameter useful by itself in evaluating the presence of microorganisms in water, turbidity is irrelevant.[15] Significant numbers of microorganisms can be present in raw-water sources which have low natural turbidity. In evaluating the effectiveness of treatments for removal of microbes, the degree of reduction of turbidity is more reliable than the turbidity value itself. For example, a treated-water-turbidity level of 0.4 ntu would meet the regulatory requirements; but if this represented a 47% reduction of turbidity, it represents a corresponding removal of about 48% of the microorganisms originally present.[16] The treatment goal should be to achieve the lowest turbidity possible. This means optimizing treatment processes to achieve optimal coagulation and flocculation when these processes are employed.

2. Variations in filtration rates when rapid-rate filtration is employed should be avoided.[9,15] Abrupt changes are the worst changes. Thus, automatic on-off cycles to match water supply to water demand are undesirable.[15] Rather, the design should provide for continuous recycling at a steady rate through the filter. The investigation of the outbreak of *Cryptosporidium* in Carrollton, Georgia, showed the practice of restarting flow through a filter that had been used previously.[17] This was acceptable practice then and all water quality standards were being met, yet the effect was a surge of oocysts into water from the filter on which they had been entrapped.

3. Increases in turbidity that occur when a filter is in operation are a warning that microorganisms previously trapped in the filter are getting through. In one study, as turbidity increased from 0.4 ntu to 0.7 ntu, the concentration of *Giardia* cysts in the finished water went from less than one per liter to more than 2,000 per liter.[9] This was greater than the influent concentration of 740 per liter.

4. All operations in a water-treatment plant need oversight by a certified operator. The SWTR requires states to establish a certification program for operators.[7] Many states already have such programs. The majority of the treatment plants in the U. S. are in small systems, some of which have only one full-time employee. This will impose further hardships on such systems. Operations which can be automated, such as automatic filter backwashing, alleviate the problem of staffing, but investigations show that this operation especially needs to be observed by an operator.[15]

5. All equipment and all filters should be maintained according to design standards. Again, the emphasis needs to be on optimal operation at all times.[15]

6. When any new filter of any type is put into operation, or following backwashing of an old filter, a period of filter-to-waste should be incorporated routinely into the operation of the water-treatment process.[6,15] This period may need to be 30 minutes or longer. Studies of the benefits of this practice offer guidance about determining the length of time desirable for various filters and various source-waters.

Not all such concepts have been presented. Others are emerging.

New Regulations to Control Waterborne Disease

As of December 31, 1990, the new SWTR began to affect the operation of every public U. S. water system that uses surface water as a source and some that use groundwater as well. Compliance deadlines for various systems range from December 31, 1990, into 1993. Mandatory disinfection of all drinking water supplies, even those from groundwater not under the direct influence of surface water, is coming.[2] The rules are being developed now.

The purpose of the surface-water regulations is to protect the public, as much as possible, from waterborne disease. The SWTR requires that all affected systems remove or inactivate disease-causing microorganisms. All must disinfect. Most must filter, also.

The emphasis of the rule is on *Giardia lamblia* and viruses. To monitor for these particular microorganisms is extremely difficult, therefore, the SWTR specifies treatment as the condition for compliance. Because of the variety of raw water qualities, local conditions, and methods of treatment, the SWTR offers several treatment methods that can be used to meet the overall goal of removal and/or inactivation of disease-causing microorganisms. This allows each water system to choose the best method of treatment for its situation.

Extensive studies have been done, and other studies continue, to evaluate the presence of pathogenic microorganisms in source waters of all qualities, the risk of contracting disease from their presence in finished drinking water, the infective dosage required to produce disease, and the degree of removal and/or inactivation accomplished by various treatment methods. From all these studies, it has been determined that all water systems regulated by the SWTR must achieve removal and/or inactivation goals of 99.9% for *Giardia* and 99.99% for viruses.[7] Systems with poor source-water quality may have to meet higher reduction goals.

Studies of the effectiveness of various disinfectants against many microorganisms show that viruses and protozoan cysts such as *Giardia* are among the most resistant-to-disinfection disease-causing microorganisms in water. Systems that remove or inactivate *Giardia* and viruses probably are getting rid of other microorganisms too, especially bacteria. This is the basis of the SWTR. This does not mean that monitoring for coliforms, which previously has been the method for indicating that disinfection was adequate, is a thing of the past. New regulations for total coliforms, including fecal coliforms and Escherichia coli, were published as a separate rule on the same day the SWTR was published.[18] The new coliform rule, which will not be discussed in this paper, is about 20 times stricter than the previous rule and will increase testing for coliforms about five-fold.[19]

All the regulations are strict. They may become stricter as more is learned about *Cryptosporidium* and other organisms which might be causing the 50 percent of the outbreaks for which causes are now unknown.

Conclusions

Parts of the information that have been presented could create fear about the safety of drinking water or distrust of the water-supply industry. That is not the author's intent. The intent is to emphasize the complexities of producing drinking water that is microbiologically safe and the intense efforts directed toward that goal.

Preventing the transmission of waterborne disease is the primary public-health responsibility of the water treatment industry. The responsibility is shared with regulators, microbiologists, epidemiologists, public health officials, and engineers. The responsibility for producing safe drinking water must be shared by the public also. Citizens, especially politicians, need to know of the tremendous efforts to provide safe drinking water and they need to understand that these efforts are increasing in number and in cost.

Safe drinking water may be a reality. Safe drinking water can be a reality. Definitely, it is a goal. But producing it is not easy.

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