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Water Disinfection: Microbes Versus Molecules—An Introduction of Issues

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"Water is, apart from the air one breathes, the only nutrient which is, as a matter of necessity, consumed by every human being from the first day to the last day of his existence, and it is consumed in considerably larger quantities than any other nutritional substance."(*1*)

Because water is essential for life, humans have for thousands of years taken measures to insure its quality. Human and other activities introduce a multitude of microbes into our drinking water. Many of these are pathogenic to humans, causing a variety of effects ranging from mild gastrointestinal distress to systemic disease and sometimes death. We are capable of providing essentially pathogen-free finished water to the consumer by treatment with various chemical substances. However, many of these substances can have adverse biological effects or can react with other substances present in the water to form by-products having adverse biological effects. This introduces a tension and a paradox. If the chemicals used to rid drinking water of disease-causing microbes are themselves potentially harmful, is drinking water safe? What trade-offs are acceptable with respect to microbial versus chemical water quality?

This conference deals with current thinking about these topics. The subjects discussed reflect the evolution of thinking, both scientifically and socially, about how best to supply the public with safe, pure potable water. The goal of this paper is to introduce the issues associated with disinfectants and disinfectant by-products in water. This will be done by presenting a historical overview of the use of chemical disinfectants to purify drinking water and the subsequent awareness of potential health concerns.

Historically, the major health issue associated with water has been the demonstrated role that water has played in spreading infectious disease. Waterborne infectious agents remain in the environment, and new ones emerge through evolution of humans and microorganisms and because of changing exposure patterns. Even though the number of reported waterborne outbreaks has been increasing over the past few years (*2*), recent concerns have focused on a newly recognized waterborne hazard. Modern analytical methods have shown that a number of potentially toxic chemicals do reach man as a result of their presence in water (*3*). The history of water treatment practices and detailed summaries of the early studies that have been conducted on the disinfection by-products in drinking water are contained in the series "Drinking Water and Health" by the National Academy of Science (*4*) and are briefly highlighted below.

Early Treatment Efforts

In the late 1800s, it was determined that filtration could eliminate turbidity and color from drinking water and remove about 99% of the bacteria originally present. Epidemiologic studies demonstrated that the incidence of cholera and typhoid fever in consumers was dramatically reduced when the water was filtered. Studies conducted in Louisville, Kentucky, in the late 1890s on Ohio River water demonstrated that filtration was also practicable on heavily sediment-laden water. By 1907, filtration was the accepted method for producing acceptable drinking water.

At about the same time, the company that supplied drinking water derived from a sewage-contaminated reservoir to Jersey City, NJ, experimented with disinfection by a chlorinated lime solution rather than installing a relatively expensive filtration plant. In the litigation that ensued to determine if the quality of water produced was the same as that which would have been produced by filtration, the court ruled that the water was pure and wholesome and suitable for drinking.

In 1912, liquid chlorine was first used to purify drinking water in Niagara Falls, NY (*5*). The treatment process was comparatively simple and effective, and equipment for using liquid chlorine for water treatment was soon made so simple and reliable that, by 1914, most of

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the drinking water supplied to cities in the United States was chlorinated in some manner.

Health Assessment of Treatment Practices

No tests for the health effects in mammals of chlorine in drinking water were conducted for about 50 years after its use began. Although this may seem irresponsible to us now, we must consider what could have been looked for. Given the state-of-the-art of toxicology at that time, pollutants that were known to cause acute effects (e.g., lead) could have been identified. However, only in the last 20 years have our scientific testing capabilities and thinking evolved sufficiently to enable testing for potential chronic effects of water pollutants. Most of these studies employ *in vitro* tests or rodent model systems, and even now many assumptions must be made before data from currently available test systems can be extrapolated to humans.

Drinking Water Standards

Seventy years ago little attention was given to chemicals in drinking water. The first standards for drinking water set by the U.S. Public Health Service in 1914 included only bacteria; those set in 1925 added only several inorganic chemicals. In the 1942 and the 1946 revisions of the standards, phenol was the only organic chemical for which a standard existed. By the early 1960s, however, the presence in drinking water of organic chemicals from new point sources and industrial and sewage effluents became a concern because they were not removed by treatment. This concern was reflected in the 1962 drinking water regulations, which included standards for alkylbenzene sulfonates and the carbon-chloroform extractables in an attempt to limit potentially toxic organic chemicals in the source water. By 1967, limits for some chlorinated hydrocarbon pesticides, organophosphates and carbamates were also recommended (*6*).

Awakening Concerns about the Safety of Disinfectants

As the potentially harmful effects of these unwanted industrial and municipal pollutants began to be recognized, the potential health effects of chlorine and its by-products also started to be examined. Although chlorine had been used for drinking water treatment since 1912 and was obviously a biocide, no long-term animal studies on chlorine had been conducted until 1968, when Druckrey (*1*) reported the results of a study in which rats were exposed to 100 ppm chlorine in their water for seven generations. No significant differences were noted between the experimental and control animals. Although Lederberg (*7*) cautioned in 1969 that both chlorine and chloramines and their reaction products formed either in the water or *in vivo* could possibly be genotoxic, research on the disinfectants and by-products was not vigorously pursued for several years. The most intense investigations at that time centered on the organic contaminants of drinking water, again reflecting the then current levels of knowledge.

In 1974, discoveries by Bellar et al. (*8*) and Rook (*9*) showed that chloroform and other trihalomethanes were produced during the chlorination step of drinking water treatment. Subsequent EPA surveys demonstrated that the trihalomethanes were the organic chemicals occurring most consistently at probably the highest concentrations of any organic chemicals in treated drinking waters. Disinfectants used in water treatment and naturally occurring humic substances in the source water are the most probable precursors to these compounds. In addition, many different studies have shown that water chlorination produces other substances, including haloacetic acids, haloacetonitriles, halopropenols, and chlorophenols. Because these types of substances are also produced during the chlorination of solutions of purified humic acids (*10*), the Safe Drinking Water Act as amended in 1980 directed that EPA conduct studies on their disinfection by-products.

The Present Dilemma

Much of the work reported during this symposium deals with the hazards associated with compounds that have been identified in drinking water. However, these compounds do not appear neatly one at a time but rather occur together in complex mixtures. From the viewpoint of experimental scientists, water treatment operators, sanitary engineers, regulators, and all those interested in providing safe wholesome water, this is a headache for several reasons: it is difficult to show cause and effect; one must be concerned with antagonisms and synergisms between chemicals; and one must also be concerned with the possibility that the effects noted are caused by chemicals produced from reactions occurring during extraction procedures.

Because part of the chlorine applied during drinking water treatment becomes incorporated into organic compounds that are either too polar or of too high a molecular weight to be extracted and definitely identified by current methods, some of the work reported in this symposium will deal with the results of testing complex mixtures from chlorinated humic acid solutions and of concentrates of drinking water containing unidentified substances. Undoubtedly, we will be grappling with how best to use such data for some time.

Safety of Disinfectant Alternatives to Chlorine

The use of disinfectants other than chlorine has been explored to find ways of controlling pathogens in drinking water without forming halogenated by-products. The potential adverse effects of these alternative disinfectants must be compared to those of chlorination—the industry standard.

Chloramine has been used successfully as a drinking water disinfectant. Stevens et al. (*11*) found that its use results in reduced trihalomethane production compared to chlorine, suggesting that it may be safer to use. However, in 1973 Eaton et al. (*12*) reported that chloramine in urban water caused a hemolytic anemia in kidney dialysis patients, and in 1976 Shih and Lederberg (*13*) reported that chloramine was mutagenic in *Bacillus subtilis*.

Chlorine dioxide has also proven to be a satisfactory disinfectant for drinking water. However, studies report that chlorite, which occurs from reduction of chlorine dioxide and which remains in the distributed drinking water, causes changes in hematocrit and hemoglobin levels in exposed rats. Heffernan et al. (*14*) confirmed this finding and reported the same effect in cats. On the whole, it seems that disinfectants are effective precisely because of their ability to react with biological material. The question then is whether this poses a hazard to human health.

Major Issues

The above considerations raise three key issues for this conference:

- Do disinfectants and their by-products pose a human health hazard?
- What is the level of the hazard?
- What trade-offs should be struck to balance the risks from exposure to chemical disinfectants and the risk from exposure to pathogenic microbes?

These issues are highlighted in section headings of this publication and are woven through all papers in the proceedings.

Risk Assessment

Currently, it is much easier—though by no means trivial—to assess microbiological risk than chemical risk. Microbes have been studied longer, and their properties are more amenable to study. Because they are living and replicate, microbes can generally be isolated, cultured, and unambiguously identified. Most importantly, effects in humans can be shown to be caused by specific organisms.

Chemicals are not so easy to assess. They cannot be cultured because they do not replicate and grow. They exist in many possible combinations (complex mixtures) in the environment, and although the mixtures can be fractionated to identify individual components, these procedures may change the chemicals present. Not only are the chemicals difficult to identify, but adverse human health effects have not been shown for many environmental chemicals.

Before a chemical substance or its active metabolite can cause harm it must be released to the environment, be taken into the body, transported to the target organ(s), reach the target molecule(s), and exert its effect(s). The damaged cell(s) must then survive the insult (i.e., escape various repair and other defense mechanisms) before the insult can result in disease.

Specific information about the identification of the chemical, and its target specificity, potency, molecular lesion, and disease outcome derived from human studies would be necessary to eliminate all assumptions in risk assessment. Obviously, such a complete toxicology data base is not a likely possibility in the near future. At this time, assumptions are needed to assess the health risk of environmental chemicals, because most data sets are incomplete and are usually derived from nonhuman organisms. A major issue facing risk assessors and decision makers is the need to link *in vitro* test systems to experimental animal models and experimental animal models to humans. The situation is ripe for breakthroughs such as occurred with the development of the Ames test in the mid-1960s. It is an exciting time, and many possibilities exist for scientific breakthroughs in the development of testing strategies that are predictive of human disease.

Course for the Future

As surely as our knowledge about drinking water disinfection has advanced over the last 70 years and has changed our concerns about the potential health hazards of drinking water, our current activities will lead to future awareness and a better appreciation of the magnitude and reality of health hazards.

A major issue facing all of us concerned with evaluating the potential health hazards of drinking water disinfectants and their by-products is how best to tackle the major unresolved questions. Certainly, work will be needed to develop sensitive and reliable measures of exposure, both in the environment and in the body; develop realistic and predictive preclinical indicators of disease; understand repair processes and the role of the immune and endocrine systems in disease processes; and develop testing methodologies for evaluating complex mixtures and identifying components responsible for the effects. These are formidable tasks, but scientifically exciting and challenging ones.

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