Water Contaminants

Introduction

Sixty-five percent water by weight, the human body is intimately associated with the ecological water cycle, which includes, most directly, sources of drinking water. In the United States, drinking water comes from one of two places: ground water, which is drawn up from wells sunk into aquifers (i.e., geological formations containing water), or surface water, which is pumped from sources open to the atmosphere, such as river, lakes, and streams. More than 80 percent of public water systems in the U.S. draw from subterranean aquifers.[1] Nevertheless, the majority (about 60 percent) of U.S. inhabitants drink from surface water sources, with only 40 percent of the U.S. population drinking ground water.[2] This is because large metropolitan areas rely on rivers and reservoirs to supply tap water. Thus, women in large cities tend to drink surface water, whereas women living in rural areas or smaller cities tend to drink well water. Eighty-five percent of the U.S. population lives in areas serviced by public water systems; the remaining 15 percent use private sources of water, the vast majority of which are ground water wells.[2]

The distinction between surface and ground water is a permeable one.[3] Ecologically speaking, aquifers and surface water are interconnected sources. All running surface water was at one time ground water, aquifers being the source of rivers and streams, and ground water is recharged with precipitation, which itself is evaporated surface water.

The average American uses 90 gallons of water each day in the home.[4] Only a small fraction of this total is actually ingested. However, exposure to chemical contaminants in drinking water sources can come from inhalation of volatile compounds in indoor air, as well as direct transfer through the skin, as during bathing and showering. Thus, an understanding of the possible role of drinking water contaminants in breast and other cancers necessitates investigations into the flow of toxicants through entire watersheds, as well as investigations into the water-use patterns of individual households, including showering, bathing, and dishwashing habits, for example.[5]

Water, a universal solvent, is prone to many types of contamination. Surface and ground water are both vulnerable to chemical contamination, but in different ways. In general, ground water is more protected from chemical contamination by its overlaying lid of soil and other geological materials. However, once adulterated, ground water remains contaminated longer. This is especially true for contamination with volatile organic compounds, such as solvents, which readily vaporize from surface water. With no oxygen, sunlight, or turbulence to facilitate their breakdown, nor open air to encourage evaporation, volatile contaminants persist far longer in ground water aquifers than in rivers and streams.[6] In general, chemicals from run-off (storm water, urban, or agricultural), atmospheric deposition, and sewage effluent – which can include pharmaceuticals and personal care products – are a bigger threat to surface water sources than to ground water.[3]

By contrast, lightweight, volatile substances, such as solvents, are a bigger threat to ground water sources. Leaking underground storage tanks and leachate from landfills also pose special risks for ground water,[3] as does waste water from septic tanks – which, like sewage effluent, can contain pharmaceuticals and personal care products.[3, 7] However, ground water aquifers are not all equally vulnerable to contamination. Shallow wells in sandy soils are more vulnerable than deeper wells in clay-rich soils. Thus, in the case of ground water, the potential for drinking water contamination is a function not only of the industrial and agricultural activities that go on above it, but of the geological substrate that lies over it.[3]

Nitrates from fertilizers and from animal waste affect both surface and ground water. Human nitrate production has increased rapidly since 1950 and now exceeds, by 30 percent, nitrogen fixed by natural sources. Nitrates migrate both to streams and to ground water. Nitrate is the most common chemical contaminant found in ground water.[8] In both surface and ground water, nitrates are highest in drinking water sources in agricultural areas. In such areas, one in every five domestic wells exceeds EPA limits for nitrates.[8]

Persistent organic pollutants, which are fat-soluble and tend to bind to sediments, are rarely found in drinking water.[3] However, pesticides that are water-soluble and highly polar, such as atrazine, are common contaminants of drinking water drawn from both surface and ground water sources. Found in 98 percent of streams sampled in the Midwest, atrazine received the highest hazard quotient of all pesticides evaluated from treated municipal water in a 2002 risk assessment.[3]

In addition to pesticides, municipal drinking water can also contain disinfection by-products. When chlorine is used as a water disinfectant, it reacts with organic matter and forms hundreds of different halogenated organic compounds, many of which have been linked to cancer in animals. One of the most mutagenic compounds formed during water disinfection is 3-chloro-4-(dichloromethyl)-5-hydroxy-2(5h)-furanone, referred to as “mutagen X” or MX.[9] Other disinfection by-products include trihalomethanes (THMs), e.g. chloroform, and haloacetic acids, e.g. the human carcinogen dichloroacetic acid.[10] DCP (2,4-dichlorophenol) is a water contaminant formed when chlorine spontaneously reacts with phenolic compounds. It is also a metabolite of the herbicide 2,4-D (see Section I, Chapter B.4). A weak estrogen, DCP thus has at least two origins in drinking water: as a disinfection by-product and as a metabolic breakdown product of a common pesticide.[11, 12] Among U.S. adults sampled, 64 percent had detectable levels of DCP in their urine.[13]

Because surface water contains more organic material than ground water and because it requires more chlorine for disinfection, levels of disinfection by-products tend to be higher in treated tap water that is pumped from surface water than in tap water drawn from ground water. The EPA has identified only half of the total number of disinfection by-products found in chlorinated water.[14] Considerably less is known about the by-products of newer-generation disinfectants. These include ozone, chlorine dioxide, and chloroamine.[15]

More than most states, California relies on surface water sources for its drinking water. In normal years, ground water provides only 30 percent of the state's water supply. During drought years, the state's reliance on ground water increases.[16] Approximately 20 million southern Californians depend on the Sacramento-San Joaquin Delta for drinking water. The Colorado River basin also supplies southern California. In the north, the Sacramento River, the state's longest river, with headwaters near Mt. Shasta, serves as a drinking water source. Fed by melting snow, the Sacramento empties into the San Francisco Bay. It is polluted by heavy metals from abandoned mining operations in its upper watershed and by agricultural chemicals in its lower watershed. In the mid-1980s, herbicides used in rice production were detected the lower Sacramento River, which serves as the drinking water source for the city of Sacramento.[17]

Two discoveries in 1979 revealed the vulnerability of California's ground water to chemical contamination. The first was the presence of two industrial solvents, perchloroethylene (PCE) and trichloroethylene (TCE), in drinking water in the San Gabriel Valley, which is located in southern California, east of Los Angeles.[18] The second was the discovery of a soil fumigant, 1,2-dibromo-3-chloropropane (DBCP), in drinking water wells in the Central Valley. By 1987, DBCP was the most widespread pesticide contaminant in California aquifers, with more than one thousand wells in the Central Valley declared undrinkable due to DBCP. A reproductive toxicant, DBCP was first used in 1955 to kill nematodes, and was outlawed in California in 1977.[19] Organic solvents were subsequently found in drinking water wells near military bases and electronic industries in the state.[19]

Water pollutants remain common. Methyl tertiary butyl ether (MTBE), a water-soluble gasoline additive, has contaminated 10,000 ground water sites across California and contaminates the drinking water of 15 million Americans in 29 states.[20] With 127 drinking water systems reporting detections, California has the most severe MTBE contamination of drinking water in the United States, according to a recent analysis of data from state environmental agencies.[20] This includes drinking water sources in population-dense areas. Most notably, in 1996, city officials discovered MTBE – at levels as high as 610 parts per billion – in two of Santa Monica's drinking water wells.[21] Perchlorate, a water-soluble rocket fuel, pollutes 292 ground water sources throughout California, especially in communities located near military bases and missile manufacturing facilities, while the pesticide DBCP pollutes the drinking water of one million residents across the Central Valley.[18] In Fresno, nitrates from agricultural fertilizer and leaking septic tanks have seeped into drinking water supplies.[18] Solvents from electronic industries have affected drinking water sources in Silicon Valley, due to leaking underground storage tanks.[17]

Another emerging issue in California is the increasing reuse of wastewater to augment fresh water supplies. Within the State Water Resources Control Board, the Water Recycling Funding

Program promotes the use of treated waste water for such purposes as crop irrigation, landscaping, irrigation of playing fields for sports, and recharging ground water.[22] Several studies have found endocrine-disrupting chemicals in reclaimed wastewater, including pharmaceuticals and personal care products.[15] For example, anti-convulsants, muscle relaxants, cholesterol-lowering drugs, insect repellants, synthetic musks, and flame retardants have been detected in runoff from farm fields irrigated with treated waste water.[23]

This chapter describes the evidence for a link between breast cancer and drinking water contaminants. It considers some of the same chemicals described in other chapters – pesticides, solvents, pharmaceuticals, and personal care products – but from a mixtures perspective. The chapter also focuses on exposure to a group of chemicals unique to drinking water: the by-products of water disinfection that are created during chlorination. The role of drinking water contaminants in breast carcinogenesis is an under-studied question.

Regulatory History

Public drinking water is regulated nationally by the Safe Drinking Water Act (SDWA), which became law in 1974. Under SDWA, the EPA has set standards for 90 contaminants in drinking water. These include four radionuclides (but not radon); inorganic contaminants such as lead and arsenic; synthetic organic contaminants, such as pesticides; volatile organic compounds, such as benzene and other solvents; and the by-products of water disinfectants, such as trihalomethanes and haloacetic acids. For each of these, the EPA sets a legal limit, called a maximum contaminant level.[24] MCLs are not health-based standards. They are set to reflect both the economic cost of removing contaminants and the technological feasibility of doing so.

Since 1999, water utilities are required to divulge to their customers an inventory of contaminants found in drinking water in an annual consumer confidence report.[4] According to these reports, ten percent of the nation's water systems are out of compliance with EPA standards for tap water quality.[1]

Maximum contaminant level *goals* (MCLGs) are also promulgated by the EPA for each of its 90 regulated contaminants. These are health-based standards, and they are not legally enforceable. Often, there are discrepancies between the MCL and the MCLG. For example, the MCLG for the dry-cleaning solvent PCE is zero, whereas the MCL is five parts per billion.[24] Standards are not always set with cancer in mind. The MCL for nitrates, for example, was promulgated to protect formula-fed babies from a type of anemia. Recent studies indicate possible adverse outcomes for other endpoints, such as cancer and diabetes, at levels below the MCL.[8]

States may create and administer their own stricter drinking water standards. Therefore, the quality of California's tap water is governed both by federal regulations and by state regulations under the California Safe Drinking Water Act. The Office of Drinking Water within the California Department of Health Services oversees the quality of the state's drinking water. Local communities are responsible for making decisions about whether or not to add fluoride to drinking water. The FDA sets standards for bottled water.

Of the 216 chemicals and pollutants identified as mammary carcinogens by Rudel,[9] at least 32 are often found in drinking water. Of these 32, only 12 are regulated under the Safe Drinking Water Act. They are acrylamide, the triazine herbicides atrazine and symazine, DBCP, 1,2 dibromoethane, 1,2-dichloropropane, 1,2,dichloroethane, benzene, carbon tetrachloride, 3,3-dimethoxybenzidine, styrene, and vinyl chloride.

Many drinking water contaminants have no SDWA standards and are thus not federally regulated.[24] These include 20 known mammary gland carcinogens, as identified by Rudel.[9] Among the chemicals with no drinking water guidelines are two that are known to pose significant risks to California's drinking water – the gasoline additive MTBE and the rocket fuel perchlorate.[25, 26] Also federally unregulated in drinking water are pharmaceuticals and ingredients found in personal care products. Three of these – conjugated estrogens, estradiol-17b, and ethinylestradiol – are mammary gland carcinogens.[9]

Hormones, pharmaceuticals, and personal care products were found in 80 percent of U.S. surface water sampled by the U.S. Geological Survey.[27] The known endocrine disruptors included antibacterial agents, insect repellants, nonylphenol, and estradiol. These substances are not completely removed in the process of sewage treatment, have no drinking water guidelines, and are not routinely tested for by water treatment plants.[27, 28] Hormones, pharmaceuticals, and personal care products are carried into the general aquatic environment and can eventually turn up in drinking water.[28, 29] A study conducted jointly by the U.S. Geological Survey and the Centers for Disease Control identified many unregulated chemicals in drinking water sampled at a water treatment facility in an urban area where surface water streams were affected upstream by sewage-treatment plants. Contaminants included prescription and non-prescription drugs, cosmetics, fragrance compounds, flame-retardants, and plasticizers. At least 11 and as many as 17 organic wastewater compounds were detected in samples of finished drinking water.[29]

The phenolic compound triclosan is an antibacterial agent of emerging concern as a drinking water contaminant. Used in dish and hand soaps, toothpaste, mouthwash, plastic cutting boards, children's toys, cosmetics, and deodorants, triclosan is now found in many U.S. streams at a median concentration of 0.14 ppb.[27] Although this phenolic compound is not classified as carcinogenic or mutagenic, it is thought to combine with chlorine in drinking water to form chloroform gas (a known carcinogen) and other chlorinated contaminants such as chlorinated phenoxy phenols.[30] Use of triclosan in hand soaps can increase individual exposure to chloroform by as much as 40 percent above background levels from tap water.[15]

The U.S. Geological Survey has also found intersex fish – such as male fish with ovaries – in many streams and rivers throughout the nation, including the Colorado River, an important drinking water source for southern California. Endocrine-disrupting chemicals from wastewater appear to be the cause, but precise methodologies to evaluate the effect of environmental estrogens on wild fish populations have not yet been developed.[31] Endocrine-disrupting chemicals found in U.S. rivers have been demonstrated to cause alterations in sexual development and reproduction in aquarium fish.[32]

Concept/Exposure Definition

Routes of exposures for drinking water contaminants include ingestion, inhalation, and dermal absorption. The relative importance of each route varies for different contaminants, depending on the volatility and polarity of the chemical, and on the age and personal habits of the individual. Compared with adults, very young children, for example, have greater overall surface area and more permeable skin. What follows here is brief overview of chemicals with identified routes of exposure. For most, the relative contribution of each route of exposure is not known.

Exposures from Ingestion

Direct ingestion is the major route of exposure to nitrates in drinking water. In the gut, nitrates are converted to nitrites. Nitrate is also a precursor in the formation of N-nitroso compounds, which, as a class, are genotoxic and potent animal carcinogens.[8]

Oral intake, along with dermal absorption, is also the primary route of exposure to the antimicrobial phenol, triclosan, which has been detected in human breast milk and serum samples from the general population[33] and in the urine of 61 percent of six- to eight-year-old girls from various parts of the U.S.[34]

Exposures through Inhalation and Dermal Absorption

For volatile organic contaminants – including many disinfection by-products – exposure through inhalation and skin absorption appears to be more significant than ingestion.[15, 35] One study reports that a ten-minute shower or a thirty-minute bath can contribute a greater internal dose of volatile organic compounds than drinking a half a gallon of tap water.[36] Showering in an enclosed stall appears to contribute the greatest dose, probably because of the inhalation of the steam. Both showering and bathing significantly increase exhaled breath and blood concentrations of chloroform.[37] One study in Rockford, Illinois, where drinking water wells were contaminated with chlorinated solvents, found that blood levels of solvents correlated more closely with household air levels than with actual water levels. In turn, air levels were correlated with length of shower run times.[38] Dishwashers, with their combination of high temperatures and high turbulence, are an especially efficient means of transferring volatile organic compounds from drinking water into indoor air.[5, 37] as is machine-washing of clothes.[37] Bleaches in both laundry and dishwashing detergents are an additional source of indoor chlorinated air pollutants.[39]

Exposures from Swimming Pools

Disinfection of swimming pool water produces trihalomethanes when body fluids, sunscreens, natural organic matter, and cosmetics react with chlorine. Trihalomethanes have been detected in the blood and exhaled breath of swimmers and non-swimmers at indoor pools.[40] Swimming pool water test kits contain 3,3’-dimethylbenzidine, a mammary carcinogen.[9] Human exposure may occur if these chemical solutions enter the pool.[9]

Exposures from Bottled Water

More than 70 percent of Californians use bottled water for some or all of their drinking water.[41] However, little information is available about bottled water quality. A four-year investigation by Natural Resources Defense Council, completed in 1999, found that bottled water rarely violated federal drinking water standards but sometimes contained chemical contaminants. These included volatile organic compounds, arsenic, and plasticizing ingredients such as DEHP phthalate. California legislation to regulate bottled water as strictly as drinking water – and which would have compelled disclosure of its source and the number and concentration of its contaminants – was defeated in 2004.

Critical Review of the Literature

The toxicological profiles of many common water contaminants – pesticides, solvents, personal care products – are described in other chapters. Disinfection by-products are considered here. The summary of human studies includes additional drinking water contaminants.

Of the 500 different by-products that have been reported in the literature, almost no quantitative occurrence data exist for most, and only a limited number have been studied for genotoxicity and other health effects.[42]

One disinfection by-product for which there is toxicological evidence is MX, a mammary gland carcinogen that is unique to drinking water. MX is not routinely monitored in U.S. drinking water nor regulated under the Safe Drinking Water Act. The absence of occurrence data for MX in finished drinking water means that its potential hazard as a breast carcinogen for women cannot be evaluated.

However, a preliminary nationwide survey of disinfection by-products in drinking water samples conducted by the EPA in 2002 revealed troubling results. First, researchers found MX at much higher levels than had previously been reported. The drinking water samples with the highest MX levels were collected from utilities using chlorine dioxide for primary disinfection. Second, researchers discovered brominated forms of MX. These appear to be even more carcinogenic than their chlorinated analogues. Third, the survey identified several new classes of disinfection by-products that had never before been described. These included brominated acids, iodo acids, and a new brominated ketone. Fourth, carbon tetrachloride was detected in some of the samples of finished drinking water. However, its source is unclear. Carbon tetrachloride could be a disinfection by-product or it could be a contaminant from the cleaning of chlorine cylinders.[42]

In Vitro Studies

In standard bacterial test systems, MX is a potent mutugen and a clastogen (that is, it can cause chromosomes to break; for a review, see McDonald and Komulainen[43]). Much lower in concentration than trihalomethanes or haloacetic acids, MX nevertheless accounts for as much as 20–50 percent of the total mutagenic activity measured in chlorinated drinking water samples.[42] Although its precise mechanism is unknown, MX appears to cause DNA damage by ionizing DNA bases due to its high reductive potential. It also may cause mutations through DNA adducts.[43]

In Vivo Studies

MX is a multi-site carcinogen in both male and female rats[43] and is a mammary gland carcinogen in females.[9] MX increases malignant mammary gland tumors, and appears to be significantly more potent than other disinfection by-products in causing cancer in animals.[43]

Brominated nitromethanes, another disinfection by-product, have also been recently demonstrated to act as genotoxic agents in mammalian cells.[42]

The antimicrobial triclosan has been shown to disrupt thyroid-hormone-associated gene expression in frogs and can accelerate the pace of post-embryonic development.[44] Very little is known about the implications of this emerging endocrine disruptor for human health.

Human Studies

Epidemiologic studies of chemical contaminants in drinking water have mostly focused on cancers other than breast cancer. These have revealed immunologic effects, bladder cancer, and hematopoietic cancers.[45] One study examined communities in 339 U.S. counties with hazardous waste sites that had contaminated ground water which served as the sole drinking water source. Women living in these areas suffered significantly more mortality from breast cancer (and also bladder, colon, and stomach cancers). Counties with hazardous waste sites were 6.5 times more likely to have elevated breast cancer mortality rates than counties without such sites.[46]

Epidemiologic data on nitrates and cancer of any kind are not sufficient to draw conclusions,[45] with the possible exception of bladder cancer, the risk for which is elevated with nitrate-contaminated drinking water, according to several studies.[47] Nitrates in municipal drinking water were not associated with increased breast cancer risk among older women in the Iowa Women's Health Study.[47]

Disinfection by-products have been consistently linked to bladder and, to a lesser extent, rectal cancers in multiple studies.[10, 37, 45] Few studies have evaluated associations between disinfection by-products and breast cancer,[9, 48] and none have high statistical power. For example, a 1992 meta-analysis of case-control studies that investigated links between chlorination of drinking water and cancers of various kinds found a relative risk of 1.18 for breast cancer – but only four of the 12 studies reported on breast cancer.[48, 49]

Disinfection by-products have been linked to adverse pregnancy outcomes in some epidemiologic studies, according to a review by Afzal.[50] These results may have relevance to breast cancer if they indicate endocrine-disruption pathways that affect ovarian functioning. For example, one study found that increased exposure to trihalomethanes was associated with decreased length of menstrual cycling that resulted from earlier ovulation.[51] Shorter cycles raise lifetime exposure to endogenous estrogen and are associated with higher breast cancer risk.[51]

Human studies of breast cancer and drinking water contaminants other than water disinfection by-products are sparse, and most suffer from exposure assessment problems.[7] In Wisconsin, researchers did not find an association between risk of breast cancer and adult exposure to atrazine. However, the range of exposure in this study was extremely limited, and few women were exposed at levels above the MCL. (For more evidence on the link between atrazine and breast cancer, see Section I, Chapter B.4.)

Only one other epidemiologic study has investigated possible links between endocrine-disrupting chemicals in drinking water and breast cancer risk. Using a case-control design on Cape Cod, Massachusetts, researchers did not find a link between adult exposure to drinking water contaminated by wastewater and the risk of breast cancer.[7] However, the range of exposures was small, with few women unexposed and none exposed at high levels. On Cape Cod, where public water is drawn from more than 100 shallow wells sunk into sandy soils, septic system effluent and surface pollutants have seeped into ground water. Previous research had demonstrated that septic waste on the Cape was a source of exposure to endocrine-disrupting compounds, including alkylphenols from detergents.[52]

Cape Cod, which has a history of unexplained elevated breast cancer risk, was also the study site for the sole investigation of organic solvents in drinking water and breast cancer. In this case, results did provide evidence of a link. Investigating PCE exposure from vinyl-lined water pipes, researchers found a small but significant increase in breast cancer among women with the highest levels of PCE exposures in their drinking water.[53] One strength of this study was that it used residence history and inspection of water pipe systems to estimate individual exposure. In addition, traditional breast cancer risk factors were extensively evaluated as possible confounders.[48] A follow-up analysis that included further information on tap water consumption and bathing habits – in order to capture various routes of exposure – supported the original study.[54]

Conclusions and Future Directions

At least four chemicals identified by Rudel[9] as mammary gland carcinogens are common contaminants in drinking water: MX (a by-product of water disinfection), perchloroethylene (a dry-cleaning solvent), atrazine, and DCBP (both pesticides). Other than these, very little is known about breast cancer's relationship to drinking water contaminants, and almost nothing is known about the effects of exposures to mixtures of contaminants. Future research should focus on exposures to real-life mixtures as well as early-life exposures. The rate of tap water consumption per body weight is highest in early childhood, with formula-fed infants receiving the greatest exposure to contaminants in tap water.[43] Moreover, atrazine, one of the most common contaminants of drinking water drawn from both surface and ground water sources, is known to disrupt mammary gland development in prenatal and neonatal life. (See Section I, Chapter B.4 for details.) Outstanding questions include:

1) How does childhood exposure to MX, a direct-acting mutagen, affect breast cancer induction? Oxidative metabolism is

known to detoxify MX, but oxidative enzyme systems (such as liver CYP2E1) are not fully active in early life.[43]

2) What is the total mutagenicity of finished drinking water? Mixtures of chlorination by-products, triclosan, pesticides, and gasoline additives, for example, may exhibit toxic effects that are complex and not predicted from the effects of single compounds.[43]

3) What are the indirect effects of water disinfection by-products on breast cancer risk, via pathways such as shortened menstrual cycles? These pathways may be important for women living in large urban areas, where trihalomethane levels in drinking water are high. San Francisco, for example, has a history of high trihalomethane levels and, on this basis, received a grade of "poor" for drinking water quality from the Natural Resources Defense Council in 2003.[55]

4) What can data on water contaminants available through the Safe Drinking Water Act reveal about breast cancer risk in different geographic areas? These data have been underused in breast cancer studies. Together with databases mandated by California's Proposition 65, they provide a means to reconstruct historical exposures to water-borne carcinogens. Tools for GIS computer mapping, already developed for use in the Cape Cod Breast Cancer and Environment Study, are also available for these studies.[7, 48, 56]

5) How many chemicals identified by Rudel[9] as mammary gland carcinogens in animals are found in California's drinking water? And are they associated with elevated breast cancer risk?

6) Is PCE-contaminated drinking water associated with elevated breast cancer rates in California, as it is in Cape Cod?

7) What potential human exposures may be associated with the growing use of reclaimed wastewater in California?

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