

Contaminants in drinking water

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An adequate supply of safe drinking water is one of the major prerequisites for a healthy life, but waterborne disease is still a major cause of death in many parts of the world, particularly in children, and it is also a significant economic constraint in many subsistence economies. The basis on which drinking water safety is judged is national standards or international guidelines. The most important of these are the WHO Guidelines for Drinking Water Quality. The quality of drinking water and possible associated health risks vary throughout the world with some regions showing, for example, high levels of arsenic, fluoride or contamination of drinking water by pathogens, whereas elsewhere these are very low and no problem. Marked variations also occur on a more local level within countries due, for example, to agricultural and industrial activities. These and others are discussed in this chapter.

Introduction

An adequate supply of safe drinking water is one of the major prerequisites for a healthy life, but waterborne disease is still a major cause of death in many parts of the world, particularly in children, and it is also a significant economic constraint in many subsistence economies.

Drinking water is derived from two basic sources: surface waters, such as rivers and reservoirs, and groundwater. All water contains natural contaminants, particularly inorganic contaminants that arise from the geological strata through which the water flows and, to a varying extent, anthropogenic pollution by both microorganisms and chemicals. In general, groundwater is less vulnerable to pollution than surface waters. There are a number of possible sources of man-made contaminants, some of which are more important than others. These fall into the categories of point and diffuse sources. Discharges from industrial premises and sewage treatment works are point sources and as such are more readily identifiable and controlled; run off from agricultural land and from hard surfaces, such as roads, are not so obvious, or easily controlled. Such sources can give rise to a significant variation in the contaminant

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load over time. There is also the possibility of spills of chemicals from industry and agriculture and slurries from intensive farm units that can contain pathogens. In some countries, badly sited latrines and septic tanks are a significant source of contamination, especially of wells. Local industries can also give rise to contamination of water sources, particularly when chemicals are handled and disposed of without proper care. The run-off or leaching of nutrients into slow flowing or still surface waters can result in excessive growth of cyanobacteria or blue-green algae¹. Many species give rise to nuisance chemicals that can cause taste and odour and interfere with drinking water treatment. However, they frequently produce toxins, which are of concern for health, particularly if there is only limited treatment.

If treatment is not optimized, unwanted residues of chemicals used in water treatment can also cause contamination, and give rise to sediments in water pipes. Contamination during water distribution may arise from materials such as iron, which can corrode to release iron oxides, or from ingress of pollutants into the distribution system. Diffusion through plastic pipes can occur, for example when oil is spilt on the surrounding soil, giving rise to taste and odour problems. Contamination can also take place in consumers' premises from materials used in plumbing, such as lead or copper, or from the back-flow of liquids into the distribution system as a consequence of improper connections. Such contaminants can be either chemical or microbiological.

Drinking water treatment as applied to public water supplies consists of a series of barriers in a treatment train that will vary according to the requirements of the supply and the nature and vulnerability of the source. Broadly these comprise systems for coagulation and flocculation, filtration and oxidation. The most common oxidative disinfectant used is chlorine. This provides an effective and robust barrier to pathogens and provides an easily measured residual that can act as a marker to show that disinfection has been carried out, and as a preservative in water distribution.

The basis on which drinking water safety is judged is national standards or international guidelines. The most important of these are the WHO Guidelines for Drinking-Water Quality². These are revised on a regular basis and are supported by a range of detailed documents describing many of the aspects of water safety. The Guidelines are now based on Water Safety Plans that encompass a much more proactive approach to safety from source-to-tap.

Microbial contamination

The contamination of drinking water by pathogens causing diarrhoeal disease is the most important aspect of drinking water quality. The

problem arises as a consequence of contamination of water by faecal matter, particularly human faecal matter, containing pathogenic organisms. One of the great scourges of cities in Europe and North America in the 19th century was outbreaks of waterborne diseases such as cholera and typhoid. In many parts of the developing world it remains a major cause of disease. It is therefore essential to break the faecal–oral cycle by preventing faecal matter from entering water sources and/or by treating drinking water to kill the pathogens. However, these approaches need to operate alongside hygiene practices such as hand washing, which reduce the level of person-to-person infection.

Detection and enumeration of pathogens in water are not appropriate under most circumstances in view of the difficulties and resources required so *Escherichia coli* and faecal streptococci are used as indicators of faecal contamination. The assumption is that if the indicators are detected, pathogens, including viruses, could also be present and therefore appropriate action is required. However, the time taken to carry out the analysis means that if contamination is detected, the contaminated water will be well on the way to the consumer and probably drunk by the time the result has been obtained. In addition the small volume of water sampled (typically 100 ml) means that such check monitoring on its own is not an adequate means of assuring drinking water safety. It is also essential to ensure that the multiple barriers are not only in place but working efficiently at all times, whatever the size of the supply. Drinking water is not, however, sterile and bacteria can be found in the distribution system and at the tap. Most of these organisms are harmless, but some opportunist pathogens such as *Pseudomonas aeruginosa* and *Aeromonas* spp. may multiply during distribution given suitable conditions³. Currently there is some debate as to whether these organisms are responsible for any waterborne, gastrointestinal disease in the community but *P. aeruginosa* is known to cause infections in immunocompromised patients and weakened patients in hospitals.

A number of organisms are emerging as potential waterborne pathogens and some are recognized as significant pathogens that do give rise to detectable waterborne outbreaks of infection. The most important of these is *Cryptosporidium parvum*, a protozoan, gastrointestinal parasite which gives rise to severe, self limiting diarrhoea and for which there is, currently, no specific treatment. *Cryptosporidium* is excreted as oocysts from infected animals, including humans, which enables the organism to survive in the environment until ingested by a new host³. This organism has given rise to a number of waterborne or water associated outbreaks in the UK, and an outbreak of cryptosporidiosis in Milwaukee in the USA resulted in many thousands of cases⁴, and probably a number of deaths among the portion of the population which were immunocompromised⁵. The most important barriers to infection are those that remove

particles, including coagulation, sedimentation and filtration. However, water is not the only source of infection. It is probable that person-to-person spread following contact with faecal matter from infected animals is more important and there have been outbreaks involving milk and swimming pools⁶. Currently, there is no scientifically based standard for *Cryptosporidium* in drinking water. A similar parasite, *Giardi*, has been responsible for a number of cases of gastrointestinal illness and in the USA, illness was referred to as beaver fever because beavers were shown to be a source in some areas. As with *Cryptosporidium*, water is not the only source but, unlike *Cryptosporidium*, it is reasonably susceptible to chlorine and because of its larger size can be more easily removed by particle removal processes³.

Although the common waterborne diseases of the 19th century are now almost unknown in developed countries, it is vital that vigilance is maintained at a high level because these diseases are still common in many parts of the world. The seventh cholera pandemic, which started in 1961, arrived in South America in 1991 and caused 4700 deaths in 1 year⁷. According to the WHO World Health Report 1998, over 1 billion people do not have an adequate and safe water supply of which 800 million are in rural areas. WHO also estimate that there are 2.5 million deaths and 4 billion cases due to diarrhoeal disease, including dysentery, to which waterborne pathogens are a major contributor. There are still an estimated 12.5 million cases of *Salmonella typhi* per year and waterborne disease is endemic in many developing countries. In this age of rapid global travel, the potential for the reintroduction of waterborne pathogens in developed countries still remains. In addition, as our knowledge of microbial pathogens improves, we are able to identify other organisms that cause waterborne disease. The Norwalk-like viruses are named after a major waterborne outbreak in North America, and there is a range of emerging pathogens including *Campylobacter*, a major cause of food poisoning, and *E. coli* O157, which has caused deaths in North America where chlorination was not present, or failed, and other barriers were inadequate³.

Microbial contamination of drinking water thus remains a significant threat and constant vigilance is essential, even in the most developed countries.

Chemical contaminants

As indicated above, there are many sources of chemical contaminants in drinking water. However, the most important contaminants from a health standpoint are naturally occurring chemicals that are usually found in groundwater.

Arsenic

Waterborne arsenic is a major cause of disease in many parts of the world including the Indian sub-continent—particularly Bangladesh and Bengal—South America, and the Far East. It is the only contaminant that has been shown to be the cause of human cancers following exposure through drinking water. Besides cancer of the skin, lung and bladder and probably liver, arsenic is responsible for a range of adverse effects, including hyperkeratosis and peripheral vascular disease^{8,9}. However, the epidemiological data also demonstrate that many local factors are important, including nutritional status. There are considerable difficulties in assessing arsenic exposure. In Bangladesh, where millions of tube wells were sunk, the concentration of arsenic can vary significantly between wells only a short distance apart. WHO have set a provisional guideline value of 10 µg/l based on the practical limit of achievability, but there is an ongoing discussion on the scientific basis for this guideline, including whether the available data would allow distinction between a standard of say 5, 10, or 15 µg/l and whether exposure to 50 µg/l, the old guideline, will result in illness.

Fluoride

Waterborne fluoride is another major cause of morbidity in a number of parts of the world, including the Indian sub-continent, Africa and the Far East, where concentrations of fluoride can exceed 10 mg/l. High intakes of fluoride can give rise to dental fluorosis, an unsightly brown mottling of teeth, but higher intakes result in skeletal fluorosis, a condition arising from increasing bone density and which can eventually lead to fractures and crippling skeletal deformity. A WHO working group concluded that skeletal fluorosis and an increased risk of bone fractures occur at a total intake of 14 mg fluoride per day, and there is evidence suggestive of an increased risk of bone effects at intakes above about 6 mg fluoride per day^{10,11}.

This is a major cause of morbidity and can manifest itself at a relatively early age with the result that affected individuals cannot work properly and may be economically as well as physically disadvantaged for life. Many factors appear to influence the risk of such adverse effects, including volume of drinking water, nutritional status and, particularly, fluoride intake from other sources.

Selenium and uranium

Selenium and uranium have also both been shown to cause adverse effects in humans through drinking water. In seleniferous areas, drinking

water can contribute to high selenium intakes, which can give rise to loss of hair, weakened nails and skin lesions, and more seriously, changes in peripheral nerves and decreased prothrombin time¹². Uranium is found in groundwater associated with granitic rocks and other mineral deposits. It is a kidney toxin and has been associated with an increase in fractional calcium excretion and increased microglobulinuria, although within the normal range found in the population. Uranium is a current topic of research with regard to exposure through drinking water¹³.

Iron and manganese

Both iron and manganese can occur at high concentrations in some source waters that are anaerobic¹⁴. When the water is aerated they are oxidized to oxides that are of low solubility. These will cause significant discolouration and turbidity at concentrations well below those of any concern for health. They may, however, cause consumers to turn to alternative supplies which may be more aesthetically acceptable but which are microbiologically unsafe.

Agricultural chemicals

Agriculture is another source of chemical contamination. In this case the most important contaminant is nitrate, which can cause methaemoglobinaemia, or blue-baby syndrome, in bottle-fed infants under 3 months of age¹⁵. There remains uncertainty about the precise levels at which clinically apparent effects occur and it also seems that the simultaneous presence of microbial contamination, causing infection, is an important risk factor¹⁶. WHO have proposed a guideline value of 50 mg/l nitrate based on studies in which the condition was rarely seen below that concentration, but was increasingly seen above 50–100 mg/l. However, when nitrite is also present this must also be taken into account, since it is about 10 times as potent a methaemoglobinaemic agent as nitrate.

Concern is often expressed about pesticides in drinking water but there is little evidence that this is a cause of illness, except perhaps following a spill with very high concentrations¹⁷. In Cambodia, media and public concern regarding pesticides in drinking water resulted in an expensive analytical exercise being carried out that found none of the pesticides of concern (Steven Iddings, personal communication, 2001). Of greater concern is the run-off of nutrients to surface waters, often combined with sewage discharges, that lead to significant growths of cyanobacteria referred to above¹. There is a wide range of toxins produced by these organisms and it is probable that not all the toxins have been identified to date. Where drinking water treatment is limited, there is a potential

for undesirable concentrations to be present in drinking water. Concerns are particularly directed at hepatotoxins such as the microcystins and cylindrospermopsin, and the neurotoxins such as saxitoxin.

Urban pollution

Industry and human dwellings are also a source of potential contaminants. The most common are heavy metals, and solvents, such as tri and tetrachloro-ethene, which are sometimes found in groundwater and hydrocarbons, particularly from petroleum oils². There is little good evidence that these pollutants occur at concentrations in drinking water that are sufficient to cause health effects, but some of the low molecular weight aromatic hydrocarbons can give rise to severe odour problems in drinking water at concentrations of less than 30 µg/l.

By-products of water treatment

Drinking water treatment is intended to remove microorganisms and, increasingly in many cases, chemical contaminants. Nevertheless, the process can in itself result in the formation of other contaminants such as the trihalomethanes and haloacetic acids from the reaction of chemical oxidants with naturally occurring organic matter. This requires a balance to be struck between the benefits of the chemical oxidants in destroying microorganisms and the potential risks from the by-products. Of these by-products, only trihalomethanes tend to be routinely monitored in drinking water and the standard for total THMs in the UK is 100 µg/l. Water treatment, however, can take many forms and can use different chemicals including chlorine, chloramines, chlorine dioxide and ozone. Each treatment methodology has certain advantages and disadvantages, but all of them form by-products of some sort. The type and quantities of by-products formed depend on a number of factors. The formation of by-products during chlorination (one of the most common treatments), for example, depends on the amount and content of organic matter, bromine levels, temperature, pH and residence time.

Uptake of trihalomethanes, generally the most common volatile DBP, can occur not only through ingestion, but also by inhalation and skin absorption during activities such as swimming, showering and bathing. For most other DBPs, ingestion is the main route for uptake¹⁸. DBPs have been associated with cancers of the bladder, colon and rectum and adverse birth outcomes such as spontaneous abortion, (low) birth weight, stillbirth and congenital malformations in epidemiological studies and to a much lesser extent at high levels in toxicological studies. Overall, however, the evidence is inconsistent and inconclusive^{9,19,20}.

Endocrine disrupters

Endocrine disrupters are chemicals that interfere with the endocrine system, for example by mimicking the natural hormones. They may be associated with a range of adverse reproductive health effects, including sperm count decline, hypospadias and cryptorchidism, and cancer of the breast and testes, although the current human evidence is weak²¹. Phthalates, bisphenols, alkyl phenols, alkyl phenol ethoxylates, polyethoxylates, pesticides, human hormones and pharmaceuticals have all been implicated and sewage effluent discharged to surface water has been shown to contain many of these substances^{17,22}. Since many surface waters which receive sewage effluent are subsequently used as drinking water sources (*i.e.* re-use of water), it is important that the water is properly treated, which will remove these substances. Effects on wildlife, such as fish exposed to sewage effluent, have been reported but there is currently little if any evidence that humans drinking tap water are affected.

Discussion

The quality of drinking water and possible associated health risks vary throughout the world. Whilst some regions show high levels of arsenic, fluoride or contamination of drinking water by pathogens, for example, elsewhere these are very low and present no problem for human health. Marked variations in levels of contamination also occur more locally, often as a result of agricultural and industrial activities. The differences in health risks that these variations represent lead to different priorities for the treatment and provision of drinking water. Microbial contamination of drinking water remains a significant threat and constant vigilance is essential, even in the most developed countries. More recent research has suggested a possible association between disinfection by-products and cancer and adverse reproductive outcomes, but potential risks are largely outweighed by the benefits of drinking water with a low microbial load. Where possible, however, further efforts should be made to reduce levels of disinfection by-products without compromising the disinfection process and at a reasonable cost to the consumer. To be able to set priorities, good quality data on the levels of contaminants in water and related morbidity and mortality are needed, although the interpretation may be complicated by the multi-factorial nature of many diseases. Well-designed epidemiological studies are also needed for some of the contaminants such as chlorination by-products, arsenic, fluoride and uranium where information on exposure–response relationships is missing or of insufficient quality. In other cases, toxicological studies are also required to help to determine the potential risk.

There is evidence from a number of countries of consumers rejecting microbially safe public supplies, because of problems with discolouration and chlorine tastes, in favour of more expensive and microbiologically less satisfactory local supplies or bottled water. There is little point in making a considerable investment in providing safe public supplies if the water is not accepted by consumers. In particular, this can lead to poorer consumers, who are more likely to receive unacceptable water supplies, paying more for their water than better off consumers. Delivering safe and acceptable water, therefore, is a key target in improving public health in many developing countries. Even in developed countries, however, the same priority remains, as shown by waterborne outbreaks such as that at Walkerton in Canada that resulted in several deaths.

There also remains a need for high quality research in a number of areas, though this must be set in the appropriate context for the countries in which the problems occur. Increased knowledge has shown the complexity of many of the issues that are related to drinking water and health. Overall, however, it is evident that the supply and maintenance of safe drinking water remain key requirements for public health.

References

- 1 Chorus I, Bartram J. Toxic cyanobacteria in water. *A Guide to their Public Health Consequences, Monitoring and Management*. Published on behalf of WHO by E & FN Spon, London and New York, 1999
- 2 World Health Organization. *Guidelines for Drinking-Water Quality*, 3rd edn. www.who.int/water_sanitation_health/GDWQ/draftchemicals/list.htm. Last accessed June 2003. Geneva: WHO, 2003
- 3 Hunter P. *Waterborne Disease. Epidemiology and Ecology*. Chichester: Wiley, 1997
- 4 MacKenzie WR, Hoxie NJ, Proctor ME, Gradus MS, Blair KA, Peterson DE, Kazmierczak JJ, Addiss DG, Fox KR, Rose JB *et al*. A massive outbreak in Milwaukee of cryptosporidium infection transmitted through the public water supply. *N Engl J Med* 1994; 331: 161–7
- 5 Hoxie NJ, Davis JP, Vergeront JM, Nashold RD, Blair KA. Cryptosporidiosis-associated mortality following a massive waterborne outbreak in Milwaukee, Wisconsin. *Am J Public Health* 1997; 87: 2032–5
- 6 MacKenzie WR, Kazmierczak JJ, Davis JP. An outbreak of cryptosporidiosis associated with a resort swimming pool. *Epidemiol Infect* 1995; 115: 545–53
- 7 Reeves PR, Lan R. Cholera in the 1990s. *Br Med Bull* 1998; 54: 611–23
- 8 IPCS. *Arsenic and Arsenic Compound*, 2nd edn. Environmental Health Criteria 224. Geneva: World Health Organization, 2001
- 9 IARC. *Some Drinking Water Disinfectants and Contaminants, Including Arsenic*. IARC Monographs on the evaluation of carcinogenic risks to humans. Volume 84. Lyon: IARC, 2003
- 10 IPCS. *Fluorides*. Environmental Health Criteria 227. Geneva: World Health Organization, 2002
- 11 World Health Organization. *Fluoride*. http://www.who.int/water_sanitation_health/GDWQ/draftchemicals/fluoride2003.pdf. Accessed June 2003. Geneva: WHO, 2003
- 12 Barceloux DG. Selenium. *J Toxicol Clin Toxicol* 1999; 37: 145–72
- 13 World Health Organization. *Uranium*. http://www.who.int/water_sanitation_health/GDWQ/draftchemicals/uranium2003.pdf. Accessed June 2003. Geneva: WHO, 2003

- 14 World Health Organization. *Manganese*. http://www.who.int/water_sanitation_health/GDWQ/draftchemicals/manganese2003.pdf. Accessed June 2003. Geneva: WHO, 2003
- 15 Fan AM, Steinberg VE. Health implications of nitrate and nitrite in drinking water: an update on methemoglobinemia occurrence and reproductive and developmental toxicity. *Regul Toxicol Pharmacol* 1996; **23**: 35–43
- 16 Avery AA. Infantile methemoglobinemia: reexamining the role of drinking water nitrates. *Environ Health Perspect* 1999; **107**: 583–6
- 17 Fawell JK, Standfield G. Drinking water quality and health. In: Harrison RM (ed.) *Pollution: Causes, Effects and Control*, 4th edn. London: Royal Society of Chemistry, 2001
- 18 Nieuwenhuijsen MJ, Toledano MB, Elliott P. Uptake of chlorination disinfection by-products; a review and a discussion of its implications for epidemiological studies. *J Expos Anal Environ Epidemiol* 2000; **10**: 586–99
- 19 Nieuwenhuijsen MJ, Toledano MB, Eaton NE, Elliott P, Fawell J. Chlorination disinfection by-products in water and their association with adverse reproductive outcomes: a review. *Occup Environ Med* 2000; **57**: 73–85
- 20 IPCS *Disinfectants and Disinfectant By-products*. Environmental Health Criteria 216. Geneva: World Health Organization, 2000
- 21 Joffe M. Are problems with male reproductive health caused by endocrine disruption? *Occup Environ Med* 2001; **58**: 281–7
- 22 Fawell J, Chipman K. Endocrine disrupters, drinking water and public reassurance. *Water Environ Manage* 2000; **5**: 4–5