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Chlorine in water disinfection

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Abstract: Disinfection of drinking-water is one of the main achievements of our time in the protection of public health. The use of chlorine for the destruction of microbiological pathogens is essential to protect the public from outbreaks of waterborne disease. Chlorine, as well as other disinfectants, produces a variety of chemical by-products. The risk from the presence of microbial pathogens in drinking-water is estimated to be several orders of magnitude greater than the risk from chlorination by-products. Any efforts to control these by-products must not compromise the microbiological quality of drinking-water.

INTRODUCTION

Safe drinking-water has been recognized for centuries as a major determinant of health

It is estimated that 1.5 billion people still lack access to clean water supplies [1]. Diseases arising from the ingestion of pathogens in contaminated water have the greatest health impact worldwide. The health effects of these diseases are heavily concentrated in the developing world and, within the developing world, among the poorer urban and rural households of the poorer countries.

One of the major achievements of this century is the extent to which waterborne diseases have become of minor significance in the mortality and morbidity of most developed countries. The use of chlorine and its compounds for the disinfection of drinking-water has played a central role in reducing the incidence of these diseases and can be considered one of the most important success stories of our times for the preservation and promotion of public health.

THE GLOBAL BURDEN OF DISEASE AND DEATH FROM THE MICROBIAL CONTAMINATION OF DRINKING-WATER

An estimated 80% of all diseases and over one-third of deaths in developing countries are caused by the consumption of contaminated water and, on average, as much as one-tenth of each person's productive time is sacrificed to water-related diseases [2]. Those at greatest risk are infants and young children, people who are debilitated or living under unsanitary conditions, the sick, and the elderly. For these vulnerable people, infective doses are significantly lower than for the general adult population.

The transmission of infectious and parasitic diseases that have been confirmed by epidemiological and microbiological studies through the ingestion of pathogens in contaminated drinking-water includes hepatitis A and E, rotaviral and Norwalk agent enteritis, cholera, typhoid, campylobacter enteritis, shigellosis, *Escherichia coli* infections, enteritis due to *Yersinia enterocolitica*, cryptosporidiosis, giardiasis, amoebic dysentery, and dracunculiasis. Symptoms of these diseases are varied but most include diarrhoea, one of the big killers of our time.

Diarrhoeal diseases are associated with unsafe water and remain a major cause of morbidity and mortality in infants and young children in developing countries. Across the globe there are an estimated 1.8 billion episodes of childhood diarrhoea annually, mostly in developing countries. Each episode of diarrhoea, if not properly managed, contributes to malnutrition and growth retardation. Diarrhoeal diseases were responsible for around 3 million childhood deaths in the developing world in 1993. An additional one million deaths a year occur in adults [3].

Cholera epidemics, frequently transmitted by unsafe drinking-water, are on the increase. Cholera has become endemic in many countries in Africa, Asia and Latin America. The cholera epidemic that began in

Peru in 1991 and spread to 16 other countries in Latin America—a region which had been free of the disease for almost a century—had disastrous impact on health and on national economies. The number of cholera cases worldwide, notified to WHO in 1991, was 595 000 and 19 300 deaths [4].

Epidemiological studies have implicated drinking-water supplies (including ice) as one of the most important transmission vehicles of the cholera epidemic in Peru. Virtually none of the water supplies implicated was found to be adequately disinfected. Throughout Latin America, the failure to disinfect water supplies has repeatedly been proven to be a major contributing factor to the propagation of cholera and many other waterborne diseases. The concern over chlorination by-products, especially trihalomethanes, has been cited as the reason for abandoning disinfection in Peru resulting in the cholera epidemic [5].

It is estimated that the 1991 outbreak of cholera cost Peru alone, approximately US$ 1 billion as a result of reduced economic activity, losses to the fishing, agriculture and tourism sectors, unemployment, and reduction of exports [1].

In a number of African countries, cholera cases are also increasing at a catastrophic pace. July 1994 was marked by the dramatic cholera outbreak that devastated the Rwandan refugee camps in Goma, Zaire. The lack of safe water and basic sanitation, and massive overcrowding created ideal conditions for the rapid spread of the disease. The world-wide total of cholera cases in 1994 was 384 400, with a death toll of 10 700 [6].

Dracunculiasis is a disease caused by the parasitic worm *Dracunculus medinensis* or 'guinea worm'. This worm, *The Fiery Serpent*, has been a major health risk for millions of people in Africa and the Indian subcontinent. The disease does not kill people, but it causes dreadful suffering and disability among the world's most deprived people. Dracunculiasis can only be contracted by drinking contaminated water.

BENEFITS TO HEALTH OF SAFE DRINKING-WATER

It would be erroneous to ascribe the source of hepatitis, cholera, amoebiasis and other intestinal infectious and parasitic diseases exclusively to unsafe drinking-water. With the exception of dracunculiasis, drinking-water is only one vehicle of transmission. Inadequate sanitary disposal of human excreta, cultural behaviour, lack of health education, poor food-handling practices, overcrowding, poverty, inadequate quantities of water for hand washing, bathing, laundering and cleaning, are all important factors in the transmission of diseases. Quantitative assessment of the risks associated with each of these individual factors is difficult and controversial because of insufficient epidemiological evidence, the number of factors involved, and the changing interrelationships between these factors. Improvements in the quality and availability of water, in excreta disposal, and in general hygiene education, are all important factors in achieving reductions in morbidity and mortality rates of infectious and parasitic diseases.

High risks are associated with the ingestion of water that is contaminated with human and animal excreta. In addition, the microbial contamination of drinking-water will result in the contamination of food, an increased number of carriers and cases, the re-contamination of drinking-water, and the vicious circle of disease spreading and death will thus be completed. Of all routes of exposure, the microbial contamination of drinking-water is particularly to be avoided because of its capacity to result in the simultaneous infection of a high proportion of the community.

Numerous studies have clearly shown that provision of microbiologically safe drinking-water can significantly reduce, directly or indirectly, the morbidity and mortality of diarrhoeal diseases, schistosomiasis, and dracunculiasis.

Table 1 summarizes the results of some methodologically rigorous studies of the impact of improved water supply and sanitation on major diseases. Provision of safe drinking-water and the proper disposal of human excreta can thus significantly reduce the morbidity and mortality of some of the most serious diseases, and can significantly reduce overall child mortality [7].

Table 1 Impact of improved water supply and sanitation in reducing disease morbidity/ mortality [7]

Disease	Median reduction (%)
Diarrhoea (morbidity)	26
Diarrhoea (mortality)	65
Dracunculiasis	78
Schistosomiasis	77
Child mortality	55

The impact of the quality of water alone was examined in a number of studies. A median reduction of 17% in diarrhoeal disease morbidity was found as a result of the use of safe versus contaminated water supplies, and infant mortality was decreased by some 20% [7] (Table 1).

One of the goals of the World Health Organization and its Member States is the eradication of dracunculiasis. Eradication depends largely on the provision of safe water: village pumps in endemic areas, filtering of surface water through finely-meshed cloth and destruction of the cyclops, the intermediate host of the worm. As a result of an intense international effort focusing on safe water supplies, the number of reported cases of dracunculiasis has declined from 892 000 in 1989 to 165 000 in 1994 [8].

Schistosomiasis (bilharziasis or snail fever) is a water-related helminthic disease acquired by contact with water used in normal daily activities for personal or domestic hygiene and swimming, or in professional activities such as fishing, rice cultivation, irrigation, etc. It affects 200 million people in 74 countries in the Americas, Africa and Asia, and kills perhaps 200 000 people [3]. Recent studies have shown that populations with safe public water supplies can have up to 40% lower incidence of the disease than those without [1]. As indicated in Table 1, the combined effects of safe water supplies and adequate sanitation amount to a reduction in morbidity of some 77%.

DRINKING-WATER DISINFECTION

As far as possible, water sources must be protected from contamination by human and animal wastes, which can contain a variety of bacterial, viral, protozoal and helminthic pathogens. It is always better to protect water from contamination than to treat it after it has been contaminated.

However, in many cases protection of the water source from pollution is problematic. In the case of contaminated water sources, several treatment processes such as coagulation, sedimentation, filtration and disinfection, will be necessary to provide multiple barriers to the spread of pathogenic microorganisms, so that the failure of any one process will not result in waterborne disease. The final barrier is disinfection. The function of the entire system, and indeed of much of water treatment, may with some justification be regarded as that of conditioning the water for effective and reliable disinfection [9,10].

The destruction of microbial pathogens almost invariably involves the use of reactive chemical agents such as free chlorine (hypochlorous acid and hypochlorite), chloramine, chlorine dioxide and ozone. Each of these disinfectants has its advantage and disadvantage in terms of cost, efficacy, stability, ease of application, and nature of disinfectant by-products (DBPs). Chlorine is by far the most commonly used disinfectant and, in developing countries, the use of chlorine is often the only affordable mean of disinfecting drinking-water.

Comparing the efficiency of the four main disinfectants, the most efficient disinfectant for the inactivation of bacteria, viruses and protozoa is ozone, whereas chloramine is the least efficient. Free chlorine is an effective disinfectant for bacteria and viruses, and compares well with the efficiency of ozone and chlorine dioxide for these microorganisms. However, it is less effective against Cryptosporidium parvum and Giardia lamblia than chlorine dioxide or ozone [11].

Several factors influence the efficiency of disinfection with chlorine. These include the pH and turbidity of the water and, of course, the concentration of chlorine and contact time.

When added to water, chlorine rapidly hydrolyses, yielding hypochlorous acid (HOCl) and hydrochloric acid. Hydrolysis to HOCl is virtually complete at pH greater than 4 and at chlorine doses up to 100 mg/L. Hypochlorous acid is a weak acid that dissociates partially into hypochlorite ion (OCl^-). At pH of about 7.5, there is an equal distribution of HOCl and OCl^-; at pH 6.5, 90% of the free chlorine is present as HOCl; at pH levels above 9, hypochlorite ions are the dominant species. Hypochlorous acid is a considerably more efficient disinfectant than hypochlorite ion, thus efficient disinfection is favoured by lower pH [12].

Turbidity can have negative effects on disinfection because high levels have been shown to protect microorganisms from the action of chlorine, and to increase the chlorine and oxygen demand [10].

Conditions for effective terminal chlorination as recommended in the WHO Guidelines for drinking-water quality are as follows [9,10]:

- pH — less than 8.0
- Median turbidity — not to exceed 1 nephelometric turbidity unit (NTU)
- Maximum turbidity — 5 NTU
- Residual concentration of free chlorine — not less than 0.5 mg/L
- Contact time — at least 30 min

These conditions of chlorination are expected to ensure the absence of bacteria and viruses in treated water but not of pathogenic helminths, cysts or oocysts of protozoa. For these microorganisms, effective filtration is an essential requirement.

Distribution systems are vulnerable to microbial contamination. Residual chlorine concentrations of approximately 0.2–0.3 mg/L are often maintained in distribution systems to serve as a sentinel for the entry of pollution and to prevent the growth of nuisance bacteria and other organisms.

Chlorine, as well as other disinfectants, reacts with certain water constituents to form new compounds with potentially harmful long-term health effects. Chlorine disinfection by-products have been extensively identified and assessed for toxicity. Considerably less is known about the nature and toxicity of the by-products of the other disinfectants, ozone, chlorine dioxide, or chloramine.

The levels of potentially toxic chlorination by-products can be reduced through appropriate treatment while maintaining the microbiological quality of drinking-water. Effective application of conventional treatment (coagulation, sedimentation, filtration) will reduce the levels of organic precursors before final disinfection, and avoiding pre-chlorination will result in an overall decrease in the concentration of DBPs.

WATER CHLORINATION: BENEFITS AND RISKS

Diseases caused by pathogenic bacteria, viruses, protozoa or helminths are the most common and widespread health risk associated with drinking-water. For this reason, the WHO Guidelines for drinking-water quality place the greatest importance on the microbiological quality of drinking-water, and repeatedly emphasize that the potential consequences of microbial contamination are such that its control must always be of paramount importance and never be compromised [9].

The disinfection of drinking-water using chlorine has saved many lives, beginning with the dramatic decline in typhoid and cholera cases which accompanied the introduction of this process in Europe and North America in the early 1900s.

The use of chemical disinfectants, including chlorine, in water treatment usually results in the formation of chemical by-products, some of which are potentially hazardous. However, the risks to health from these by-products are extremely small in comparison with the risks associated with inadequate disinfection, and it is important that disinfection should not be compromised in attempting to control such by-products [9].

In 1991, the International Agency for Research on Cancer evaluated the carcinogenic potential of chlorinated drinking-water. IARC concluded that [13]:

> 'There is inadequate evidence for the carcinogenicity of chlorinated drinking-water in humans.
> There is inadequate evidence for the carcinogenicity of chlorinated drinking-water in experimental animals.'

Weighing the risks of microbial versus chemical contamination, the WHO Guidelines for drinking-water quality recommends that, where local circumstances require that a choice must be made between meeting either microbiological guidelines or guidelines for disinfectant by-products, the microbiological quality must always take precedence and, where necessary, a chemical guideline value can be adopted corresponding to a higher level of risk. Efficient disinfection must never be compromised [9].

Efforts are being made to provide quantitative assessment of the health risk from the microbial contamination of drinking-water for comparison with the potential risk from chlorination by-products. Although risk assessment of this kind is fraught with difficulties, Regli et al., concluded that the risk of death from known pathogens in untreated surface water appears to be at least 100–1000 times greater than the risk of cancer from known chlorination by-products, and the risk of illness from pathogens in untreated surface water appears to be at least 10 000–1 million times greater than the risk of cancer from DBPs in chlorinated drinking-water. Depending on the source water quality, these same relative differences in risk may pertain to filtered systems without disinfection versus filtered systems with chlorination [14].

Control of the microbiological quality of drinking-water is a much higher health priority, especially in developing countries, than the control of chlorination by-products. The use of chlorine for the disinfection of drinking-water is critical for the control of waterborne diseases thus disinfection should not be compromised to minimize the levels of chlorination by-products.

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