Microbiological safety of water

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Significant advances in water treatment over the last century have resulted in massive improvements in the microbiological safety of public drinking water supplies in the UK and the developed countries. Incidences of illness due to poor treatment or post-treatment contamination are rare, but when they occur tend to attract considerable media attention. A well managed water treatment works and supply system can provide high quality drinking water wherever in the world it is located. As a rule, throughout the world, private supplies tend to be of a poorer quality than public supplies, but poorly managed public supplies have the potential to make a large number of people ill and continued effort is needed to maintain and improve drinking water quality world-wide.

The history of water safety

The development of public water supplies, first seen in ancient times, assumed greater importance with the progressive increase in urbanisation. A public water supply has potentially great advantages, not only due to the convenience it brings but also in terms of health benefits deriving from its use in washing and cleaning. Potentially, however, a public water supply can be a risk to the health of large numbers of people due to the size of population exposed should contamination occur. This has been borne out by recorded outbreaks of disease, classically the outbreaks of cholera in European cities in the 19th century.

The first clear documented proof that public water supplies could be a source of infection for humans came from epidemiological studies of cholera carried out by Dr John Snow in the 1850s. Snow's study of an outbreak of cholera associated with a public water pump in Broad Street, London and his removal of the handle is the most famous, but his epidemiological study of the water supply areas of two London water companies is perhaps a more definitive piece of work. At that time, water was supplied to London by a number of small companies, many taking their water directly from the Thames. The Southwark and Vauxhall company obtained its water from the Thames at Battersea, whilst the Lambeth company obtained its water again from the Thames, but a

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considerable distance upstream, above the major sources of pollution from human sewage. In one particular area of about 300,000 residents, the pipes of both companies were laid in the streets with houses connected to one or other source of supply. Snow's analysis of cholera deaths showed striking results: houses served by the Lambeth company had a lower incidence of cholera than the city of London in general, whereas those served by the Southwark and Vauxhall company had a very high incidence. As the other factors, including socio-economic conditions, were identical for each of the populations served by the two companies, Snow concluded that the water supply was the route by which the cholera agent was transmitted.

It is noteworthy that this work was carried out before the germ theory of disease had been fully developed, principally through the work of Robert Koch and Louis Pasteur. The causative agent of cholera, *Vibrio cholerae*, was finally isolated by Robert Koch some 30 years later in 1883. By the end of the 19th century the presence of the causative agents of the classical waterborne diseases of cholera, typhoid and dysentery had been identified in the faeces of patients, re-inforcing the link between faecally contaminated water and these diseases. Since that time, it has been recognised that the key to microbiologically safe drinking water is the exclusion of faecal contamination from the supply.

Outbreaks of cholera and typhoid in the 19th and the early 20th centuries led to the wide-spread use of filtration to treat water supplies followed by the gradual introduction of the use of chlorine, usually on an intermittent basis, from 1910 onwards. The Croydon typhoid outbreak in 1937 led to continuous chlorination of water being used almost universally on public supplies, the exception being those well or borehole sources with excellent microbiological quality. Today, all public water supplies in the UK contain disinfectant, normally chlorine, at a low level at the customer's tap. This helps to protect against contamination, which may occur if the integrity of the distribution system is breached (*e.g.* through burst mains or cross contamination).

The principles of water treatment were established in the 19th and early 20th centuries with surface water sources being subject to coagulation and filtration processes (or just filtration) to remove particles including bacteria, and a disinfection stage or stages to make the water microbiologically safe. Underground sources subject to natural filtration are typically of very high quality and normally a simple disinfection stage is sufficient. The introduction of variations to the treatment processes and alternative disinfectants, such as ozone and UV irradiation, resulted in a variety of options being available to treatment engineers. Traditional processes still form the core of advanced treatment today and it is their legacy that has made public supplies largely compliant with modern water quality standards in many countries.

Bacteriological indicators of contamination

Towards the end of the 19th century, it was increasingly realised that some bacteria were specifically associated with faecal matter, most notably *Bacterium coli* described by Theodore Escherich in 1885. As this organism appeared to occur in great numbers in all faeces, particularly compared to the enteric pathogens, it was suggested that detection of this *B. coli* in water would be indicative of the presence of faecal matter and, hence, the possible presence of enteric pathogens. Testing was based on the detection of fermentation of lactose at 37°C, characteristic of the organism. Over the years, however, it became apparent that *B. coli* was actually a group of closely related bacteria, the principal species of which is now named *Escherichia coli*, and the others are collectively known as the 'coliforms'. These bacteria are facultative anaerobes and tolerant of bile salts. *E. coli* is differentiated from the other coliforms by being able to ferment lactose and produce indole from tryptophan at 44°C. Although methods of isolation have changed over recent years, *E. coli* has remained the principal indicator of faecal pollution.

E. coli has, at least in temperate climates, the characteristics desirable of an indicator organism (*i.e.* it should be abundant in faeces, capable of easy isolation and examination and should not grow in the aquatic environment). In recent years, the enterococci, faecal bacteria of the genera *Enterococcus* and *Streptococcus*, have also been given a significant status as faecal indicators.

The use of bacterial indicators for drinking water quality assessment is well established and national and international standards have been established based upon them. Typically standards require that in supplied water *E. coli*, coliforms and enterococci are not detected in 100 ml samples taken on a regular basis. If these organisms are present in raw (untreated) water and can be shown to be absent in treated water from a particular treatment works, it is assumed that they have been removed successfully. The indicator principle assumes that any pathogenic organisms will also have been removed through the treatment works. It has been generally acknowledged that it is not normally practical to look for pathogens themselves in water due to the nature of the methods and the low levels that might be found.

This maxim generally holds and has helped to protect public health over many years. Outbreaks of bacterial enteritis linked to public supplies are very rare nowadays, only occurring when there has been gross post-treatment contamination of a supply. In some situations, however, it has been recognised that it is worth looking directly for pathogens, particularly in the case of the protozoan *Cryptosporidium*[1]. This organism has only been considered a significant pathogen of humans since 1976 and particularly following the advent of AIDS in the late

1970s. Waterborne outbreaks have been documented from the early 1980s onwards. As regards water treatment, it is removed in coagulation and filtration processes, but is very resistant to chlorine and, therefore, an absence of faecal indicators does not necessarily indicate an absence of *Cryptosporidium*.

Drinking water standards

Quantitative standards for water quality first emerged during the early part of this century. In the US, a bacteriological standard of less than 1 coliform per 100 ml was first expressed in 1914. In 1934, the first edition of the *Bacteriological Examination of Water Supplies* was published in the UK. This has become the primary reference for water microbiologists in this and many other countries and the sixth edition, under the title *The Microbiology of Water 1994: Part 1 – Drinking Water* was published in 1994[2]. (It is currently undergoing revision with regard to the forthcoming implementation of the new EU Directive on drinking water quality.) This document is referenced alongside the current regulatory standards and is useful for understanding the principles of drinking water microbiology in both regulatory and non-regulatory situations. Another key source of information is the World Health Organization's *Guidelines for Drinking Water Quality*, first published in 1984. An updated version of this 3 volume work was completed in 1996[3]. These volumes include detailed information on microbiological and chemical parameters and their pathogenic and toxic effects.

From these WHO guidelines (and their predecessors), standards have been derived in different parts of the world. These guidelines are not standards in themselves and must be dealt with in the context of the country in which they are employed. The EU Directive on drinking water quality, which was strongly influenced by WHO guidelines, was published in 1980[4] and led to a revision of the *Microbiology of Drinking Water* and ultimately in the UK, to the Water Supply (Water Quality) Regulations in 1989[5]. A new directive was adopted in 1998 which is expected to be implemented into national law in member states by the year 2000[6].

Obviously, it is not enough to have standards to work to in order to have safe drinking water; there must be an appropriate level of monitoring and reporting. The UK regulations contain comprehensive information on monitoring frequencies at treatment works, service reservoirs and consumer taps. The frequency of monitoring at treatment works depends upon the volume of water produced by that works and, in the case of customer taps, the volume of water or the population supplied within defined water supply zones. These are geographical

areas with populations of less than 50,000 and containing reasonably uniform quality issues.

In England and Wales, the Drinking Water Inspectorate (DWI) is responsible for monitoring compliance with the regulations and a report on compliance is issued annually by the Chief Inspector. Compliance with UK legislation is very high, with 99.9% of samples being free from *E. coli*. In addition to the role of the DWI, health authorities are kept informed of abnormal water quality, which may affect public health, through the Consultants in Communicable Disease Control (CsCDC). Whereas chemical standards are set on a basis of life-time exposure and an occasional exceedence is not necessarily serious, microbiological standards are set on their potential immediate impact and the presence of *E. coli* in treated water is viewed very seriously. Depending on the situation, the finding of *E. coli* by water companies may lead to an advisory boil water notice being issued. Boil water notices have no legal status and the issuing of them is under the control of the water company, although the health authorities are often closely involved with the decision. Serious pollution incidents of drinking water may lead to the setting up of an Incident Management Team or Outbreak Control Team depending on the nature of the contamination. Representatives of water companies, health authorities and environmental health departments would all sit on such a group.

The Secretary of State (in reality the DWI) may take enforcement action if compliance with regulatory standards is breached. In practice, this does not occur if breaches are minor and trivial or if the water company makes immediate attempts to rectify problems. Enforcement action, if it does occur, involves the water company preparing a timetable of improvements to ensure that non-compliance with regulatory standards is halted. Under section 70 of the Water Industry Act 1991[7], the criminal charge of supplying water unfit for human consumption was introduced. Due diligence is allowable as a defence. Successful prosecutions have been brought against several water companies for supplying highly turbid water, alkaline water and water with a discernible chemical taste . In these cases, there is no evidence that the water was unsafe, but the water was deemed unfit for consumption in that customers felt that they could not use the water for drinking and domestic purposes. Prosecutions due to failure of bacteriological standards are extremely uncommon. In February 1999, a major water utility pleaded guilty of supplying raw river water to two properties in November and December 1997[8]. This was due to contractors connecting the water supply of the properties to a raw water pipe from the river to a reservoir by error. In this case, the water contained high levels of faecal bacteria.

Mechanical damage to a water main may cause depressurisation and could allow ingress of environmental material, although in the vast

majority of cases the damaged main will still retain enough pressure to exclude extraneous material. It can be isolated and repaired without contaminated water reaching the consumer. During planned depressurisations for repair, relining or replacement, the risk of water contamination is minimised by specific hygiene procedures being followed by the water companies. These are developed in line with advice and key guideline documents, which require disinfection, flushing and sampling before the water mains are brought back into service. Water in the distribution network is also vulnerable to contamination if mismanaged on a customer's premises (*e.g.* an industrial site beyond the responsibility of the supplier). Mains water may be particularly vulnerable to contamination if the supply is in contact with contaminated water in a factory without the appropriate safety devices being fitted to prevent back-flow or back siphonage. Regulations are implemented by water companies to prevent wastage or contamination of water. Where water companies believe that regulations may be being broken, they may carry out inspections and insist on corrective work being carried out. Prosecution of industrial users is also an option.

World-wide, the situation exists whereby WHO guidelines on water quality are used to generate national regulations. In many cases, countries work directly to WHO guidelines. However, even if standards exist it does not mean they are being met. In many cases, the monitoring may be limited and this fact, combined with lack of data on compliance, makes it unclear how good drinking water quality is.

Private supplies in the UK are defined in the Water Industry Act 1991 as any supplies of water provided otherwise than by a statutorily approved water undertaker. The Private Supplies Regulations 1991[9] made under the Act require local authorities to take samples at certain frequencies dependent upon the size of supply. They also have powers to require improvements to be applied to unwholesome supplies. Although the standards set for private supplies are equivalent to those for public supplies, in practice the overall quality of private supplies is not nearly as good. Although some private supplies are well managed and produce excellent quality water, many will show intermittent faecal pollution. Since the monitoring of smaller private supplies is very infrequent, this may not be registered in analytical results and, even if it is, householders may not fit appropriate treatment to these water systems. This underlines the situation that the presence of standards does not necessarily guarantee good quality water.

The risk from contaminated water systems

Public health surveillance requires the monitoring of waterborne disease, but in practice the detection of many incidents is difficult. In England and

Wales, possible waterborne outbreaks are identified by health officials at a local level, *e.g.* through the CsCDC or Directors of Public Health. The Communicable Disease Surveillance Centre (CDSC) receives information from various sources about clusters of cases in England and Wales and the Drinking Water Inspectorate also has an interest in possible waterborne outbreaks.

Although after outbreaks have been identified there may be a hypothesis that water is associated with the illness, it is very difficult to prove beyond reasonable doubt that such a hypothesis is correct. Several factors contribute to this. Firstly, water samples are often taken retrospectively and samples taken from the time of the exposure are rarely available. Secondly, some organisms may be difficult to detect and, thirdly, case control studies on water supplies are hampered by the fact that most people have some exposure to water, even if only through washing vegetables or brushing teeth. This means that in a case control study when a population within an area has been ill, it will often be found that most of the population has been exposed to the risk factor under investigation. This is a very different scenario from a classic case control study where the cases have all visited for example a particular food outlet. It is thought that in the case of *Cryptosporidium*, that populations drinking certain water supplies may be exposed repeatedly to oocyst antigens and, therefore, develop some protective immunity. Outbreaks within the population may then reflect not only the possibility of higher levels of oocysts in the supply but variability in the immunity and exposure of the population, which may be hard to quantify[10]. Nevertheless, epidemiological studies can be used in certain cases to implicate the water supply; for example, when an outbreak can be traced to a particular treatment works where a population as a whole received various water sources.

Case control studies on an outbreak of cryptosporidiosis in Bradford in 1992 using both laboratory and neighbourhood controls showed an association between development of cryptosporidiosis and the consumption of unboiled tap water from the suspected treatment works[11]. In the instance of the North London 1997 outbreak, a case control study similarly indicated a link between the outbreak and tap water from a particular treatment works[12]. Various blends of this borehole water were supplied to different areas. Dose response data in both outbreaks and elsewhere, were used to indicate that water was the likely source of the pathogen, with increasing likelihood of illness being associated with higher consumption of the contaminated water. In the Bradford outbreak, there was a significant association between the amount of water usually drunk and the likelihood of illness. In the North London outbreak, a chi-squared test for trend with tap water consumed at home showed that the proportion of cases in the case

control study increased significantly with consumption. The main problem with this sort of data is that there is a potential for significant recall bias by consumers. This is much less of a problem in the case of an outbreak being linked to a particular food outlet.

Problems with the recognition of water-borne disease has led to assignment of categories to disease outbreaks by the CDSC and the terms strongly, probably and possibly are used to describe association with water[13]. The criteria for classification of outbreaks under these descriptions are:

Strong association with water

Three scenarios exist for this category. In the first two, the pathogen in clinical cases must be found in the water, either in combination with analytical epidemiological evidence, or with descriptive epidemiology and the absence of an obvious alternative cause. In the third scenario, an analytical epidemiological study implicates the water supply and there have been water quality and/or water treatment problems but the pathogen has not been detected in water.

Probable association with water

This category includes the combination where descriptive epidemiology is good, there is no obvious alternative explanation and there is also evidence of water treatment and/or water quality problems. It also covers scenarios where analytical epidemiology has been carried out or the particular pathogen is found in the water in the absence of other evidence.

Possible association with water

Possible outbreaks are ones which occur in association with water quality and/or treatment problems but where there is no pathogen found in the water and no supporting epidemiology, or where descriptive epidemiology stands on its own without other evidence.

Outbreaks of water-borne disease

Although drinking water generally meets regulatory standards in developed countries and diseases such as typhoid and cholera are no longer spread by this route, there have still been outbreaks of water-borne gastrointestinal infection in countries with the most advanced water treatment systems. Outbreaks caused by protozoan pathogens such as *Giardia* and *Cryptosporidium*, bacteria such as *E. coli* O157 and

Campylobacter spp. and various viruses have been documented in recent years. Incidents involving water supplies typically attract considerable high profile media and public attention, giving the impression that water-borne outbreaks are common. In reality illness rates from contaminated water are a very small part of the disease burden in the UK.

In the last 10–15 years, *Cryptosporidium* has been the prime cause of water-borne disease associated with mains water supplies. This organism is very resistant to conventional disinfectants and can occur in mains supplies if water treatment is not fully effective. It is also a major problem in private water supplies. A study of 19 outbreaks due to drinking water in England and Wales between 1992 and 1995 comprised 10 outbreaks due to public supplies and 9 outbreaks due to private supplies[14]. The 10 outbreaks in public supplies were all caused by *Cryptosporidium*. Under the definitions ascribed by the CDSC, 7 were 'probably' associated with water and 3 'strongly' associated with water, including the Bradford outbreak previously mentioned.

Of the 9 outbreaks in private supplies, 5 were described as 'strongly', 2 'probably' and 2 'possibly' associated with water. In one outbreak, no pathogen was identified whilst the others involved *Campylobacter* spp. alone (5 outbreaks) *Cryptosporidium* alone (1 outbreak) or a combination of the two (1 outbreak). *Giardia* was identified as a cause of one outbreak in a Worcestershire village where the likely cause was direct faecal contamination of a shallow spring supply by grazing animals[15].

Water-borne disease from pathogenic *E. coli* strains is more likely in private rather than public supplies. Recent work has shown that this organism is as susceptible to chlorine as other *E. coli*[16]. In one recorded incident, isolation of *E. coli* O157:H7 from a well water in Canada was linked to a case of bloody diarrhoea in a 16-month-old child where water was the most likely route of infection[17]. In 1995, contaminated stream water was accidentally pumped by a local business into the mains supply of a village in Scotland resulting in 6 confirmed cases of *E. coli* O157 infection, 8 confirmed cases of *Campylobacter* spp. infection and 633 other people reporting gastrointestinal upset[18].

Outbreaks caused by small round structured or Norwalk type viruses have been described. In a 1994 incident, evidence suggested transfer of viruses from contaminated water into custard slices in a South Wales factory[19]. The mains water may have been contaminated due to an illegal connection between a pipe carrying river water and the mains water on the same industrial estate. Difficulties in the isolation of enteric viruses from environmental samples reduce the chances of demonstrating a link between water and viral illness; however, there is no suggestion from surveillance data that water-borne viral illness is nearly as prevalent as water-borne cryptosporidiosis.

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