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Review

Factors contributing to the public health and economic importance of waterborne zoonotic parasites

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Abstract

This is the first of a series of review articles in a Special Issue publication on waterborne zoonotic parasites. A brief historical overview of the occurrence and importance of waterborne parasites, dating from early civilization is presented. The article considers the diversity of parasites including protozoa, nematodes, cestodes and trematodes and the related zoonotic organism microsporidia. Many of the life cycle stages and their characteristics, which make parasites environmentally resistant and suitable for waterborne transmission are discussed. Surfaces of transmission stages consist of multiple layers of proteins, lipids, chitin or other substances capable of withstanding a variety of physical and chemical treatments. Delivery of waterborne parasites is facilitated by various mass distribution systems to consumers, and by transport and intermediate hosts such as fish and filter-feeding invertebrates which are consumed by humans. The article discusses the trends in global warming and climate change and potential for concurrent rise in waterborne disease outbreaks due to parasites. Impacts of technological modernization and globalization on the transmission of zoonotic waterborne zoonotic parasites are considered, including the effects of large-scale agricultural practices, rapid transportation of goods, and widespread movement of individuals and animals. Finally, transmission features and parasite attributes which contribute to concerns about accidental or orchestrated waterborne disease outbreaks are discussed.

Keywords: Parasites; Waterborne transmission; Disease outbreaks; Zoonoses; Globalization; Global warming; Climate change

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Contents

1. Introduction

The scarcity and quality of fresh water have been major challenges in maintaining or improving public health and prosperity in many parts of the world. Good public health and productive animal husbandry require clean water. Until recently, people living in North America, Europe, and other developed regions have not been very concerned about infectious disease agents in water. However, within the last decade large disease outbreaks due to *E. coli*, *Giardia* and *Cryptosporidium* from the use of contaminated water have raised serious concerns about waterborne zoonotic pathogens, and mechanisms for monitoring and treatment.

Waterborne parasites include a diverse group of organisms ranging from unicellular amoebae to complex metazoans such as trematodes and cestodes. Although many of these infect animals or humans, some have developed zoonotic life cycle strategies, and others, normally free-living, are opportunistic parasites. Some parasites have direct life cycles, whereas others require complex multi-stage development involving one or more invertebrate and/or vertebrate intermediate hosts and a variety of modes of transmission. Most parasites have at least one life cycle stage which is adapted to survive environmental exposure and subsequent transmission to new hosts.

Unlike bacteria and viruses, parasites generally have unique features which often make them remarkably suited for survival in the environment and dissemination by water. Many of these parasites are difficult to detect and control. Some have the potential to cause severe public health problems, while others are capable of inflicting considerable losses in livestock. The resulting production and economic losses can be extensive. This article reviews biological and other factors which contribute to the importance of parasites as formidable waterborne agents of infectious diseases in animals and humans.

2. Historical highlights

Since early civilization, long before there was any knowledge of microorganisms, attempts have been made to purify water (see Baker, 1981). Ancient drawings on the walls of tombs depict the use of purification systems by the Egyptians 15–13 centuries B.C. Later, Hippocrates (460–354 B.C.) recommended boiling and straining drinking water in order to maintain good health. Settling reservoirs, forms of filtration, and a public system of aqueducts capable of delivering large volumes of water were used in Rome about 340–225 B.C. The quality of the water delivered, although in lead-lined pipes, was variable but was monitored according to set criteria, including taste, odour, and whether consumers remained healthy.

The first observation of a microorganism was made by Anton van Leeowenhoek in 1681 when he invented the light microscope and discerned *Giardia* in his own feces. Two centuries later, it was discovered that microorganisms were responsible for waterborne epidemics of typhoid (1879), cholera (1883), and dysentery (1898). Many parasites discovered decades ago have only recently been recognized as important zoonotic pathogens, or the cause of waterborne epidemics. *Cryptosporidium* oocysts were discovered in mice in the early 20th century, while the first reports of human cryptosporidiosis did not occur until 1976 (see Fayer, 2004). Nearly two decades later, this parasite was implicated in the world's largest recorded waterborne disease outbreak involving approximately 403,000 people (MacKenzie et al., 1994). Today, parasites are rapidly gaining recognition as globally ubiquitous organisms, and one of the most common causes of waterborne intestinal disease in humans. For example, *Giardia* is the most commonly diagnosed intestinal parasite in developed countries, and it is commonly encountered in livestock and wild animals (see Thompson, 2004).

3. Resistance of parasites

Waterborne parasites produce transmission stages which are highly resistant to external environmental conditions, and to many physical and chemical disinfection methods routinely used as bactericides in drinking water plants, swimming pools or irrigation systems. Resistant stages include cysts of amoebae, *Balantidium*, and *Giardia*, spores of *Blastocystis* and microsporidia, oocysts of *Toxoplasma gondii*, *Isospora*, *Cyclospora* and *Cryptosporidium* and eggs of nematodes, trematodes, and cestodes. These exogenous transmission stages are microscopic in size and of low specific gravity, which facilitate their easy dissemination in fresh water, or seawater. Several examples of zoonotic cysts, oocysts and eggs capable of waterborne transmission are depicted in Fig. 1.

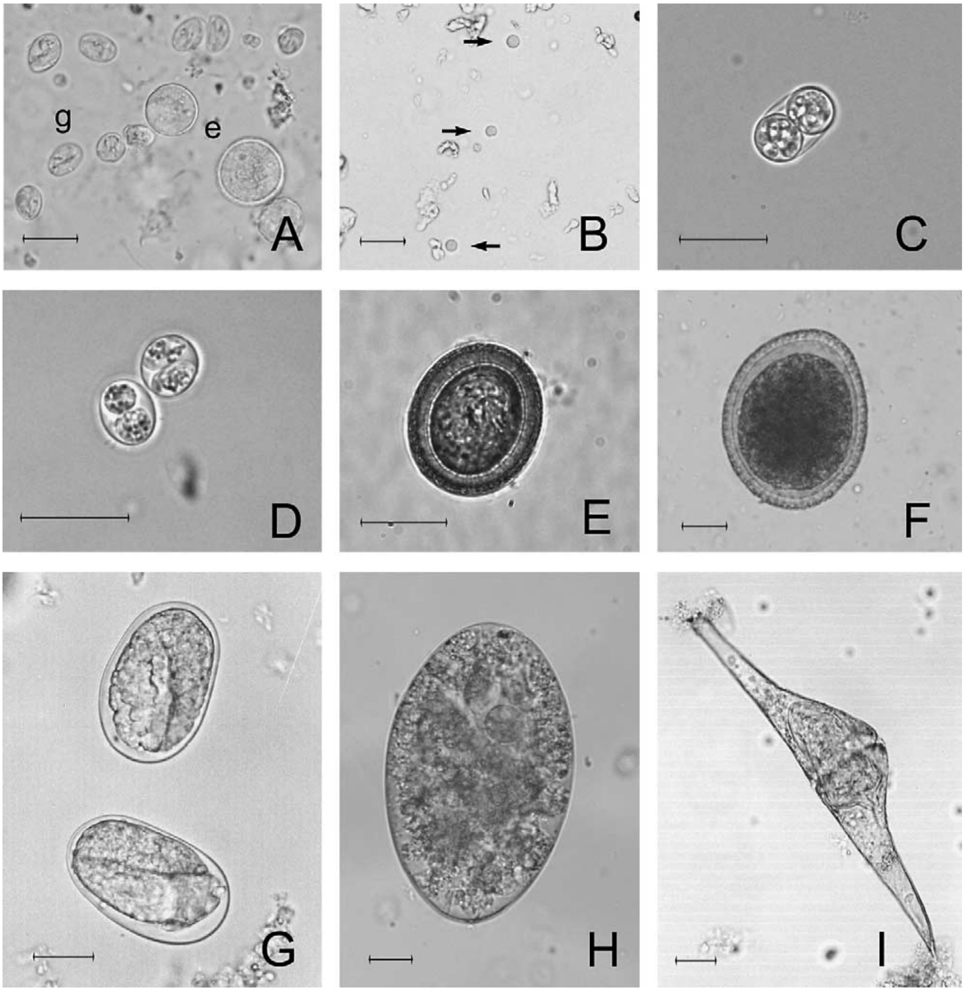

Fig. 1. Life cycle stages of some zoonotic parasites transmissible via water: (A) *Giardia duodenalis* cysts (g) and *Entamoeba* cysts (e); (B) *Cryptosporidium parvum* oocyst; (C) *Isospora* oocysts; (D) *Toxoplasma gondii* oocysts; (E) *Taenia* or *Echinococcus* egg; (F) *Toxocara* egg; (G) *Strongyloides* eggs; (H) *Fasciola hepatica* egg; (I) *Schistosoma spindale* egg; bar = 20 μm.

3.1. Physical armour of transmission stages

The exogenous stages of waterborne parasites possess outer surfaces capable of withstanding a variety of physical and chemical treatments. The resistant surfaces are comprised of multiple polymeric layers of lipids, polysaccharide, proteins or chitin. Examples of these are the two protein layers of coccidian oocysts derived from the coalescence of wall-forming bodies, the chitinous wall of microsporidian spores, the multi-layered (inner lipid/protein-, middle protein/chitin-, outer protein/mucopolysaccharide) shell of *Ascaris* eggs, and the impermeable embryophore of the *Echinococcus* egg which is constructed of polygonal blocks of keratin-like protein held together by a cement substance.

3.2. Resistance to physical factors of temperature, desiccation and irradiation

In mild weather conditions, exogenous stages of parasites in water may survive for long periods of time. At about 20 °C *Giardia* cysts survive for 24 days, and *Cryptosporidium* oocysts remain viable longer than 6 months. However, thermal death points of parasites vary considerably, ranging from 40 to 100 °C depending upon the length of exposure and the life cycle stage. Although endogenous stages rarely survive temperatures above 40–45 °C, exogenous stages have adapted to wide temperature fluctuations. Eggs of *Echinococcus granulosus*, for example, can withstand temperatures ranging from −50 to 70 °C, but are killed at −70 °C or when heated to 100 °C for at least 1 min (Eckert et al., 2001). Coccidia oocysts require moderate temperatures for development to the infective stage to occur, and some species survive 80 °C for 1 h. Trophozites of *Giardia* spp. do not withstand temperature fluctuations as well as the cyst stage. The latter has a thermal death point of 60–70 °C, and remains viable at 37 °C for 4 days, and at 4–8 °C for longer than 77 days (Robertson, 1995). A similar thermal death point has been established for microsporidian spores and cysts of amoebae. Oocysts and eggs perish at high temperatures. Thus in hot arid regions where water is scarce and parasites in the environment die rapidly, large waterborne outbreaks are unlikely to occur.

Exogenous stages of many species of parasites survive freezing temperatures and are capable of overwintering, but are often susceptible to freeze–thaw cycles. Exceptions include the cyst stages of *Giardia* and *Acanthamoeba* which can survive several freeze thaw cycles lasting up to 14 days. Otherwise, many parasites are able to survive extremely low temperatures as evidenced by the ultra-low cryopreservation procedures successfully used in research laboratories working with waterborne parasites.

In addition to extreme temperatures, desiccation and irradiation adversely affect parasites in the environment. Both sporulation and survival of coccidia oocysts are drastically reduced at low relative humidity (RH). *Eimeria tenella* oocysts survived for 52 days at 90% RH, but survival time was reduced to 32 days when the RH was 61% (Farr and Wehr, 1949). Similarly, eggs of *Echinococcus multilocularis* survived for 478 days at 95% RH and 4 °C, but only for 24 h at 27% RH and 25 °C (Veit et al., 1995). Microsporidia remained viable after extended periods of desiccation at ambient temperatures (see Didier et al., 2004).

Irradiation from natural or artificial sources is also harmful to these exogenous stages. Irradiation from direct sunlight kills oocysts of *Eimeria zuernii*, the cause of winter coccidiosis in cattle (Marquardt et al., 1960). When exposed to direct sunlight, both sporulated and unsporulated oocysts are killed in 4 or 8 h, respectively. Gamma- and ultraviolet-irradiation also can be particularly lethal to many parasites (see Fayer, 2004; Quintero-Betancourt and Rose, 2004), and have been used as an effective treatment for controlling waterborne cysts, spores, oocysts and eggs of *Giardia*, *Acanthamoeba*, *Encephalitozoon*, *Cryptosporidium*, *Toxoplasma* and *Echinococcus*.

3.3. Resistance to chemicals

Although the increasing levels of chemical pollution in water systems adversely affect many aquatic host species, there is no report of effects on the viability of waterborne parasites. Reasons for this may include the protection provided by the formidable outer casings of their exogenous stages and the lack of adequate studies in this area. Nevertheless, it is well known that the exogenous stages of parasites, unlike most other pathogens, are notoriously resistant to many chemicals. The types and levels of concentrations of chemicals routinely used as disinfectants in water-treatment plants, swimming pools, hospitals and other institutions do not kill transmission stages of many waterborne parasites. For example, standard concentrations of chlorine used in drinking water are inadequate to control oocysts of *Cryptosporidium*, *Toxoplasma* and other coccidia (see Dubey, 2004; Fayer, 2004). In fact, full strength bleach is used to remove contaminating microorganisms from cultures of coccidian oocysts, prior to in vitro cultivation. Similarly, a solution of 2% sulfuric acid or 2.5% potassium dichromate is used to inhibit bacterial and fungal growth in cultures of oocysts. Eggs of nematodes, such as ascarids, remain viable in a variety of chemicals including 10% formalin and copper sulfate, and microsporidian spores survive for at least 5 min in 70% ethanol, 0.1N HCl or 0.1N NaOH (Santillana-Hayat et al., 2002). However, despite the chemical resistance of many parasites, water-treatment regimens can be devised and used as an effective tool in the control of several waterborne parasites (Quintero-Betancourt and Rose, 2004).

3.4. Biomagnification and dispersal

Transmission of waterborne parasites may be enhanced by the use of transport hosts which collect and concentrate resistant exogenous stages. The gills of filter-feeding freshwater and marine oysters, clams, mussels and cockles have been found to accumulate significant numbers of oocysts of zoonotic species of *Cryptosporidium* (see Fayer, 2004), and *Giardia duodenalis* cysts have similarly been found in molluscan shellfish (see Thompson, 2004). It has also been suggested that *T. gondii* in aquatic invertebrates is responsible for outbreaks of toxoplasmosis in marine mammals (Gajadhar et al., 2004).

Wide-range distribution of *Cryptosporidium* oocysts may be facilitated by migrating waterfowl, acting as (uninfected) transport hosts. Gulls, ducks and geese have all been suggested to be capable of this (Fayer et al., 2000). In some cases, parasites themselves can serve as transport hosts for other pathogens. For example, the cysts of free-living *Acanthamoeba* sp. have been shown to harbour *Legionella* and *Mycobacterium*, providing them with an environmentally resistant mode of transport to susceptible hosts (see Schuster and Visvesvara, 2004).

4. Global warming and climate change

Few events have the potential to trigger significant widespread natural and socioeconomic shifts as do global warming and climate change. Although in the last two decades changing climate patterns and increases in temperatures have been experienced around the world, there is little or no agreement on the significance of this ''global warming''. Nevertheless, it is generally agreed that ''greenhouse gasses'' such as carbon dioxide, methane, ozone, and nitrous oxide are deleterious to the environment. Furthermore, there is international acceptance of computer generated predictions that, without reductions in production of these gasses, the mean global temperature will rise 1.4–5.8 °C, droughts, floods and run-offs will increase in frequency, and the sea level will rise 11–77 cm by the year 2100 (Arnell, 1996; IPCC, 2001).

It seems clear that unless addressed, climate change and global warming will result in changes in aquatic environments. Some such changes may have already occurred, but they are difficult to recognize over a short period of time. There is some evidence that terrestrial invertebrate intermediate hosts such as mosquitoes and ticks have moved into areas that have previously been too cool for their survival (Rogers and Randolph, 2002; Sutherst, 1993). Many invertebrate species serve as biological or transport hosts for agents of serious infectious diseases, and their presence in new areas represents the potential for increased spread of pathogens. Likewise, the expansion of suitable habitats for invertebrate hosts of waterborne parasites could result in increased distribution and risk of waterborne infections in humans and animals. For example, climatic changes are likely to affect the known geographical distribution of fresh water snails, such as *Biomphalaria* spp., the invertebrate hosts of *Schistosoma* spp. transmissible to humans, livestock and other animals (Morgan et al., 2001). The distribution of many other trematodes, including the liver and lung parasites *Fasciola*, *Clonorchis* and *Opisthorchis* could be similarly affected by climatic changes.

5. Impact of modernization and globalization

Good public health and sound economic development rely on the availability of clean fresh water. Supplies of potable water are not evenly distributed around the world, and technological modernization, globalization, and commercialization have significantly impacted its quality and patterns of consumption. Modern technologies have been developed and applied to produce clean water to sustain activities and developments in regions where potable water was previously unavailable or of questionable quality. Protecting this accomplishment requires constant vigilance to mitigate risks resulting from the high international traffic of people and goods from endemic areas.

Disposal of manure from large feedlots and mega-barns, and the need to rid increasing amounts of human sewage from growing urban centres, have contributed to concerns about the high risks of disease outbreaks caused by waterborne parasites and other pathogens. *Cryptosporidium* originating from human and animal effluent has been the cause of serious disease outbreaks in large populated areas (Milwaukee, USA). In the massive outbreak of cryptosporidiosis in MacKenzie et al. (1994), oocysts from Lake Michigan water entered a water-treatment plant and it was originally suggested that heavy rains and cattle manure on fields in the watershed might have explained the source of infection. Oocysts subsequently derived from the outbreak were instead shown to be of human origin (Genotype 1). However, in other human outbreaks Genotype 2, capable of infecting both cattle and human hosts were identified. These latter outbreaks occurred in Maine, Pennsylvania and British Columbia (Peng et al., 1997).

In many temperate regions most of the fresh fruits and vegetables consumed are imported to satisfy demands of growing urban populations. Modern agricultural practices, increased global trade, and rapid forms of transportation facilitate the transmission of various parasites from developing regions to urban areas. Sewage-contaminated water used for agricultural irrigation has been known to contain transmissible forms of *Taenia*, microsporidia, *Cyclospora*, *Toxoplasma*, *Cryptosporidium* and *Giardia*. Oocysts of *Cryptosporidium* and *Cyclospora* were found on vegetables from markets in an endemic region of Peru (Ortega et al., 1997), and several North American outbreaks of cyclosporosis were associated with the importation of contaminated fresh imported raspberries (Herwaldt and Beach, 1999; see Mansfield and Gajadhar, 2004). An epidemic of human ascariasis has been associated with imported vegetables contaminated with *Ascaris* eggs (Raisanen et al., 1985). Also, various samples of fruit and vegetables in Norway have been shown to be contaminated with *Giardia* and *Cryptosporidium* (Robertson and Gjerde, 2001).

Although modern water-treatment technology is capable of preventing the transmission of many waterborne parasites (see Quintero-Betancourt and Rose, 2004), new approaches and methods are not available globally, nor can they be effectively applied in all locations because of prohibitive costs, and lack of regulations or adequate enforcement. Test methods and quality systems have been developed to monitor waterborne parasites (see Bellamy, 2004; Zarlenga and Trout, 2004). However, the recent trend to privatize urban water services, including monitoring and treatment, has increased public costs and made the maintenance of water quality more difficult. For example, following full-scale privatization in two European jurisdictions, the responsibilities for maintenance of water quality, public health and security of water supply and environmental issues became unclear and ambiguous (Johnson and Handmer, 2002).

A huge billion dollar industry has developed in providing bottled drinking water which has been successfully marketed as a pure and safe product for human consumption. However, the adequacy of regulations governing the quality and enforcement of standards of bottled water vary, depending on the country of origin (Warburton et al., 1992; Bharath et al., 2003). Although consumers may experience safe bottled water produced in developed countries, they may well be exposed to severe health risks when using water bottled in developing regions. Studies have revealed evidence of protozoa (Rivera et al., 1981) and other pathogens in water bottled in developing countries. Ironically, many victims of waterborne infectious disease outbreaks in developing countries are foreign tourists or the wealthy who consume bottled water to avoid waterborne pathogens.

6. Accidental and orchestrated outbreaks

The large volumes of water processed in modern treatment plants, and the systems used for distribution create increased risk of large-scale waterborne disease outbreaks. Many large urban centres are served by a single water system with few or no measures in place to detect and prevent contamination accidents. A systematic qualitative analysis of possible *Cryptosporidium* outbreaks has indicated that in industrialized countries, given the necessary economic support and political will, adequate control of outbreaks is likely to occur. In less industrialized countries, however, the risk of epidemics could be much higher, depending again on the interplay of economics, politics and technology (Casman et al., 2001).

A common cause of waterborne outbreaks in developed regions is the accidental contamination of water supplies with human sewage, due to system failure or human error. This was the case in Milwaukee, USA, and in North Battleford, Canada (MacKenzie et al., 1994; Stirling et al., 2001). Although effluents from farms are often blamed as the contaminating source for waterborne outbreaks of parasitic diseases, this has been shown to be the likely source of infection in relatively few cases (Peng et al., 1997). Most parasites found in the feces of livestock are not infective for humans. However, some are zoonotic, and are capable of causing epidemics in humans or animals.

In the present era, with concerns regarding homeland security, deliberate contamination of water supplies could have serious socioeconomic and political impacts, as well as public health consequences. However, despite many publicized threats to sabotage municipal water supplies, there is no evidence that this has occurred. The US Centers for Disease Control and Prevention has categorized biological agents according to their ease of dissemination, severity of disease caused, and requirements for diagnosis and control. Several waterborne zoonotic parasites, including *Cryptosporidium*, *Giardia*, *Toxoplasma*, and *Cyclospora* are ranked in the second highest category of biological agents capable of causing serious epidemics in human or animal populations. Water supplies could be intentionally contaminated at reservoirs, treatment plants, water distribution systems, or in containers. The standard safeguards used in developed regions to address the presence of all microorganisms in water supplies include disinfection, sedimentation, filtration, dilution, and non-specific inactivation such as sunlight. Although these measures may be sufficient to protect humans against most waterborne infectious agents, they have little or no effect on many of the protozoa and other parasites transmitted via water. Well recognized examples of resistant parasites include *Giardia* and *Cryptosporidium*, but exotic or emerging waterborne parasites such as *Cyclospora*, *Toxoplasma*, *Blastocystis*, *Balamuthia*, microsporidia, helminths, and unknown others should also be considered as serious potential threats to consumers (see Didier et al., 2004; Dubey, 2004; Mansfield and Gajadhar, 2004; Nithiuthai et al., 2004; Schuster and Visvesvara, 2004; Tan, 2004). Some waterborne parasites such as *Acanthamoeba*, *Naegleria*, and *Schistosoma*, establish infection by invading the eye or nasal passage, or by skin penetration (see Nithiuthai et al., 2004; Schuster and Visvesvara, 2004). These often result in life-threatening illnesses which are difficult to diagnose and treat.

7. Concluding remarks

With some exceptions, parasites have been unrecognized or ignored in the developed world, as a serious threat to public health, agriculture and the economy. However, the growing influence of previously non-existent factors such as globalization, climate change, and modern technology has dramatically increased concerns about waterborne disease outbreaks caused by parasites. The large increase in the numbers of people immunocompromized by AIDS or cancer therapies and of people travelling to endemic areas of the world increases the likelihood of disease outbreaks. As well, many exotic or emerging parasites are appearing in new areas, and indigenous infectious disease agents are being widely and readily distributed by modern water distribution systems to satisfy increasing populations and economic growth.

The ability of many parasites to survive for long periods of time in the environment and resist many natural and artificial conditions make them some of the most difficult agents of waterborne zoonotic diseases to control. The characteristics and zoonotic potential of these parasites require elucidation. Research is needed to detect and identify known and unknown zoonotic parasites occurring globally or in defined areas. It is also necessary to determine the basic biology of these organisms, and to develop practical methods for control and treatment. In today's world, infectious disease agents such as waterborne zoonotic parasites are not restricted by geography or economy, and have become a significant global threat.

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References

Arnell, N., 1996. Global Warming, River Flows and Water Resources. Wiley, New York, 224 pp.

Baker, M.N., 1981. The Quest for Pure Water, 2nd ed. American Water Works Association.

Bellamy, J.E.C., 2004. Quality assurance considerations for detection of waterborne zoonotic parasites using *Cryptosporidium* oocyst detection as the main example. Vet. Parasitol. 126, 235–248.

Bharath, J., Mosodeen, M., Motilal, S., Sandy, S., Sharma, S., Tessaro, T., Thomas, K., Umamaheswaran, M., Simeon, D., Adesiyun, A.A., 2003. Microbial quality of domestic and imported brands of bottled water in Trinidad. Int. J. Food Microbiol. 81, 53–62.

Casman, E., Fischhoff, B., Small, M., Dowlatabadi, H., Rose, J., Morgan, M.G., 2001. Climate change and cryptosporidiosis: a qualitative analysis. Clim. Change 50, 219–249.

Didier, E.S., Stoval, M.E., Green, L.C., Brindley, P.J., Sestak, K., Didier, P.J., 2004. Epidemiology of microsporidiosis: sources and modes of transmission. Vet. Parasitol. 126, 145–166.

Dubey, J.P., 2004. Toxoplasmosis — a waterborne zoonosis. Vet. Parasitol. 126, 57–71.

Eckert, J., Gottstein, B., Heath, D., Liu, F.J., 2001. Prevention of echinococcosis in humans and safety precautions. WHO-OIE Manual on Echinococcosis in Humans and Animals: A Public Health Problem of Global Concern, OIE, Paris, pp. 238–247.

Farr, M.M., Wehr, E.E., 1949. Survival of *Eimeria acervulina*, *E. tenella* and *E. maxima* oocysts on soil and under various conditions. Ann. NY Acad. Sci. 52, 468–472.

Fayer, R., 2004. *Cryptosporidium*: a waterborne zoonotic parasite. Vet. Parasitol. 126, 37–56.

Fayer, R., Morgan, U., Upton, S.J., 2000. Epidemiology of *Cryptosporidium*: transmission, detection and identification. Int. J. Parasitol. 30, 1305–1322.

Gajadhar, A.A., Measures, L., Forbes, L.B., Kapel, C., Dubey, J.P., 2004. Experimental *Toxoplasma gondii* infections in grey seals (*Halichoerus grypus*). J. Parasitol..

Herwaldt, B.L., Beach, M.J., 1999. The return of *Cyclospora* in 1997: another outbreak of cyclosporiasis in North America associated with imported raspberries. Cyclospora Working Group. Ann. Int. Med. 130, 210–220.

IPCC (Intergovernmental Panel on Climate Change), 2001. In: McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (Eds.), Climate Change 2001: Impacts, Adaptation and Vulnerability — Contributions of Working Group II to the IPCC Third Assessment Report. IPCC Secretariat, Geneva.

Johnson, C., Handmer, J., 2002. Water supply in England and Wales: whose responsibility is it when things go wrong? Water Policy 4, 345–366.

MacKenzie, W.R., Hoxie, N.J., Proctor, M.E., Gradus, M.S., Blair, K.A., Peterson, D.E., Kazmierczak, J.J., Addis, D.G., Fox, K.R., Rose, J.B., Davis, J.P., 1994. A massive outbreak in Milwaukee of *Cryptosporidium* infection transmitted through the water supply. New Engl. J. Med. 331, 161–167.

Mansfield, L.S., Gajadhar, A.A., 2004. *Cyclospora cayetanensis*, a food- and waterborne coccidian parasite. Vet. Parasitol. 126, 73–90.

Marquardt, W.C., Senger, C.M., Seghetti, L., 1960. The effect of physical and chemical agents on the oocysts of *Eimeria zuernii* (Protozoa, Coccidia). J. Protozool. 7, 186–189.

Morgan, J.A.T., DeJong, R.J., Snyder, S.D., Mkoji, G.M., Loker, E.S., 2001. *Schistosoma mansoni* and *Biomphlaria*: past history and future trends. Parasitology 123, S211–S228.

Nithiuthai, S., Anantaphruti, M., Waikagul, J., Gajadhar, A., 2004. Waterborne zoonotic helminthiases. Vet. Parasitol. 126, 167–193.

Ortega, Y.R., Roxas, C.R., Gilman, R.H., Miller, N.J., Cabrera, L., Taquiri, C., Sterling, C.R., 1997. Isolation of *Cryptosporidium parvum* and *Cyclospora cayetanensis* from vegetables collected in markets of and endemic region of Peru. Am. J. Trop. Med. Hyg. 57, 683–686.

Peng, M.M., Xiao, L., Freeman, A.R., Arrowood, M.J., Escalante, A.A., Weltman, A.C., Ong, C.S.L., MacKenzie, W.R., Lal, A.A., Beard, C.B., 1997. Genetic polymorphism among *Cryptosporidium parvum* isolates: evidence of two distinct human transmission cycles. Emerg. Inf. Dis. 3, 567–573.

Quintero-Betancourt, W., Rose, J.B., 2004. Drinking water processes for removal of *Cryptosporidium* and *Giardia*. Vet. Parasitol. 126, 219–234.

Raisanen, S., Ruuskanen, L., Nyman, S., 1985. Epidemic ascariasis — evidence of transmission by imported vegetables. Scand. J. Prim. Health Care 3, 189–191.

Rivera, F., Galvan, M., Robles, E., Leal, P., Gonzalez, L., Lacy, A.M., 1981. Bottled water polluted by protozoa in Mexico. J. Protozool. 28, 54–56.

Robertson, L.J., 1995. Viability of *Giardia* cysts and *Cryptosporidium* oocysts. In: Betts, W.B. (Ed.), Protozoan Parasites and Water. Royal Society of Chemistry, Cambridge, pp. 97–103.

Robertson, L.J., Gjerde, B., 2001. Occurrence of parasites on fruit and vegetables in Norway. J. Food Protect. 64, 1793–1798.

Rogers, D.J., Randolph, S.E., 2002. The global spread of malaria in a future warmer world. Science 289, 1763–1765.

Santillana-Hayat, M., Sarfati, C., Fournier, S., Chau, F., Porcher, R., Molina, J.-M., Derouin, F., 2002. Effects of chemical and physical agents on viability and infectivity of *Encephalitozoon intestinalis* determined by cell culture and flow cytometry. Antimicrob. Agents Chemother. 46 (6), 2049–2051.

Schuster, F.L., Visvesvara, G.S., 2004. Amoebae and ciliated protozoa as causal agents of waterborne zoonotic disease. Vet. Parasitol. 126, 91–120.

Stirling, R., Aramini, J., Ellis, A., Lim, G., Meyers, R., Fleury, M., Werker, D., 2001. Waterborne cryptosporidiosis outbreak. Canada Communicable Disease Report 29, No. 22. North Battleford, Saskatchewan, Spring, pp. 185–192.

Sutherst, R.W., 1993. Arthropods as disease vectors in a changing environment. Environmental Change and Human Health, Wiley, Chichester, pp. 124–145.

Tan, K.S., 2004. *Blastocystis* in humans and animals: new insights using modern day methodologies. Vet. Parasitol. 126, 121–144.

Thompson, R.C.A., 2004. The zoonotic significance and molecular epidemiology of *Giardia* and giardiasis. Vet. Parasitol. 126, 15–35.

Veit, P., Bilger, B., Schad, V., Schafer, J., Frank, W., Lucius, R., 1995. Influence of environmental factors on the infectivity of *Echinococcus multilocularis* eggs. Parasitology 110 (1), 79–86.
Warburton, D.W., Dodds, K.L., Burke, R., Johnson, M.A., Laffey, P.J., 1992. A review of the microbiological quality of bottled water sold in Canada between 1981 and 1989. Can. J. Microbiol. 38, 12–19.
Zarlenga, D.S., Trout, J.M., 2004. Concentrating, purifying and detecting parasites. Vet. Parasitol. 126, 195–217.