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Emerging food-borne parasites

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ABSTRACT

Parasitic food-borne diseases are generally underrecognised, however they are becoming more common. Globalization of the food supply, increased international travel, increase of the population of highly susceptible persons, change in culinary habits, but also improved diagnostic tools and communication are some factors associated with the increased diagnosis of food-borne parasitic diseases worldwide. This paper reviews the most important emerging food-borne parasites, with emphasis on transmission routes. In a first part, waterborne parasites transmitted by contaminated food such as *Cyclospora cayetanensis*, *Cryptosporidium* and *Giardia* are discussed. Also human fasciolosis, of which the importance has only been recognised in the last decades, with total numbers of reported cases increasing from less than 3000 to 17 million, is looked at. Furthermore, fasciolopsiosis, an intestinal trematode of humans and pigs belongs to the waterborne parasites as well. A few parasites that may be transmitted through faecal contamination of foods and that have received renewed attention, such as *Toxoplasma gondii*, or that are (re-)emerging, such as *Trypanosoma cruzi* and *Echinococcus* spp., are briefly reviewed. In a second part, meat-borne parasite infections are reviewed. Humans get infected by eating raw or undercooked meat infected with cyst stages of these parasites. Meat inspection is the principal method applied in the control of *Taenia* spp. and *Trichinella* spp. However, it is often not very sensitive, frequently not practised, and not done for *T. gondii* and *Sarcocystis* spp. Meat of reptiles, amphibians and fish can be infected with a variety of parasites, including trematodes (*Opisthorchis* spp., *Clonorchis sinensis*, minute intestinal flukes), cestodes (*Diphyllobothrium* spp., *Spirometra*), nematodes (*Gnathostoma*, spp., anisakine parasites), and pentastomids that can cause zoonotic infections in humans when consumed raw or not properly cooked. Another important zoonotic food-borne trematode is the lungfluke (*Paragonimus* spp.). Traditionally, these parasitic zoonoses are most common in Asia because of the particular food practices and the importance of aquaculture. However, some of these parasites may emerge in other continents through aquaculture and improved transportation and distribution systems. Because of inadequate systems for routine diagnosis and monitoring or reporting for many of the zoonotic parasites, the incidence of human disease and parasite occurrence in food is underestimated. Of particular concern in industrialised countries are the highly resistant waterborne protozoal infections as well as the increased travel and immigration, which increase the exposure to exotic diseases. The increased demand for animal proteins in developing countries will lead to an intensification of the production systems in which the risk of zoonotic infections needs to be assessed. Overall, there is an urgent need for better monitoring and control of food-borne parasites using new technologies.

1. Introduction

Food- and waterborne infections have received considerable attention in the last decade. Some of these

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Table 1
Most important foodborne parasites.

	Protozoa	Helminths	Arthropods
Meat borne	*Toxoplasma gondii* *Sarcocystis* spp.	*Trichinella* spp. *Taenia* spp.	
Reptile, amphibian borne		*Spirometra* spp. (sparganosis) *Gnathostoma* spp., *Diphyllobothrium* spp. *Alaria* spp.	Pentastomatidae
Fish borne		*Anisakis* spp. *Capillaria philippinensis* *Gnathostoma* spp. *Diphyllobothrium* spp. *Clonorchis sinensis* *Opisthorchis* spp. Minute intestinal flukes	
Arthropod borne	*Paragonimus* spp. *Macracanthorhynchus hirudinaceus*		
Mollusc borne	*Giardia* spp. *Cryptosporidium* spp.	*Angiostrongylus cantonensis* *Echinostoma* spp.	
Plant borne	*Giardia* spp. *Cryptosporidium* spp. *Cyclospora cayetanensis* *T. gondii* *Trypanosoma cruzi*	*Fasciola* spp. *Fasciolopsis buski* *Echinococcus granulosus* *Echinococcus multilocularis*	

infections are well recognized, but are considered emerging because they have recently become more common (WHO, 2002), or are more detected because of better diagnostic tools and improved communication. Predominantly bacterial infections, such as *Salmonella* serotype Enteritidis, *Escherichia coli* serotype O157:H7, *Campylobacter*, *Listeria monocytogenes*, *Mycobacterium bovis*, etc. have been associated with water- or food-borne infections, while parasitic infections have received less attention. Indeed, in the Community Summary Report on Trends and Sources of Zoonoses and Zoonotic Agents in the European Union in 2007 (EFSA, 2009), trichinellosis and echinococcosis are the only parasitic zoonoses considered, while infections such as taeniosis and toxoplasmosis are known to be common in the EU. However, experts of the Institute of Food Technologists, US, warn that parasites are a food safety concern that is generally underrecognised but is probably on the increase due to the globalization of the food supply. In the past, the risk of human infection with parasites was considered to be limited to distinct geographic regions because of parasites' adaptations to specific definitive hosts, select intermediate hosts and particular environmental conditions. These barriers are slowly being breached—first by international travel developing into a major industry, and second, by rapid, refrigerated food transport which became available to an unprecedented degree at the end of the 20th century (Orlandi et al., 2002). Other factors that may explain the emergence of some zoonotic parasitic diseases are the increase of the population of highly susceptible persons because of ageing, malnutrition, HIV infection and other underlying medical conditions; and changes in lifestyle, such as the increase in the number of people eating meals prepared in restaurants, canteens and fast food outlets as well as from street food vendors who do not always respect food safety, and the increase of eating raw or undercooked meats (WHO, 2002). Emerging zoonoses have been defined as zoonoses that are newly recognised or newly evolved, or that have occurred previously but show an increase in incidence or expansion in geographical, host or vector range (Report of the WHO/FAO/OIE Joint Consultation on Emerging Zoonotic Diseases, WHO, Geneva, May 3–5, 2004). It is estimated that 75% of emerging human pathogens are zoonotic (Woolhouse, 2002).

This paper reviews the most important emerging foodborne parasites (Table 1), with emphasis on transmission routes.

2. Waterborne parasites transmitted by contaminated food

Water is a major vehicle for many environmental stages of parasites. These stages can contaminate foodstuffs such as fruits, vegetables and shellfish. It is often difficult to associate an outbreak with a particular food item, and therefore, if the food-borne route is suspected, to identify how the food implicated became contaminated (Slifko et al., 2000). Because of these difficulties, the acquisition of parasitic infections via the food-borne route is almost certainly under-detected by a factor 10 or more (Casemore, 1990). Among emerging waterborne parasitic infections that may be acquired by food are *Cyclospora cayetanensis*, *Giardia*, *Cryptosporidium*, *Fasciola* and *Fasciolopsis*.

2.1. Cyclospora

Outbreaks of *C. cayetanensis*, a coccidian parasite, which can cause a watery diarrhoea, nausea and vomiting in humans, have been increasingly observed since the 1990s, especially in North America and Asia. Almost 1500 cases occurred in the United States (US) and Canada in 1996 associated with eating raspberries from Guatemala (Herwaldt and Ackers, 1997). A year later, over 100 laboratory confirmed cases occurred in 19 clusters throughout the US and Canada and on a cruise ship. Again, raspberries from Guatemala were implicated as the probable vehicle of infection for these clusters although preventive measures had been implemented (CDC, 1997). Other outbreaks are thought to have been spread through lettuce (CDC, 1997) or fresh basil (Hoge et al., 1995).

2.2. *Cryptosporidium* and *Giardia*

Cryptosporidium and *Giardia* are major causes of diarrhoeal disease in humans worldwide and are major causes of protozoan waterborne diseases (Smith et al., 2007). Extensive genetic diversity of these parasites has impacted their taxonomy, which is still a matter of debate. There is still uncertainty about host-specificity and zoonotic potential of isolates. Sixteen 'valid' *Cryptosporidium* species and a further 33 genotypes have been described, but only few are zoonotic. *Cryptosporidium parvum* is the major zoonotic *Cryptosporidium* species. With regard to *Giardia*, only two Assemblages (i.e., A and B) seem to be zoonotic, although recent findings suggest that zoonotic transmission occurs more rarely than previously believed (Monis et al., 2009). Life cycles of *Cryptosporidium* and *Giardia* are completed within a single host, with transmission by the faecal–oral route. The transmissive stages, *Cryptosporidium* oocysts or *Giardia* cysts, are produced in large numbers and are infectious when excreted. Both parasites have low infective doses, which make them particularly adapted for environmental infection: 9–1042 *C. parvum* oocysts (Okhuysen et al., 1999); 25–100 *Giardia* cysts (Rendtorff, 1954). In addition, the (oo)cysts are very resistant to environmental and water treatment stresses, which assists their dissemination, and have the potential to be transmitted from non-human to human hosts and vice versa, enhancing the reservoir of (oo)cysts markedly (Smith et al., 2007). Waterborne outbreaks as well as infections through handling animals, contact with children and through recreational waters have been reported. (Oo)cysts of these parasites may also contaminate soft fruits and salad vegetables and cause infections in humans by these routes (Vuong et al., 2007). (Oo)cysts of these parasites have also been found in shellfish, such as oysters and mussels that are often eaten raw (Smith et al., 2007; Schets et al., 2007). These shellfish are filter feeders that have been demonstrated to accumulate bacteria and viruses such as *Salmonella*, *Vibrio*, norovirus, and *Cryptosporidium* and *Giardia* from contaminated water (Schets et al., 2007). However, the actual public health threat posed by these parasites via these shellfish is unclear, largely because there is no evidence of infection transmission (Robertson, 2007).

2.3. Fasciolosis

Fasciolosis is primarily a parasitic infection affecting the livestock sector: economic losses caused by this parasite are estimated at more than US$2000 million annually (reviewed by Mc Manus and Dalton, 2006). Fasciolosis is caused by two species of liver fluke, *Fasciola hepatica* and *Fasciola gigantica*. *F. hepatica* has a cosmopolitan distribution due to its capacity to infect many different species and to the ability of the intermediate snail host to adapt to a wide range of ecological niches (Mas-Coma et al., 2005). *F. gigantica* has a more restricted distribution due to the reduced ability of the aquatic snail intermediate hosts to invade new niches and is generally found in tropical regions of Africa, South and East Asia and the Middle East. Human infection is always associated with local endemic animal fasciolosis, although the distribution of human infection and level of prevalence may not always correlate with that observed in animals (Mas-Coma, 2004; Mas-Coma et al., 1999a, 2005). Infection is usually acquired by the ingestion of various freshwater aquatic plants, such as watercress, on which the metacercariae have settled. Farm management practices and the culturing of edible aquatic plants in greenhouses has limited the extent of human infection in industrialized regions, but in some developing countries wild aquatic plants or plants grown in fields where infected animals can freely roam form a regular part of the daily diet. Metacercariae can also be found floating in water and, therefore, infection can be acquired through drinking water (Mas-Coma, 2004). The importance of human fasciolosis has only been recognised in the last decades. Prior to 1992 total reported cases of human fasciolosis was estimated to be less than 3000, but more recent studies provide figures of 2.4 million (Rim et al., 1994; Curtale et al., 2005) and 17 million (Hopkins, 1992). Clinical signs of fasciolosis are caused by the migration of the young flukes through the liver causing abdominal pain, indigestion, weight loss, mild fever and malaise. Aberrant migrations of *Fasciola* can also occur (Le et al., 2007). While the actual situation remains unclear it is certain that, due to the increased number of surveys carried out with better diagnostic assays, human fasciolosis is highly prevalent in certain regions of the world. Countries where fasciolosis is emerging as a major plant-borne disease include the high altitude Andean rural regions of Bolivia and Peru (Mas-Coma et al., 1999b), the Northern provinces of Iran bordering the Caspian sea (Rokni et al., 2002; Moghaddam et al., 2004), the Nile Delta region of Egypt (Esteban et al., 2003) and the Central provinces of Vietnam (De et al., 2003). Most human cases have been attributed to *F. hepatica* (Mas-Coma et al., 1999a), however, most Vietnamese cases have been ascribed to *F. gigantica* (De et al., 2003). Human fasciolosis is likely to be underreported in Asia, since the lack of farm management, the sharing of water sources by animals and humans and the similar likelihood of contamination of edible aquatic plants and rice with infective fluke metacercariae to that observed in other regions where fasciolosis is an important zoonosis.

2.4. *Fasciolopsis*

Fasciolopsis buski is an intestinal trematode of humans and pigs that is acquired by consumption or handling of aquatic plants, such as water chestnut, water hyacinth, water morning glory, etc. on which metacercariae have attached, or by drinking or using untreated water. Human infection takes place when peeling off the hull or skin of infected plants between the teeth. Pigs are the only important animal reservoir, although they harbour few flukes. Fasciolopsiosis occurs focally, is widespread, linked to freshwater habitats with stagnant or slow moving waters, and is associated with common social and agricultural practices and promiscuous defaecation. Endemic areas are remote rural places and semi-urban areas in SE Asian countries, China, Bangladesh, etc. Morbidity in endemic areas is high, and the disease can be fatal. Worms cause extensive intestinal and duodenal erosions, ulceration, haemorrhage, abscesses and catarrhal inflammation (Mas-Coma et al., 2005).

3. Parasites transmitted by faecal contamination of food and drinks

Infective stages of parasites shed in the environment with faeces can contaminate foodstuffs such as vegetables, fruits of fruit juices. Although the list of parasites transmitted through this route is exhaustive, in this review only a few parasites that have recently gained interest will be discussed.

Human infection with *Toxoplasma gondii*, a cosmopolitan zoonotic protozoan parasite, can be contracted by the oral ingestion of oocysts present in cat faeces and the environment, or tissue cysts present in the meat of infected animals. This parasite will be discussed in the chapter on meat-borne parasite infections.

3.1. *Trypanosoma cruzi*

An unusual parasite in this list of food-borne parasitic zoonoses is *T. cruzi*, the causative agent of Chagas disease, one of the most important parasitic diseases of the Americas. *T. cruzi* is commonly transmitted to humans and other mammals by blood-sucking Triatominae that live in cracks, crevices and roofs of poor quality dwellings, mostly in poor rural areas. Other ways of transmission are blood transfusion, organ transplantation and congenital infection. The existence of animal reservoirs complicates control; dogs are increasingly recognized as important animal reservoirs of the infection (Hotez et al., 2008). A number of recent outbreaks in Brazil and Venezuela suggest that this parasite may also be transmitted through oral infection via fruit juices, contaminated with faeces from infected bugs. These findings are of particular interest as outbreaks may occur through this route in non-endemic regions, such as (peri-)urban areas (Rodriguez-Morales, 2008). Chagas disease is mainly a chronic problem; the symptoms are usually mild in the early stage of infection but serious symptoms may appear in the chronic phase, such as heart disease and malformation of the intestines. If untreated, the chronic disease is often fatal. Current drug treatments are generally unsatisfactory; available medications are highly toxic and often ineffective, particularly those used to treat the chronic stage of the disease (Viotti et al., 2009). The major approaches for controlling Chagas disease include improved case management and vector control programmes, together with housing improvement (Hotez et al., 2008).

3.2. *Echinococcus*

Echinococcosis in humans occurs as a result of infection by the larval stages of taeniid cestodes of the genus *Echinococcus*. The infection is acquired through accidental ingestion of parasite eggs shed by a carnivore final host. These eggs may contaminate fruits and vegetables resulting in a food-borne infection. Six species have been recognized, of which four are of public health concern: *Echinococcus granulosus* (cause of cystic echinococcosis), *Echinococcus multilocularis* (cause of alveolar echinococcosis), and *Echinococcus oligarthus* and *Echinococcus vogeli* (causes of polycystic echinococcosis). Several studies have shown that these diseases are an increasing public health concern (Moro and Schantz, 2009).

3.2.1. *E. granulosus*

The life cycle of *E. granulosus* involves domestic dogs and other canids as definite hosts and domestic and wild ungulates as intermediate hosts. Humans are accidental intermediate hosts. Ten genotypes of *E. granulosus* exist, which can be differentiated by molecular methods using mitochondrial DNA sequences, and which have different host affinities. The sheep G1 strain is the most cosmopolitan genotype and is most commonly associated with human infections (Mc Manus and Thompson, 2003). In humans the liver is the most common site for hydatid cyst development, followed by lungs. Other locations are the spleen, kidneys, heart, bone and central nervous system. Cysts grow slowly, between 1 and 5 cm in diameter per year, and it may take many years before clinical symptoms appear, usually as the result of dysfunction of the organ in which the cyst develops. If a cysts ruptures, the sudden release of its contents can precipitate allergic reactions ranging from mild to fatal anaphylaxis (Moro and Schantz, 2009). Diagnosis is made by combining anamnesis, radiological imaging and immunodiagnostic techniques (Moro et al., 2005). Treatment is often cumbersome and involves surgical removal of cysts, chemotherapy with benzimidazoles and percutaneous aspiration, injection and re-aspiration (PAIR) (Pawlowski et al., 2001). There are several options for control and a number of eradication programmes, mostly on islands (Iceland, New Zealand, Tasmania), have been very successful (Moro and Schantz, 2009). Control of stray dog populations, treatment of dogs with cestodicidal drugs, prohibition of home slaughter of sheep and correct slaughter practices and disposal of infected organs, supported by health education programmes, are effective ways to break the life cycle. Most promising is the development of vaccines for sheep and dogs (Heath et al., 2003). Mathematical modeling has shown that the most effective intervention against echinococcosis is a combination of sheep vaccination and dog anthelmintic treatment (Torgerson, 2006). Unfortunately, in most endemic areas, effective control has not yet been achieved or even attempted, and cessation of control programmes may lead to re-emergence as is seen in Peru and central Asian states (Moro and Schantz, 2009).

3.2.2. E. multilocularis

A parasite that has received increasing attention is *E. multilocularis*, the causative agent of alveolar echinococcosis, a life-threatening zoonosis. The life cycle involves foxes and other wild carnivores, the final hosts, and rodents, the natural intermediate hosts. Domestic dogs, and to a lesser extent cats may also act as final hosts when they eat infected wild rodents (Eckert and Deplazes, 2004). Eggs of *E. multilocularis*, shed with the faeces by infected carnivores may contaminate the fur, wild fruits and vegetables. Humans may acquire infection by accidentally ingesting eggs while manipulating furs or live animals and by eating contaminated food (Moro and Schantz, 2009). There is evidence that the parasite is spreading from endemic to previously non-endemic areas in North America, Europe and Japan, mainly as a result of increase and movement of fox populations. In addition, fox and coyote populations have increasingly encroached upon suburban and urban areas of many regions. Although the long asymptomatic period of alveolar echinococcosis makes identification of infection trends difficult to assess, an increase of times 2.6 of the annual incidence has been estimated in endemic areas in Europe in the last years (Schweiger, 2007). In intermediate hosts, including humans, the metacestode form of *E. multilocularis* establishes in the liver where it proliferates by exogenous budding and invades the surrounding tissues, behaving like a tumour (Eckert and Deplazes, 2004). Because of the slow development, alveolar echinococcosis typically becomes symptomatic in persons of advanced age. Diagnosis is made by radiological techniques, supported by serological analysis and exploratory laparatomy. Treatment is problematic and is done by surgical resection of the entire larval mass, followed by long-term treatment with benzimidazoles (Wilson et al., 1992). Prevention in humans mainly relies on education and awareness campaigns and on monthly treatment with praziquantel of dogs and cats that are at risk for infection. Elimination of *E. multilocularis* from its wild animal hosts is impractical (Moro and Schantz, 2009).

4. Meat-borne parasite infections

Among the major food-borne parasites are *T. gondii*, *Sarcocystis* spp., *Taenia* spp. and *Trichinella* spp. Humans get infected by eating raw or undercooked meat infected with cyst stages of these parasites. In most countries measures are taken to prevent humans from becoming infected with meat-borne helminths by inspecting the meat in the slaughterhouse or laboratory. For toxoplasmosis and sarcocystosis no specific meat inspection is done. Meat inspection for cysticercosis has a low sensitivity, resulting in a high number of infected carcasses entering the food chain. In addition, in developing countries a large proportion of the carcasses escape meat inspection because it is not practised or because the animals are not slaughtered in abattoirs. Cooking is effective in killing the parasites if the appropriate temperature is reached in the core of the meat product. Freezing and other meat processing techniques such as drying, smoking, curing etc. are other effective ways to reduce the risk of infection by consuming contaminated meat, except for some species of *Trichinella*, which show remarkable resistance.

4.1. T. gondii

Toxoplasmosis, caused by the protozoan parasite *T. gondii* is still seen as a neglected and underreported disease, despite having a disease burden similar to that of salmonellosis and campylobacteriosis (Kijlstra and Jongert, 2009). This zoonotic parasite, transmitted to humans by accidental ingestion of sporulated oocysts shed with the faeces by felidae, or by eating raw or undercooked meat contaminated with tissue cysts, is ubiquitous throughout the world. In Western and Asian countries the consumption of undercooked meat is the most likely source of infection (Cook et al., 2000; Fallah et al., 2008; Han et al., 2008) with major public health impact (Kijlstra and Jongert, 2009). Indirect evidence comes from the observation that *T. gondii* seroprevalence is lower in strict vegetarians (Hall et al., 1999; Roghmann et al., 1999). However, the eating of unwashed raw vegetables or fruit is identified as an important risk factor in most epidemiological studies (Antoniou et al., 2007; Cavalcante et al., 2006; Fallah et al., 2008; Liu et al., 2009). Toxoplasmosis is generally considered a serious health problem in pregnant women, who can pass the infection to the foetus or newborn, and in immuno-compromised people. In adult immunocompetent persons the infection is usually subclinical. However, recent studies show that most cases of ocular toxoplasmosis are attributed to acquired disease, which means that prevention should be directed not only to pregnant women and immuno-compromised persons, but also towards the general population (Kijlstra and Jongert, 2009). Many animals used for meat production show evidence of *T. gondii* infection as measured by serum antibody response. Viable parasites have been isolated from the meat of game, sheep, goat, horse, chicken and pig, but not from beef (Tenter et al., 2000). Indoor farming has markedly reduced the seroprevalence of *T. gondii* in pigs, which is estimated at around 6% (EFSA, 2009). A nationwide survey of *T. gondii* in meat obtained from retail meat stores in the US showed a prevalence of only 0.38% in pork (Dubey et al., 2005). However, a re-emergence of toxoplasmosis is observed in pigs raised in organic farms with outdoor access (Kijlstra et al., 2004). Heating and freezing meat are the most efficient ways to kill *T. gondii* tissue cysts. However, interventions to prevent the introduction of *Toxoplasma*-infected meat into the food chain would be technically feasible in countries where the meat chain is well organised. Monitoring of farms and adjustment of farm management can play an important part in the control of *Toxoplasma* infection (Kijlstra and Jongert, 2009).

4.2. Taenia spp.

Taenia saginata, *T. saginata asiatica* and *T. solium* are taeniid tapeworms of humans. The terms cysticercosis and taeniosis refer to food-borne zoonotic infections with larval and adult tapeworms, respectively. Their life cycles depend on the link between humans and cattle (*T. saginata*) or pigs (*T. saginata asiatica* and *T. solium*) (Flisser et al., 2005). Humans acquire an intestinal tapeworm by eating raw or undercooked meat infected with cysticerci.

Among these tapeworms, *T. solium* is unique because the cysticercus stage can also infect humans and cause cysticercosis. In humans cysticerci may lodge in the brain and cause neurocysticercosis, one of the most important causes of acquired epilepsy in endemic areas (García et al., 2003). Human cysticercosis is not acquired by eating meat but through accidental ingestion of eggs shed with the stools by a tapeworm carrier. Infection by *T. solium* is eradicated in most industrialised countries, mainly due to general socio-economic development and intensification of pig husbandry systems. It is still present in tropical countries where pigs are raised and pork is consumed. It is associated with poverty and poor hygiene, allowing pigs to have access to human faeces. Increased immigration and travelling have made this parasitic infection an important import disease. Such introduced infections account for an increased global distribution to non-endemic regions, such as the US (Sorvillo et al., 2007). It has been estimated that millions of persons worldwide are infected with *T. solium*, mainly in Latin America, South and South-East Asia and Sub-Saharan Africa. In Africa, the rapid expansion of smallholder pig production has led to a significant increase of cysticercosis in pigs and humans (Phiri et al., 2003). Control of *T. solium* is based on health education, improvement of sanitation and pig husbandry systems, meat inspection and mass treatment of humans. Novel approaches include single dose treatment with oxfendazole of pigs and vaccination of pigs with recombinant antigens (Gonzales et al., 1996; Lightowlers et al., 2000). Both methods are promising but need to be validated in the field.

T. saginata is a cosmopolitan parasite. The beef tapeworm is found in industrialised countries as well as in developing countries. Cysticerci do not resist high temperatures and dietary habits and culinary practices affect transmission. Taeniosis is more common in populations/age groups that consume raw or undercooked beef (Murrell, 2005). The parasite is of less clinical importance than *T. solium* because it causes only taeniosis and not cysticercosis in humans. Intestinal taeniosis may be associated with abdominal discomfort, nausea, weight loss and anal pruritis, but very occasionally more severe symptoms, such as intestinal perforation and peritonitis have been observed (Jongwutiwes et al., 2004). However, bovine cysticercosis can inflict serious economic losses to the cattle industry (Yoder et al., 1994; Giesecke, 1997). These are mainly due to condemnation, refrigeration and downgrading of infected carcasses. The prevalence of human taeniosis is unknown in most countries. The incidence may be estimated from the sales of taenicidal drugs. In Western countries prevalence rates between 0.01% and 10% have been reported (Cabaret et al., 2002). In Eastern African countries like Ethiopia up to 70% of the population reports to have been infected with a tapeworm (Kebede et al., 2009). Prevalence data on bovine cysticercosis usually come from meat inspection results. The prevalence of bovine cysticercosis in Europe ranges from 0.007% to 6.8% with a wide variation between countries, regions and slaughterhouses (Cabaret et al., 2002). This prevalence is higher in Eastern African countries (Kebede et al., 2009). Many studies report on the low sensitivity of meat inspection, resulting in an underestimation of the prevalence of bovine cysticercosis by a factor 3–10 (Geerts et al., 1981; Kyvsgaard et al., 1990; Dorny et al., 2000). This partly explains the persistence of *T. saginata* in industrialised countries. Heavy infections in cattle are rather uncommon and are mostly associated with illegal application of sludge from septic tanks on pasture or crops, or by indiscriminate defecation by farm workers or associated with camping and tourism. Light infections are much more common. They are the result of accidental ingestion of eggs that are found disseminated in the environment. How these eggs are spread from tapeworm carriers, who often live in urban areas, to the rural areas is not well known, but it is clear that sewage treatment plants and water streams are pivotal. Infection of cattle appears to be associated with the effluent from sewage treatment plants (Kyvsgaard et al., 1991), the free access of cattle to surface water and flooding of pastures (Boone et al., 2007).

T. saginata asiatica distribution is restricted to Asian countries. Whereas on a genetic basis it is considered a subspecies of *T. saginata*, it has distinct morphological and biological characteristics. The Asian tapeworm is acquired by consumption of raw or undercooked pig liver and viscera (Eom and Rim, 2001). Epidemiological data are scarce. In a hospital-based survey on tapeworms in Vietnam *T. saginata asiatica* was more common than *T. saginata* and *T. solium* (Somers et al., 2007).

4.3. *Trichinella* spp.

Nematodes of the genus *Trichinella* are one of the most widespread zoonotic pathogens in the world. Infection by *Trichinella* spp. has been detected in domestic and wild animals of all continents, with the exception of Antarctica (Pozio and Murrell, 2006). Until recently, all *Trichinella* infections occurring in animals and humans were attributed to *Trichinella spiralis*. Today, eight species and four genotypes within two clades (encapsulated and non-encapsulated) are recognised in this genus (Pozio and Murrell, 2006; Zarlenga et al., 2006; Krivokapich et al., 2008). Trichinellosis in humans occurs with the ingestion of *Trichinella* larvae that are encysted in muscle tissue of domestic or wild animal meat. The most important source of human infection worldwide is the domestic pig. However, meats of wild boars and horses have played a significant role during outbreaks within the past decades (Gottstein et al., 2009). The occurrence of trichinellosis in humans is strictly related to cultural food practices, including the consumption of raw or undercooked meat. The average yearly incidence of the disease in humans worldwide is probably close to 10,000 cases with a mortality rate of about 0.2%; however, the number of infections is underreported in many countries due to the lack of appropriate serological tests and knowledge of the disease on the part of physicians (Pozio, 2007). Clinical disease in humans is characterized by an intestinal phase followed by a muscular phase, which is accompanied by heavy muscle pains, fever and eosinophilia. Trichinellosis is not only a public health hazard but also an economic problem in porcine animal production and food safety. Due to the predominantly zoonotic importance of infection, the main efforts in many countries have focused on the control of *Trichinella* or the elimination of *Trichinella* from the food chain (Gottstein et al., 2009). New regulations laying down rules for official controls for *Trichinella* in meat in order to improve food safety for consumers have recently been released in Europe. The evidence that the disease can be monitored and to some extent controlled with a rigorous reporting and testing system in place should be a motivation to expand appropriate programs worldwide (Gottstein et al., 2009).

5. Parasites transmitted by fish, reptiles, amphibian, crustaceans and snails

Meat of reptiles, amphibians and fish can be infected with a variety of parasites, including trematodes (*Opisthorchis* spp., *Clonorchis sinensis*, minute intestinal flukes), cestodes (*Diphyllobothrium* spp., *Spirometra*), nematodes (*Gnathostoma*, spp., Anisakidae), and pentastomids that can cause zoonotic infections in humans when consumed raw or not properly cooked. Freezing, cooking and other treatments of the meat, such as salting, reduce or eliminate the chances of transmission when properly applied. However, smoking or pickling may not always be effective in eliminating the infective larvae (Toro et al., 2004). Again, as for other food-borne parasites, culinary habits play a major role in the exposure to these parasites. Traditionally, these parasitic zoonoses are most common in Asia because of the particular food practices and the importance of aquaculture (Keiser and Utzinger, 2005). However, some of these parasites may emerge in other continents through aquaculture and improved transportation and distribution systems to bring aquatic foods to local and international markets, changing culinary practices and increased tourism (Keiser and Utzinger, 2005).

5.1. Cestodes

Sparganosis is a zoonosis that occurs occasionally in humans. It is caused by larva migrans of *Spirometra* tapeworms. This infection is reported in many countries but is most common in eastern Asia. Migrations occur in the eye, subcutaneous tissues, the central nervous system or other organs. Infections are acquired through drinking contaminated water or eating frog or snake meat (Wiwanitkit, 2005).

Diphyllobothriosis, a parasitosis caused by flatworms of the genus *Diphyllobothrium*, is contracted by consuming raw or undercooked fish (Dupouy-Camet and Peduzzi, 2004). These parasites are found in Europe, North and South America and Asia. About 20 million people are infected worldwide (Chai et al., 2005). Several species have been described that occur either in freshwater fish or sea fish; *Diphyllobothrium latum* is the most common species infecting humans (Scholz et al., 2009). A decline of human diphillobothriosis is seen in several countries of North America, Asia and Europe, while the infection has shown to re-emerge in some countries such as Russia, South Korea, Japan and South America (reviewed by Scholz et al., 2009). In Europe *D. latum* seems to be emerging in the subalpine lakes, more than 100 cases of human infections were reported in the last decade in the French, Swiss and Italian regions bordering these lakes (Dupouy-Camet and Peduzzi, 2004). Factors allowing the continuation of the parasitic cycle include the continued dumping of wastewater into lakes, yachtsmen who also fish, and a possible animal reservoir (Dupouy-Camet and Peduzzi, 2004). In North America there has been a decline in human cases while in South America an increase in reports from fish, especially salmonids suggests high levels in these fish species (Dick et al., 2001). Despite the large size of most *Diphyllobothrium* species, many infections are reported to be asymptomatic. In about 20% of the infections, diarrhoea, abdominal pain, or discomfort occurs. Prolonged or heavy *D. latum* infection may cause megaloblastic anaemia due to a parasitic-mediated dissociation of the vitamine B_{12} intrinsic factor complex within the gut lumen, making B_{12} unavailable to the host (Vuylsteke et al., 2004).

5.2. Nematodes

Angiostrongylus cantonensis is a zoonotic parasite that causes eosinophilic meningitis in humans after they ingest infective larvae in freshwater and terrestrial snails and slugs, paratenic hosts (such as freshwater fish, shrimps, frogs, and crabs), or contaminated vegetables. Rats are the natural final hosts. Mild meningeal irritation signs, paresthesia and cranial nerve abnormalities are the most common clinical signs. However, severe cases with brain involvement have been reported. With the increase of income and living standards, and the pursuit of exotic and delicate foods, populations around the world, but particularly in Asia have seen angiostrongyliasis become an important food-borne parasitic zoonosis (Alicata, 1991; Zhang et al., 2008).

The consumption of raw or undercooked seafish may lead to infection with several nematodes belonging to the Anisakidae family. The worm species most commonly involved in human infections is *Anisakis simplex*. *Pseudoterranova decipiens* is less frequent, while infection with the closely related *Anisakis physeteris* and *Contracaecum* spp. has been reported in only a very few cases (reviewed by Audicana and Kennedy, 2008). The life cycle of these nematodes involves larval stages with several intermediate and paratenic hosts and the adult stage, during which the worm parasitizes the stomach of marine mammals, such as seals and dolphins. Humans can be accidental hosts by eating raw or undercooked fish or seafood that contains the third-stage larvae of *A. simplex*. After ingestion, larvae can be invasive, penetrating the digestive tract and producing a disease, known as anisakiosis or anisakidosis. There is some evidence that gastric invasion is more often associated with infections by *P. decipiens* and intestinal invasion with infections by *A. simplex* (Oshima, 1987). Usually within a few hours after the ingestion of a living worm, *A. simplex* causes an acute and transient infection that may lead to abdominal pain, nausea, vomiting, and/or diarrhea. Some patients develop syndromes simultaneously exhibiting clinical manifestations of allergy and infection after eating living parasites (Audicana and Kennedy, 2008). The *A. simplex* allergens are highly resistant to heat and freezing; though cooking is expected to kill the parasites it may not result in loss of their allergenicity, and sensitisation may occur (Audicana et al., 2002). *A. simplex* may be the cause of chronic and relapsing acute urticaria, frequently labeled as idiopathic (Falcão et al., 2008). *Anisakis* and *Pseudoterranova* third stage larvae utilize a very large number of fish species as intermediate hosts and high prevalences have been found, especially in herring, hake, black plaice and cod. In a study performed on fish fillets sold in Belgium, 84.5% of examined fish were found infected with *A. simplex*. Pollock was the most heavily infected fish and the species with the largest number of *Anisakis* larvae (7.8 larvae/kg fish fillet) (Piccolo et al., 1999). Uncooked fish are rendered safe for human consumption by freezing (−20 °C for at least 24 h) or cooking. Methods for preparation of fish such as salting, curing, marinating, pickling, and smoking at 40 °C, which are generally sterilizing for other food-borne pathogens are not sufficient for anisakids (Audicana and Kennedy, 2008). The only way to avoid contracting anisakiosis and allergic reactions associated with the presence of dead larvae is not to eat raw or even cooked parasitized sea fish. The increasing popularity of sushi bars where raw fish dishes are served, has often been suggested as contributing to the spread of anisakid infections. However, according to Oshima (1987) the apparent increase in human cases is related more to advances in diagnosis than to the commercialization of sushi.

5.3. Trematodes

The liver flukes, *C. sinensis* and *Opisthorchis* spp. are considered an emerging public health problem. Keiser and Utzinger (2005) estimated that about 600 million and 80 million people are at risk for infection with *C. sinensis* and *Opisthorchis* spp, respectively. The oriental liverfluke, *C. sinensis*, is of major socioeconomic importance in parts of Asia, including China, Japan, Korea, Taiwan and Vietnam. The parasite is transmitted via snails to freshwater fish, and then to human beings and other piscivorous mammals. It is estimated that about 35 million people are infected globally, of whom approximately 15 million are in China, which is a threefold increase in this country in the last decade (Lun et al., 2005). It is believed that clonorchiosis is having an increased human-health impact due to the greater consumption of raw freshwater fish. Clonorchiosis causes substantial clinical or subclinical disease. Heavy infections can cause jaundice, portal hypertension, ascites, gastrointestinal bleeding, formation of gallstones, inflammation and hyperplasia of the biliary epithelium leading to deposition of fibrous tissue and invasion of the pancreatic duct (Lun et al., 2005).

The closely related *Opisthorchis* spp. have different geographic distributions, Kazakhstan, Russian Federation, Siberia, Ukraine, Germany and Italy for *O. felineus*, and Cambodia, Laos, South Vietnam and Thailand for *O. viverrini*. The epidemiology and clinical presentation of *Opisthorchis* infections are similar to those described for clonorchiosis (Keiser and Utzinger, 2005).

There is strong epidemiological evidence that both *O. viverrini* and *C. sinensis* are associated with cholangiocarcinoma. Following a case–control study of 103 patients with cholangiocarcinoma, Parkin et al. (1991) concluded that two-thirds of cases of this liver tumour in Thailand could be attributed to infection with *O. viverrini*. Suspected mechanisms leading to carcinogenesis include chronic irritation of the bile duct epithelium, nitric oxide formation, intrinsic nitrosation and activation of drug-metabolizing enzymes.

Several genera of flukes cause intestinal infections in humans. These intestinal parasites are acquired through eating freshwater (e.g. *Metagonimus yokogawai*) and brackish water fish (e.g. *Heterophyes heterophyes*) that contain metacercariae are an unrecognized food safety risk in communities with tradition of eating raw fish (Dung et al., 2007). Little is known of the population at risk of these trematodes. Symptoms include abdominal pain, diarrhoea and lethargy.

The future impact of fish-borne zoonotic trematodes may be linked closely to the expected growth of aquaculture in Asia, where nearly 90% of the world's freshwater production is centered (Keiser and Utzinger, 2005). However, there is disagreement on the relative importance of pond-cultured fish versus wild caught fish in the epidemiology of human infection. Several food safety risk analyses of Asian aquaculture have reported that there are as yet no conclusive epidemiological studies that link the transmission of liver fluke infections to aquaculture, although in some countries, especially China where most of its fish are produced through pond culture, the high rates of *C. sinensis* infection are difficult to account for by consumption of wild fish alone. This is a crucial question, for both prevention and control planning, and for the expansion of fish farming in Asia, and deserves a higher research priority in the endemic countries (Chai et al., 2005).

Another important zoonotic food-borne trematode is the lungfluke (*Paragonimus* spp.) (reviewed by Liu et al., 2008). *Paragonimus westermani* is of major socioeconomic importance in Asia, but lungflukes have also been found in some African countries, such as Nigeria, Cameroun and Liberia and in South America. The parasite is transmitted via snails to freshwater crabs or crayfish, then to humans and other mammals, such as cats and dogs, and causes paragonimiosis. At least 294 million people are at risk of infection with *Paragonimus* spp., with 195 million residing in China. Epidemiological data suggest that paragonimiosis is increasing in some regions of China (Liu et al., 2008). The infection is acquired by eating raw or undercooked or even inadequately cured, dried, pickled or salted infected crustacean host infected with metacercariae. Following infection, the excysted larvae migrate through the intestinal, the abdominal cavity, the diaphragm to the pleural cavity and the lungs where they develop into the adult worms. The worms may also be found in ectopic locations such as the brain and heart. Paragonimiosis is usually insidious in its onset and mildly chronic in its course. The symptoms are characteristically referable to the chest, abdomen, lymph nodes or brain. In pulmonary paragonimiosis the most remarkable clinical feature is a cough, blood-tinged sputum and, less frequently, hemoptysis, distressing chest pain and dyspnea. Symptoms of pulmonary paragonimiosis can be confused with those of tuberculosis. When migrating to the brain, which is the commonest extra-pulmonary location, the worms are responsible for epilepsy, such as occurs in neurocysticercosis. Control of the parasite is difficult because of the existence of a zoonotic reservoir (mainly dogs and cats) and the deeply rooted customs of eating raw, undercooked or freshly pickled crabs or crayfish in endemic areas (Liu et al., 2008).

5.4. Pentastomids

Gnathostomiosis is known to occur mainly in South East Asia, but has more recently been reported to emerge as a cause of human infection in Peru, Ecuador and Mexico (Rojas-Molina et al., 1999). It is regularly reported in travellers returning from endemic areas where they have eaten undercooked freshwater fish (Hale et al., 2003). Intermittent cutaneous migratory swellings are the commonest manifestation.

6. Conclusions

The rise in general public concern over security of the food chain and food safety has helped to focus more attention on zoonotic parasites. However, for many of the zoonotic parasites, the systems for routine diagnosis, monitoring or reporting are inadequate, or even non-existing. As a consequence, the incidence of human disease and parasite occurrence in food is underestimated. (Re-) emergence of many food-borne parasites therefore often seems rather the result of improved diagnosis and reporting than of a real increase. Food-borne parasitic diseases are included in a new initiative of the World Health Organisation on Estimating the Burden of Food-borne Diseases (WHO, 2006, 2007). This initiative should help in quantifying the relative importance of food-borne parasites.

Of particular concern in industrialised countries are waterborne protozoal infections, which are difficult to control, given their high level of resistance to environmental conditions, increased immigration and travelling, which have increased the exposure to exotic diseases and the risk of (re-)introducing these diseases. The increasing demand for animal proteins, particularly in developing countries will lead to an increase of livestock and fish production and an intensification of the production systems. The risks of zoonotic diseases to enter these production systems, such as porcine cysticercosis in Africa and clonorchiosis in China, will have to be carefully examined.

Among the options for a better monitoring and control of food-borne parasites are using new risk assessment tools, monitoring of water and food utilising new technologies, including serological and molecular approaches, health education, social and economic development, mass treatment and vaccination.

Conflict of interest

None of the authors (Dorny, P., Praet, N., Deckers, N., Gabriel, S.) has a financial or personal relationship with other people or organisations that could inappropriately influence or bias this paper (emerging food-borne parasites).

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