Review

Echinococcosis – an international public health challenge

P.R. Torgerson *, C.M. Budke

Institute for Parasitology, University of Zurich, Winterthurerstrasse 266a, CH-8057 Zurich, Switzerland

Abstract

This review aims to summarise some of the recent studies that have been undertaken on parasites of the genus Echinococcus and the diseases which they cause. Although the adult parasite, which inhabits the intestine of various carnivore species is not pathogenic, the larval or metacestode stages can be highly pathogenic, causing economic losses to livestock and various forms of echinococcosis in humans, some of which have a high fatality rate. There is growing evidence that there are at least 5 species of Echinococcus rather than the generally accepted 4 species. Within these species there are a number of genotypes or strains. This can have implications for surveillance and control. In some wealthy countries, cystic echinococcosis caused by Echinococcus granulosus has been successfully controlled or indeed eradicated. However, in most parts of the world it remains a serious threat to human health. In the former Soviet Union, the disease has rapidly increased in incidence after the end of communist administration. Human alveolar echinococcosis, caused by Echinococcus multilocularis, is more sporadic. However, in some Chinese communities there is a disturbingly high human prevalence and in Europe there has been an increase in the detection rate of E. multilocularis in animals in the last 10 years. Echinococcosis can present diagnostic challenges, particularly in the definitive host in areas of low endemicity. Much of the recent work relating to the use of coproantigen and PCR to overcome these difficulties is summarized. New ideas for controlling the parasite are becoming available and these include both the use of vaccination and the application of mathematical models to determine the most cost effective means of control. Effective measures that are affordable are vital if the parasite is to be controlled in poor countries.

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1. Introduction

The genus Echinococcus is of great importance because it contains a number of zoonotic species that can cause serious ill health in man. There are at least 4 species in the genus, but recent molecular evidence suggests that there should be a taxonomic revision to at least 5 species (Table 1) or even possibly 6 (Le et al., 2002; McManus, 2002; Thompson and McManus, 2002). There is also significant strain variation in the species Echinococcus granulosus. With each species the definitive host is a carnivore, whilst the intermediate host can be one of a large number of mammalian species. The parasite is of pathogenic and economic significance in intermediate and aberrant intermediate hosts, where the larval parasite develops into a hydatid cyst. The genus is found throughout the world although a number of species have a limited geographical distribution.

2. Species and distribution

Cystic echinococcosis (CE) caused by the larval stage of E. granulosus is the most widespread of these parasites (Fig. 1). Dogs are the usual definitive hosts whilst a large number of mammalian species can be intermediate hosts, including domestic ungulates and man. In the UK, the parasite has a restricted distribution, being found mainly in mid and southern Wales. In Europe, zoonotic strains of E. granulosus are present in every country with the exceptions of Ireland, Iceland and Denmark. It is most intensely endemic in the Mediterranean areas and parts of Eastern Europe such as Bulgaria. In Asia the parasite is intensely endemic in large parts of China and is an important re-emerging zoonosis.
in the former Soviet Republics in Central Asia (Torgerson et al., 2002a,b). The parasite is also found throughout the Indian Subcontinent and the Middle East. In Africa, *E. granulosus* is widespread and is a particular problem in northern African countries such as Tunisia, Morrocco, Libya and Algeria. South of the Sahara the parasite is of specific concern in certain locations such as Turkana in Kenya. In North America the parasite is found in Canada and Alaska, but seems to assume mainly a sylvatic cycle. In the continental USA, the parasite is very sporadic with just a few foci such as certain communities in Utah and California. In South America the parasite is extensive, particularly in Argentina, Uruguay and the Peruvian Andes. In Australia the parasite is common due to a sylvatic cycle between dingoes and wallabies with over 25% of dingoes and up to 65% of macropod marsupials infected (Jenkins and Morris, 1995; Jenkins, 2002). In some developed countries, due to the application of successful control programmes, it is becoming increasingly uncommon. In Iceland, New Zealand, Tasmania and southern Cyprus the parasite has been effectively eradicated (Economides and Christofi, 2002). In many poorer parts of world, particularly where sheep husbandry is an important agricultural industry, the disease is widespread.

The most frequent strain associated with human CE appears to be the common sheep strain (G1). Although in some locations strains such as the Tasmanian sheep strain (G2), camel strain (G6), pig strain (G7/G9) and cervid strain (G8) occur in a significant number of cases. The cattle strain (G5) has been implicated in some cases of human CE (Thompson and McManus, 2002). The proposed *Echinococcus equinus* (or *E. granulosus* strain G4) does not appear to be zoonotic and the only intermediate hosts reported to date are equines. Furthermore, the parasite is widespread in Ireland (Hatch, 1970) but zoonotic strains of *E. granulosus* are absent and no autochthonous cases of CE have been reported. *E. equinus* was recognized as distinct from the sheep strain and promoted to a subspecies (*E. granulosus equinus*) by Williams and Sweatman (1963). Rausch (1967) dismissed this as the sheep and horse strain exist sympatrically. However, the epidemiological evidence, particularly host specificity, supports a separate taxonomic status. Recent molecular evidence, which implies that *E. granulosus* (G4) strain is at least as distinct from the sheep strain (G1) as either is from *E. multilocularis*, strongly supports the taxonomic status as the separate species *E. equinus* (Le et al., 2002; McManus, 2002; Thompson and McManus, 2002). The parasite seems to have the dog as the only known definitive host and equine species as its intermediate host. Geographically it is present in many areas where *E. granulosus* is found. The cycle of *E. equinus* appears to be maintained by the feeding of horse offal to dogs. In the UK and Ireland,
this is typically by the feeding of material from horses to foxhounds.  

*Echinococcus vogeli* and *E. oligarthus* have been occasionally reported as causing a polycystic type of human hydatid disease in Latin America. Little is known about the epidemiology and the transmission to man in the handful of cases reported (Rausch and D’Alessandro, 2002).

*Echinococcus multilocularis*, commonly known as the fox tapeworm, can be found in areas of central and northern Europe, northern Asia, and parts of North America (Fig. 2). It has also been proposed that *E. multilocularis* may be in parts of northern Africa, but currently there is not enough information to substantiate this claim (Schantz et al., 1995). The life cycle of *E. multilocularis* is primarily sylvatic. The red fox (*Vulpes*...
vulpes) is the most well known host but the arctic fox (Alopex lagopus), the coyote (Canis latrans), the wolf (Canis lupus), the raccoon-dog (Nyctereutes procyonides), the sand fox (Vulpes corsa), and the Tibetan fox (Vulpes ferrilata) are all known definitive hosts, depending on geographic location. Other canids (including domestic dogs), and occasionally felids, can also be definitive hosts if they become infected through the ingestion of an intermediate host harboring an infective metacestode. The principal intermediate hosts include rodents of the family Arvicolidae, with a number of reports of infection in the Sciuridae, Cricetidae, Dipodidae and Muridae; some of which may be important locally. Lagomorphs of the family Ochotonidae are frequently infected in parts of China. There have been occasional reports of infections in insectivores such as the Soricidae and Talpida.

3. Clinical aspects

In the definitive host, adult Echinococcus penetrate deeply between the villi into the crypts of Lieberkühn. Despite this intimate host parasite relationship there are few if any lesions. Consequently, there appears to be no ill effect on the definitive host even in the presence of very heavy infections.

In the intermediate host, hydatid cysts have been found in a large variety of mammalian species and often grow slowly, sometimes taking several years to develop. Cysts most frequently affect the liver and lungs but they can also develop in other internal organs including the central nervous system. The cysts vary greatly in size and shape and may be present in large numbers in one organ. The location of cysts and cyst morphology not only depends on host factors but also on the strain or species of Echinococcus involved. Hydatid cysts frequently remain asymptomatic for the life span of the host. However, in man symptoms can be severe and it is reasonable to assume that in at least a proportion of infected animals some clinical signs may arise.

Sheep and goats are typically infected with multiple, pleomorphic E. granulosus cysts mainly localised in the liver and lungs. Anaphylaxis has been induced experimentally in sheep although sudden death in sheep or other animals has not been recorded (Eckert et al., 2001). In cattle, cysts are often multiple and unilocular with the liver and lungs most frequently infected. If cattle are infected with the cattle strain the predominant location is the lungs. In horses, cysts typically grow slowly in the liver and even long-lived cysts may remain small and asymptomatic (Roneus et al., 1982). Even though large cysts frequently remain asymptomatic (Thompson and Smyth, 1975), clinical manifestations have been recorded. In one case reported in Switzerland a nine-year-old Irish horse presented with massive liver enlargement, increased levels of liver enzymes, liver dysfunction, obstructive lung disease, intermittent colic, anorexia and emaciation. This horse was heavily infected with several hundred hepatic and pulmonary cysts ranging from 1 to 3 cm in diameter (Hermann et al., 1988). In pigs the liver is most commonly infected, although cysts can be found in any organ.

Perhaps the most important effect of echinococcosis in domestic livestock is the potential economic impact of the infection. Whilst clinical symptomatology may be relatively unusual, there are reports of decrease in feed conversion ratios, lowering of milk production in lactating animals, decreases in reproduction rates and decreases in the value of wool or hides from infected animals (Kenzhebaev, 1985; Polydorou, 1981; Ramirez, 1982). These effects have been analysed economically (Torgerson et al., 2000, 2001; Torgerson and Dowling, 2001), and it is possible that in some societies the economic effects of infection in domestic stock may be the most important economic effect costing the livestock industries millions of dollars in endemic areas.

In wildlife, the predilection site of the cysts may render the host more susceptible to predation. In the moose in Canada, hydatid cysts frequently occur in the lungs, and those animals most heavily infected are caught more frequently by timber wolves and are often the first to be shot by hunters (Ran and Canon, 1979). Likewise, heavily infected wallabies in Australia may be more susceptible to predation by dingoes due to compromised lung function (Jenkins and Morris, 1995).

The effects of E. multilocularis on the intermediate host tends to be more profound due to the tumour-like proliferation of the metacestode. In the comparatively short-lived natural intermediate hosts, to which the parasite is well adapted, metacestodes develop rapidly and death often occurs, usually around 5 months after infection. Clinical and pathological changes in experimentally infected rodents include enlargement of the abdomen, increase in body weight due to the proliferating metacestode, weakness, apathy, anorexia, ascites and finally death. Upon post-mortem examination, infiltration of the liver, peritoneal cavity, other abdominal organs, and the lungs may be evident.

Domestic and wild pigs, dogs, monkeys and some other animal species have been described as aberrant hosts for E. multilocularis (Deplazes and Eckert, 2001). Among these hosts, horses and swine appear to be the least susceptible with the development of small lesions, typically only 1–20 mm in diameter, as well as suppressed development of the metacestode tissue (Eckert, 1996; Ohbayashi, 1996). Dogs with metacestode infection of the liver and or peritoneum presented with abdominal enlargement, ascites, and hyper-γ-globulinaemia (Haller et al., 1998). Recently, concurrent infection of the dog as both the definitive and the intermediate host has been recorded. Infected simians may show
clinical signs such as emaciation, inappetence, and jaundice. In one example, a 10–20 cm diameter lesion was found in the liver of a naturally infected orangutan in a Japanese zoo (Taniyama et al., 1996).

4. Human echinococcosis

Human echinococcosis results when man ingests eggs, which have been shed in the faeces of the definitive host. The initial phase of CE is asymptomatic with small well-encapsulated cysts. After an undefined period of several months to years, the infection may become symptomatic as a space-occupying lesion. However, 60% of infections will remain asymptomatic (Pawlowski et al., 2001). The liver is the most common organ involved, usually with over two thirds of cysts. The lungs are infected in about 20% of cases, with other organ involvement accounting for less than 10% of cases. The treatment options for CE include surgical removal of the lesions and in many parts of the world CE is the most common reason for abdominal surgery. Surgery has a success rate of up to 90% (Pawlowski et al., 2001). An alternative to surgery is the PAIR technique (Puncture-Aspiration-Injection-Reaspiration), (World Health Organisation, 1996). Chemotherapy, using benzimidazoles, has also been used with some success. In calcified cysts, there is an indication for a wait and see approach to treatment.

Alveolar echinococcosis (AE), due to the metacestode stage of E. multilocularis, is an often-fatal condition if untreated. The cyst is multivesicular and highly infiltrative locally. The primary site of metacestode development is almost exclusively the liver. Secondary metastasis may form in a variety of adjacent or distant organs in longer standing cases, making surgical management difficult. Patients present with cholestatic jaundice and/or epigastric pain, fatigue, weight loss, hepatomegaly or abnormal routine laboratory findings (Pawlowski et al., 2001). Treatment options include partial and radical surgical resection for localized lesions in combination with long-term chemotherapy using benzimidazoles. In rare cases, liver transplantation has been undertaken.

Human infections with E. vogeli and E. oligathus results in polycystic echinococcosis. Relatively few cases have been described and they were all in Latin America. In 80% of cases the lesions involved the liver; the rest were located in the lung or single organ sites (D’Alessandro, 1997). The most common clinical presentation includes liver masses, enlarged abdomen, abdominal pain, weight loss and fever. In about 25% of cases there are signs of biliary hypertension and biliary obstruction. From the limited numbers of cases that have been reported the fatality rate is at least 26%.

Echinococcus equinus (E. granulosus strain G4) appears to be non-pathogenic to man.

5. Epidemiology and transmission to man

Echinococcus granulosus has both sylvatic cycles, often involving wild carnivores and ungulates; and domestic cycles, usually involving dogs and farm livestock. It is the latter transmission cycle that is the most common and poses the greatest threat to human health. The highest incidence rates in man are often seen in areas where there is a close association with man and domestic livestock, often using dogs as working dogs. A common source of infection for dogs is offal from infected sheep, which often harbour the zoonotic G1 strain responsible for many cases of human CE. The resultant high infection levels in these dogs then pose a risk to human contacts.

The potential for domestic transmission of E. granulosus is highest in poor countries where the level of education may be low, veterinary services inadequate and there is the widespread practice of home slaughtering. In such circumstances, the rates of infection in dogs can reach between 20% and 50% with perhaps an excess of 50% of the sheep population being infected. The risks associated with infection are illustrated by the deteriorating situation in Central Asia. Prior to the break up of the Soviet Union, CE in man was at relatively low levels. However, following independence of the Central Asian republics there was widespread structural and economic reform. This resulted in privatisation of farms, abandonment of centralised meat processing facilities and a return to small subsistence-type agricultural practices. Veterinary services also collapsed due to a lack of government funding. This has resulted in an epidemic of human CE, with the annual incidence of surgical cases reported by hospitals in excess of 4–5 times the number reported prior to 1991 (Torgerson et al., 2002a,b, 2003a) (Fig. 3). A similar pattern is also emerging in other former communist countries like Bulgaria (Todorov and Boeva, 1999).

Nevertheless, providing resources are available, a dramatic reduction in prevalence and even eradication is possible. This is due mainly to the factors that affect the transmission dynamics. The parasite has a relatively low biotic potential, and density dependent constraints may only act at the level of the definitive hosts (Gemmell,
1990; Lahmar et al., 2001; Torgerson, 2003a; Torgerson et al., 2003b). In Iceland, Tasmania, New Zealand and Southern Cyprus control has been highly successful and eradication or near eradication has been achieved. However, these are island nations. In continental countries, eradication would be harder to achieve because of the potential for reintroduction from neighbouring countries and the presence of sylvatic cycles. Nevertheless, control is possible such that the parasite can be maintained at low levels.

In endemic areas a considerable proportion of horses can be infected with E. equinus (Thompson and Smyth, 1975). Interestingly, this parasite is widespread in Ireland where zoonotic strains of E. granulosus are absent. However, the sheep strain of E. granulosus is highly endemic in some parts of Wales in the UK, and the reasons why E. equinus has managed to establish in Ireland but not E. granulosus, despite the free movement of animals between the UK and Ireland is not known. It is possible that this is due to the relatively low sheep population and density of sheep that has, until relatively recently, existed in Ireland. This would lower the probability of transmission and thus make establishment difficult. In contrast in Wales, the sheep population has always been at a high density. If this hypothesis is correct, then there will be an increasing risk of introduction of E. granulosus into Ireland as there has been a large increase in the sheep population over the last 20 years to avail of EU subsidies.

Human AE remains a sporadic human disease over much of the northern hemisphere. The majority of cases are a result of environmental contamination with infected fox faeces and subsequent transmission to humans. In the central European endemic area, the red fox (Vulpes vulpes) is likely to be responsible for most of the environmental contamination with E. multilocularis eggs (Eckert and Deplazes, 1999). In addition to the prevalent sylvatic life-cycle, a semi-domestic life-cycle has developed in some areas of the world. One of the first known examples of this phenomenon was on St. Lawrence Island off the Alaskan coast where, in the 1950s, a cycle between dogs and voles was discovered (Schantz et al., 1995). Later, stray dogs on the Japanese islands of Reubun and Hokkaido also tested positive for E. multilocularis, with a prevalence rate of 1.6% on Reuben Island (Yamashita, 1973) and 2% on Hokkaido Island (Iida, 1969). More recently, a cycle involving dogs and rodent species has been encountered in the Sichuan and Gansu provinces of China, where in one study 6 out of 58 dogs were found to be positive on post-mortem examination (Craig et al., 1992). Felids have also been shown capable of acting as aberrant definitive hosts for E. multilocularis with a low or negligible egg excretion rate (Petavy et al., 2000). It has been estimated that prevalence rates in cats in Europe range from 0% to 5.5% (Eckert, 1998).

The existence of this semi-domestic cycle may have resulted in a relatively high prevalence rate of human AE in some communities. In Gansu Province in China there are communities where the ultrasound prevalence rate reaches 5% (Craig et al., 1992) and similar rates have also been detected in Sichuan Province (Wang et al., 2001). Presently active epidemiological research is being undertaken in this region and it seems likely that there may be direct transmission from domestic and stray dogs to the human population. Preliminary unpublished results suggest a prevalence rate of E. multilocularis in dogs of as much as 30%. In the pastoral Tibetan communities of Sichuan it is possible that dogs are becoming infected by scavenging rodents in the montane treeless steppe region and subsequently transmitting the disease by close contact with the local human communities.

In Europe, E. multilocularis is being found in new regions previously thought to be free from the parasite (Fig. 4). Presently, it is not certain if this is due to improvements in diagnosis or a recent extension of the parasite's range (Romig For EurEchinoReg, 2002). There has been a drastic increase in the fox population density and an increase in the prevalence of infection in previously endemic areas recorded in the last 10 years. Likewise, there appears to have been an increase in the prevalence in intermediate hosts (Romig et al., 1999). This increase in parasite density could have increased the risk for man of exposure to E. multilocularis and subsequent development of AE. The reasons for the increase in fox numbers are not known. However, fox mortality due to rabies has been reduced to virtually zero (Thulke et al., 1998), and the increase in the fox population is associated with the implementation of the rabies immunization campaign. However, similar increases in fox populations have also occurred in the UK where rabies is absent indicating that additional factors

![Fig. 4. The geographical range of E. multilocularis in Europe recognized in 1990 and 2000. Data from Eckert et al. (2000) and Romig For EurEchinoReg (2002). © Institute für Parasitologie, Universität Zürich.](image)
are important. In particular, foxes have become increasingly adapted to urban habitats and this may account for a significant part of the population increase (Deplazes et al., 2002).

The only known final host of *E. vogeli* is the bush dog (*Speothus venaticus*) whose distribution includes all the tropical sylvatic areas of South America except Chile, Argentina and Uruguay. The cestode has also been found on one occasion in a domestic dog. In addition, it has been possible to experimentally infect domestic dogs (Rausch and D’Alessandro, 2002). The natural hosts, bush dogs, are timid and elusive and may play little role in infecting man. However, paccas, the typical intermediate host, are widely hunted for food with the aid of dogs, which are often rewarded by being fed the viscera.

*Echinococcus oligathus* has been recorded naturally in 6 species of felids that occur in Central and South America. Experimentally the domestic cat has also been infected. Only three cases of echinococcosis due to *E. oligathus* have been confirmed in man (Rausch and D’Alessandro, 2002) and it is not known how these individuals became infected.

There is evidence of indirect transmission of echinococcosis to man through, for example, contaminated food or water supplies rather than with direct contact with dogs (Carmona et al., 1998; Dowling et al., 2000; Larrieu et al., 2002; Torgerson et al., 2003a). Furthermore, there is also epidemiological and experimental evidence that taeniid eggs can be transmitted considerable distances by mechanical carriers such as insects or birds (Gemmell, 1990; Torgerson et al., 1995).

### 6. Diagnosis

In the intermediate host, the presence of *E. granulosus* has usually been detected at post-mortem by examination of the viscera. This can provide important epidemiological data, which can be used to define the likely infection pressure (Cabrera et al., 1996; Ming et al., 1992; Torgerson et al., 1998). The main disadvantage of this approach is that a slaughterhouse sample is potentially biased. In Kenya ultrasound detected hydatid cysts in sheep and goats with a sensitivity and specificity of 54% and 97%, respectively (Sage et al., 1998). Ultrasound has also been used in horses (Hermann et al., 1988). Currently, there is no suitably sensitive and specific serological test available for individual diagnosis in livestock species (Eckert et al., 2001). Nevertheless, serum antibody activity is used for detecting infection at the herd or flock level. This may be useful in hydatid screening programmes, particularly, when cysts may be too small to easily identify at necropsy. Antibodies that react against hydatid cyst fluid antigen can be detected from 4 weeks after exposure, and greater than 90% sensitivity using antigen B enriched hydatid fluid extracts have been recorded. However, there are cross reactivity problems with *Taenia hydatigena*, *T. ovis* and *Fasciola hepatica* (Eckert et al., 2001). When conducting surveillance work, it is very important to also record the age structure of the intermediate host population as the numbers of hydatid cysts increase with age due to the lack of naturally induced protective immunity (Roberts et al., 1986); a high abundance or prevalence of infection in young livestock would be considered of much greater significance than a similar level in older stock.

The diagnosis of *E. multilocularis* in intermediate and aberrant hosts should be based on several criteria. These consist of the use of macroscopic and histological examinations, including the morphology and size of hooks on the protoscolices. In very small lesions additional techniques may be necessary such as immunohistology with monoclonal antibodies, DNA-hybridisation or PCR techniques (Eckert et al., 2001). In living animals such as dogs or monkeys, ultrasound examination of the abdominal organs is indicated with specific antibody detection (Deplazes and Eckert, 2001).

The most reliable means of diagnosis of *Echinococcus* in the definitive host is by necropsy, as the worm burden can be estimated and parasites collected for identification (Eckert, 1997). Straightforward coprological examination may reveal the presence of taeniid eggs, but will not distinguish infection with *Echinococcus* spp. and *Taenia* spp. The parasymptomimetic drug aracoline when given to dogs causes purgation of the entire intestinal contents. The drug also paralyses tapeworms which can then be collected and identified. This is an unpleasant technique but remains the only quantitative technique that can be used in the living dog and continues to play an important role in epidemiological studies (Torgerson et al., 2003b). However, the technique is time consuming, can be hazardous to the operator and occasionally produces severe reactions in the dogs. Also, not every dog will purge, and a significant number of carriers are not detected (Schantz et al., 1995). Consequently immunological and molecular approaches have been developed.

The detection of parasite-specific antigens in faecal samples is perhaps one of the most useful ways for collecting prevalence data in large surveys. The test is based on a parasite-specific layer of capture IgG antibodies which retains antigens from faecal supernatants. These coproantigen ELISAs report sensitivities of up to 93% and specificities of up to 99%. Tests have been developed for the detection of *E. granulosus* (Allan et al., 1992; Deplazes et al., 1992) and *E. multilocularis* (Deplazes et al., 1999). Discrimination between *E. granulosus* and *E. multilocularis* infections is difficult and the detection of very low burdens of less than 20 parasites may also be problematical. Longitudinal studies have demonstrated that coproantigen production can be detected in faeces within 10–20 days of infection, some 1–4
weeks prior to eggs appearing in the faeces (Allan et al., 1992; Deplazes et al., 1992; Jenkins et al., 2000; Malgor et al., 1997). Once the worms are expelled, coproantigen levels drop rapidly and become negative within 3–4 days. The *E. granulosus* coproantigen ELISAs have been used in a number of studies in the Middle East, Wales, Southern and Eastern Europe, and South America (reviewed by Fraser et al., 2002). Likewise, coproantigen ELISAs have been used for the surveillance of *E. multilocularis* in Japan and Europe.

Other techniques with greater specificity would be useful when the prevalence rate in the dog population is relatively low (Christofi et al., 2002) and for discriminating dogs with positive taeniid egg counts. A PCR has been developed for detecting *E. multilocularis*-specific DNA (Dinkel et al., 1998; Mathis et al., 1996) and is presently being developed for the detection of *E. granulosus* DNA (Cabrera et al., 2002a). Although this technique is sensitive enough to detect parasite-specific DNA from a very small number of eggs, it is not quantitative and is not suitable for large scale screening of samples; an important consideration in the design of control and surveillance systems. Thus, PCR based techniques are well suited as confirmatory tools once preliminary screening has been completed. In particular, positive predictive values for the coproantigen test become poor when the prevalence is very low. In such a scenario, coproantigen positive dogs could then be screened with a PCR based technique to distinguish between true and false positive results.

There is recent evidence that there are significant variations of parasite burdens with the age of the definitive host. Lahmar et al. (2001) and Torgerson et al. (2003b) have demonstrated that young dogs are likely to have the highest burdens of *E. granulosus* in highly endemic regions. Likewise, Hofer et al. (2000) demonstrated that young foxes had significantly higher mean burdens of *E. multilocularis* than older foxes. The suggestion has been made that this may be due to host protective immunity and the relatively short life-span of the parasite compared to that of the host. Therefore, the age structure of the definitive host population should also be considered when designing surveillance or epidemiological studies.

7. Control

Control of CE has always involved a combination of routine anthelmintic treatment of dogs, control and reduction of stray dog populations, supervision of the slaughter of livestock and subsequent disposal of offal, and education of the public. The prepatent period of *E. granulosus* is approximately 6 weeks and hence this has usually been the recommended treatment interval. Praziquantel is currently the most effective anthelmintic available for this purpose. Mathematical models have been developed to describe the transmission dynamics (reviewed by Gemmell, 1990) and more recently to simulate control options (Torgerson, 2002a). Although six-weekly anthelmintic treatment is highly effective, it is expensive in terms of manpower and logistics, and therefore, less suitable for use in poor countries. Simulation models suggest it may be possible to lengthen the interval between anthelmintic treatments to at least 3 months and still reduce prevalence rates in dogs and livestock to less than 1% within 10–15 years (Torgerson, 2003a). This idea has been supported by field studies in Uruguay (Cabrera et al., 2002b) and New Zealand (Gemmell, 1990). The lengthening of the treatment intervals to beyond the prepatent period can work because the mean time to reinfection is often considerably longer than six weeks. New intervention strategies are also being developed. One of the most promising is the development of a vaccine in sheep, which in trials has demonstrated close to 100% protection (Lightowlers et al., 1996, 1999). Widespread vaccination of sheep would prevent the transmission of the parasite to dogs, but would not have an immediate effect as it only prevents new infections and does not eliminate cysts already present. Thus, it would take a number of years before all the previously infected sheep were removed from the population. Therefore, it would be pertinent to combine vaccination with anthelmintic prophylaxis in dogs to prevent or lower transmission to man from the start of the control programme.

One major obstacle to any programme is the capture rate of either host in the life-cycle. Studies in China have suggested that the capture rate in dogs is little more than 50–60% of the population (Fen-Jie, 1993). Thus, a considerable proportion of dogs escape anthelmintic treatment and undermine attempts at control. This is due, *inter alia*, to the large population of stray dogs that is often present in endemic areas and vigorous attempts to reduce the stray dog population should be an integral part of a control strategy. Nevertheless, the uncertainty in the treatment rate can be modelled stochastically (Torgerson, 2003a) and a probability distribution of the outcome of intervention determined with likely best and worst-case scenarios. Vaccination of sheep can also be included in the model. For example, routine three-month anthelmintic treatment gives very good long-term results providing at least 75% of the dog population (including strays) is treated. Six-monthly anthelmintic treatment only reduces the levels of echinococcosis substantially if the treatment rate is well in excess of 90%, which is unlikely to occur in practice. Providing at least 75% of sheep are vaccinated, echinococcosis will be reduced considerably, but not for several years after implementation. However, lowering the flock immunity to 60% results in a significant risk of failure. Nevertheless, if control consists of a combination of vaccination
and routine anthelmintic treatment, the model suggests a high probability of success even if anthelmintic treatment is only given every 6 months to 60% of dogs with as few as 60% of sheep vaccinated. This illustrates the cumulative effect of controlling the parasite at more than one point in its life cycle and may indicate the most promising means of control, particularly in a low-income country (Fig. 5) where control of CE presents the greatest challenges. In such countries, CE is at its most intensely endemic, resources are scarce and continual reintroduction from sylvatic cycles or neighbouring countries are constant threats. In this respect, economic analysis should be an important priority (Torgerson, 2003b; Torgerson and Dowling, 2001; Torgerson et al., 2000, 2001) to develop the most cost-effective means of control. Thus, economic models that define the cost of the disease can be combined with the simulation models summarised above. This would predict the results of intervention strategies to determine the most cost-effect use of resources to lower the incidence in man and the prevalence in domestic animals.

The only other species of Echinococcus for which control has been attempted is E. multilocularis. The control of this parasite is more problematical than E. granulosus because of the mainly sylvatic cycle of the parasite. However, the use of aircraft to distribute baits in Germany (20 baits per km², each containing 50 mg of praziquantel) has reduced the prevalence of the parasite in rural foxes (Eckert et al., 2000; Romig et al., 1999; Schelling et al., 1997). Furthermore, a five-year dog- and fox-culling programme appears to have eliminated the parasite from Reuben Island, Japan (Craig et al., 1996).

8. Conclusions

Despite the large efforts that have been put into the research and control of echinococcosis, it still remains a disease of worldwide significance. In some areas of the world, CE caused by E. granulosus is a re-emerging disease in places where it was previously at low levels. There are also disturbing trends in the distribution of E. multilocularis with an increased detection rate in Europe and a number of intensely infected communities in China. If this deteriorating trend is to be stopped then additional efforts are needed to control these diseases.

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