

## **4 Nematodes**

Serge Morand, Salah Bouamer and Jean-Pierre Hugot

### **1 Introductory remarks**

More than 25,000 species of nematodes have been described including some 10,000 free-living marine and terrestrial nematodes, 3,500 parasites of invertebrates, and 12,000 parasitic nematodes of vertebrates (Poulin and Morand 2000; Hugot et al. 2001). These are assigned to more than 2270 genera and 256 families (Anderson 1992). When considering the estimated number of living species, which May (1988) evaluated at 1,000,000 and Hammond (1992) at 500,000, Nematoda are the most speciose phylum after Arthropoda. If we consider the lower estimate, only 5.3 % of the living species in Nematoda have been described. Knowing that, on average, 364 new nematode species were listed per year in the Zoological Records between 1979 and 1988 (Hammond 1992), it could take 1,300 years to achieve an extensive record of the living species of Nematoda. Although our knowledge of nematode species diversity is poor, we know a lot about the life-history of nematodes and in particular those parasitizing small mammals.

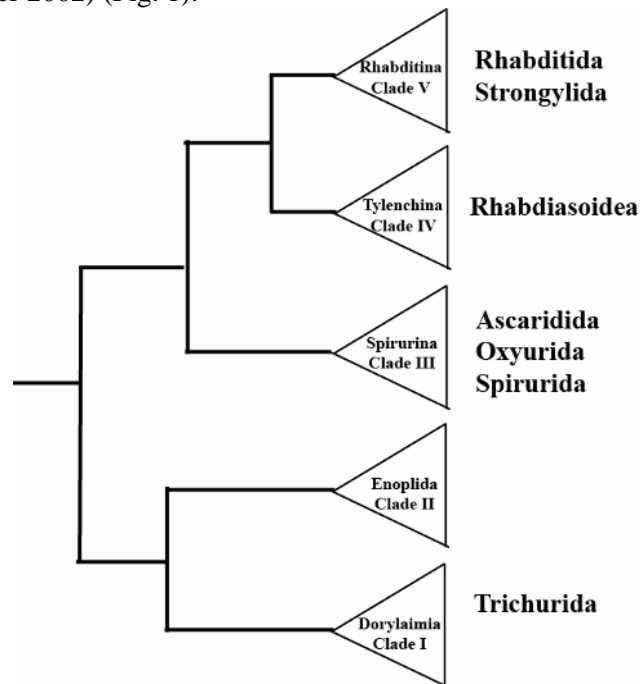
Nematodes have a uniform development and simple anatomical structure, but they display a great diversity of life-cycle with direct (monoxeny) and indirect (heteroxeny) transmission. Nematodes rarely kill their mammal hosts; they are sub-lethal parasites. Due to their impact on host-reproduction and survival, they have the potential to regulate their host populations.

### **2 Taxonomy and phylogeny**

On the basis of complete 18S ribosomal RNA (rRNA) sequences, Aguinaldo et al. (1997) proposed that nematodes were related to arthropods in a clade of moulting animals they called Ecdysozoa.

According to recent molecular phylogenies (Blaxter et al. 1998; de Ley and Blaxter 2002), five major clades in the phylum Nematoda are recognized, with seven independent transitions from free-living towards parasitism on vertebrates.

Here, we follow Anderson (2000), the “CIH Keys to the nematode parasites of vertebrates” (Anderson et al. 1974-1983) and the recent phylogenetic framework based on molecular methods (Blaxter et al. 1998; de Ley and Blaxter 2002) (Fig. 1).



**Fig. 1.** Phylogenetic relationships among the five major nematode clades, with groups known to parasitize small mammals indicated in bold. The phylogeny was adapted from De Ley and Blaxter (2002).

Seven nematode orders have members that are found in small mammals (Fig. 1): Rhabditida, Strongylida, Panagrolaimida, Ascaridida, Oxyurida, Spirurida and Trichurida. Nematode superfamilies with some member species (as examples) that parasitize small mammals (small marsupials, insectivores, rodents, lagomorphs and elephant shrews) are as follows:

- **Clade I**
  - Order Trichurida
    - Superfamily Trichinelloidea

- 
- Trichuridae (whipworm): *Trichuris leporis* (caecum of rabbits), *Trichuris muris* (caecum of rats).
  - Capillariidae: *Calodium* (*Capillaria*) *hepaticum* (liver of various small mammals).
  - Trichinellidae: *Trichinella muris* (muscle cells of mice and rats), *Trichinella nativa* (rodents), *Trichinella pseudospiralis* (rodents).
  - Superfamily Muspiceoidea
    - *Muspicea borreli* (house mice; protandrous hermaphrodite).
  - **Clade III**
    - Order Ascaridida
      - Superfamily Ascaridoidea (roundworms)
        - Ascarididae: *Baylisascaris laevis* (intestine of marmots and ground squirrels in North America); *Toxocara pteropodis* (intestine of flying foxes).
      - Superfamily Heterakoidea
        - Aspidoderidae, *Paraspidodera indica* (intestine of squirrels from India).
      - Superfamily Seuratoidea
        - Seuratidae: *Seuratum cadarachense* (intestine of Gliridae).
      - Superfamily Subuluroidea
        - *Maupasina weissii* (caecum of elephant shrews).
    - Order Oxyurida (pinworms)
      - Superfamily Oxyuroidea
        - Heteroxynematidae: *Aspicularis tetraptera* (intestine of the Old World mice and rats).
        - Oxyuridae: *Passalurus ambiguus* (large intestine of lagomorphs), *Syphacia obvelata* (large intestine of rodents).
    - Order Spirurida
      - Superfamily Gnathostomatoidea

- 
- *Gnathostoma* spp. (intestine of various small mammals).
    - Superfamily Physalopteroidea
      - *Physaloptera hispida* (stomach of cotton rats in North America).
    - Superfamily Rictularioidea
      - *Rictularia proni* (intestine of mice).
    - Superfamily Spiruroidea
      - *Protospirura numidica* (stomach and oesophagus of rodents), *Mastophorus muris* (stomach of Muridae).
    - Superfamily Filarioidea
      - Onchocercidae: *Achantocheilonema mansonbabri* (subcutaneous tissues and fascia of rodents; fleas are vectors), *Litomosoides carinii* (pleural and body cavity of cotton rats; microfilariae in blood; mites are vectors).
    - Superfamily Acuarioidea
      - Acuariidae: *Stammerinema suffodiax* (intestine of a dasyurid marsupial from Australia); *Antechiniella suffodiax* (intestine of a water rat from Australia).
    - Superfamily Thelazioidea
      - Pneumospiruridae; *Metathelazia caballeri* (lungs of a Chiroptera in Malaysia); *Thelazia iheringi* (ocular cavity of a rat from Brazil).
  - **Clade IV**
    - Superfamily Rhabdiasoidea
      - Rhabdiasidae: *Strongyloides ratti* (rodents), *Strongyloides venezuelensis* (Old World rats), *Parastrongyloides* spp. (insectivores and marsupials; dioecious parasitic forms).
  - **Clade V**
    - Order Rhabditida
      - Superfamily Rhabditoidea
        - Rhabditidae: *Pelodera strongyloides* (free-living, occasionally invade dermis),

- 
- Rhabditis orbitalis* (L3 can invade conjunctival sac of rodents).
- Order Strongylida (bursate nematodes)
    - Superfamily Ancylostomatoidea
      - *Ancylostoma* spp. (intestine of rodents).
    - Superfamily Metastrongyloidea
      - Chabertiidae: *Oesophagostomum selfi* (intestine of rats from Taiwan).
    - Superfamily Ancylostomatoidea
      - Ancylostomidae: *Cyclodontostomum purvisi* (intestine of rats in Indonesia).
    - Superfamily Strongyloidea
      - Strongyloidae: *Lamothiella romerolagi* (intestine of a rat and lagomorphs from Mexico); *Characostomum howelli* (intestine of a rat from Tanzania).
    - Superfamily Molineoidea
      - Molineidae: *Molineus neotetraci* (intestine of Insectivora and Chiroptera from China).
    - Superfamily Trichostrongyloidea
      - *Heligmosomoides polygyrus* (intestine of mice), *Nippostrongylus braziliensis* (*Rattus* spp.), *Obeliscoides cuniculi* (intestine of rabbits).
    - Superfamily Metastrongyloidea (lungworms)
      - *Parastrongylus cantonensis* (pulmonary arteries of rats) and *P. costaricensis* (mesenteric arteries of rodents), *Protostrongylus boughtoni* (lungs of snowshoe hares in Canada; gastropods are intermediate hosts).

The numbers of nematode genera and families differ greatly among the major groups of small mammals, with rodents harbouring the highest diversity in both genera and families (Table 1).

**Table 1.** Diversity of nematodes (numbers of genera and families) reported in four groups of small mammals.

Nematode diversity	Rodents	Lagomorphs	Chiropterans	Insectivores
Number of genera	141	32	34	6
Number of families	36	10	14	6

### 3 Life-cycle and biology

Nematodes display a wide variety of life cycles, some simple and direct (monoxenous) and some complex and indirect (heteroxenous) with one or more intermediate hosts (Anderson 1988), with or without host tissue migration (Read and Skorping 1995; Morand 1996). Despite the diversity and sometimes complexity of nematode life cycles, all of them can be related to the same basic pattern with two phases. The first phase takes place inside the definitive host where maturation and reproduction usually occur, and the pre-parasitic phase occurs either as a free-living larva in the external environment or inside an intermediate host.

Maupas (1900) noted that free-living rhabditoids passed through 5 stages separated by 4 moults and that the third stage (L3) initiated new populations when all other stages died due to depletion of environment resources. This developmental rule applies to the great majority of nematodes including parasites with five stages, plus the egg, constituting the basic pattern: the four larval stages (L1, L2, L3, L4) and one adult stage. Sometimes, the sexually immature adult stage is called L5. In all nematodes of clades III, IV and V, the L3 is the infective stage, whether the nematode requires an intermediate host or not, has free-living stages, or develops in the egg (Chabaud 1955).

#### 3.1 Modes of infection

The routes of nematode infection are various (Adamson 1986; Anderson 1988) (Table 1) and include:

- Skin penetration by the infective third-stage larvae in Rhabditida (*Strongyloides* spp.) and in some Trichostrongylidae of rodents (*Nippostrongylus brasiliensis*);
- Oral ingestion of eggs containing the infective stage in Trichuridae (*Trichuris leporis*, *Trichuris muris*) and in Oxyuroidea (*Syphacia* spp.);

- Ingestion of the infective L3 contained in the tissues of the intermediate hosts in the heteroxenous groups Metastrongyloidea and Spirurida;
- Injection of the infective L3 by blood-sucking arthropod vectors in Filarioidea;
- Ingestion of eggs by coprophagy in rodents and lagomorphs in Oxyuroidea;
- Ingestion of eggs by allo- or auto-grooming in Oxyuroidea, Trichostrogylidae and Muspiceoidea;
- Ingestion of the infected flesh through cannibalism and scavenging in some Capillariidae and Trichinellidae, with the same mammal species serving both as definitive and intermediate host;
- Autoinfection with internal cycles in Strongyloididae (*Strongyloides* spp.);
- Transplacental and transmammary transmission in *Strongyloides* spp. and *Toxocara pteropodis*.

**Table 2.** Diversity of the modes of infection in the parasitic nematodes of small mammals.

Example	Infective stage	Route of infection	Internal migration	Intermediate host	Paratenic host
Trichuridae	Egg (L3)	Oral	No (larvae in intestinal cell)	No	No
Trichinellidae	L1	Oral	Yes (larvae in skeletal muscle fiber)	No	Yes
Trichostrogylidae	L3	Oral/skin	No/Yes	No	No
Metastrongylidae	L3	Oral	Yes (L3)	Yes	Yes
Ascarididae	Egg (L2)	Oral	No/Yes	No/Yes	No/Yes
Oxyuridae	Egg (L3)	Oral	No	No	No
Physalopteridae	L3	Oral	No	Yes	No
Onchocercidae	L3	Skin	Yes	Yes	No

### 3.1.1 Grooming

Hernandez and Sukhdeo (1995) stressed the significance of self- and allogrooming in the transmission of *Heligmosomoides polygyrus*. They showed experimentally that higher numbers of nematodes were recovered from mice that were allowed to self-groom compared to infection levels in mice that had been prevented from self-grooming.

### **3.1.2 Cannibalism and necrophagy**

*Capillaria hepatica* is the only known nematode of mammals that depends on the death of the definitive host for transmission. The adults live in the liver parenchyma and the females deposit eggs into the sinuous tracts, in which they are encapsulated. Eggs exit when liberated by cannibalism or necrophagy. Eggs then pass through faeces and are released into the environment where they can remain viable for over one year. Embryonated eggs, that are eaten, hatch in the intestine and L1 larvae thus liberated migrate to the liver where maturation takes place.

### **3.1.3. Paratenesis and paratenic host**

Many nematodes use a paratenic host in their transmission. The paratenic host is “an organism which serves to transfer a larval stage or stages from one host to another but in which little or no development takes place” (Anderson 1999). Such a transmission process is called paratenesis.

For example, Mustelidae do not acquire metastrongyloid nematodes directly by eating infected gastropods (the first obligatory intermediate host), but by preying upon paratenic hosts - shrews or rodents. When an infected gastropod is eaten by a shrew or a rodent, the infective larval nematode invades the tissues and usually encapsulates in the liver of these hosts. As there is no development of the encapsulated larvae, these hosts are purely paratenic. Modes of transmission that involve paratenic small mammal hosts is also widespread in the spiruroid parasites of carnivores.

### **3.1.4 Transplacental transmission**

*Toxocara pteropodis* is a nematode parasite of flying-foxes (Megachiroptera) of the genus *Pteropus* in Australia, Oceania and southeastern Asia. Prociv (1989) reported that adult nematodes mature in the intestines of suckling bats. The eggs pass in faeces until the end of infection, which ends at about the time of weaning. Third-stage larvae, hatched from infective eggs, are ingested by adult bats and migrate to the liver. In females, at the end of parturition, some hepatic larvae are mobilized and pass through the mammary glands into the intestine of the neonate bat.

### **3.1.5 Arrested development**

Arrested development or hypobiosis is well known in Trichostrongylidae parasitic on lagomorphs and rodents. This phenomenon occurs when a large percentage of L3 and L4 remain in the intestine mucosae long after the end of the normal prepatent period. Extrinsic factors such as fluctuat-



ing temperatures and intrinsic factors such as immunity influence the induction and the length of the arrested development, as well as the number of arresting larvae.

Arrested development plays an important role because it allows species with limited adult life spans to survive when external conditions are unsuitable for the development and survival of larval stages. In temperate regions where transmission cannot occur in winter, larvae acquired in autumn may remain arrested in the host gut mucosa until spring, to await favourable external conditions for transmission. Host immunity may also cause arrest. The number of arrested larvae in a host may be related to the number of adult nematodes already present (Behnke and Parish 1979). When adults die, there is a relaxation of the immunity, which allows some arrested larvae to leave the gut to mature and replace adult nematodes.

### 3.2 Sex determination and sexual patterns

The great majority of vertebrate parasitic nematodes are gonochorous with sex determined chromosomally. XX/XO sex determination is very common across Nematoda. It occurs in both the free-living (*Caenorhabditis elegans*) and numerous parasitic (*Trichinella spiralis*, *Haemonchus contortus*, *Strongyloides ratti*) nematodes, suggesting that the ancestral phylogenetic state is possibly the XX/XO sex determination. Only a handful of nematodes are known to have Y chromosomes. These are *Brugia malayi*, *Onchocerca volvulus*, *Baylisascaris transfuga*, *Contracaecum incurvum* and *Trichuris muris*. Since Y chromosomes are only known in these few distantly related nematodes, White (1973) suggested that they probably emerged recently.

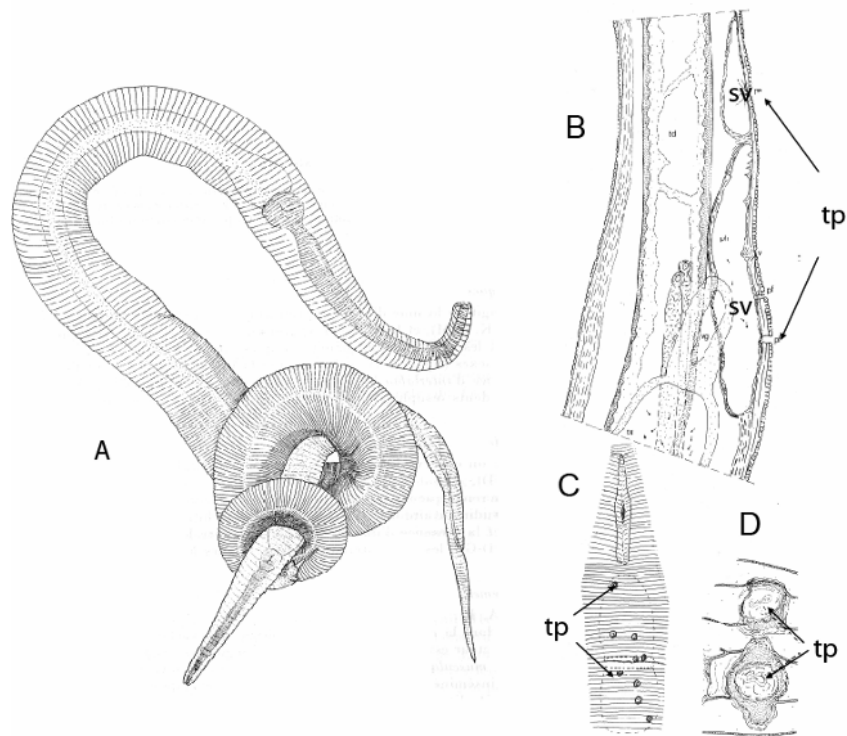
Nematode species display a great variety of reproduction patterns. In *Strongyloides ratti*, parasitic females are XX and produce male (XO) and female (XX) larvae. Male larvae are only able to develop into free-living adult males, whereas female larvae can either develop into free-living adult females or develop directly into new parasitic females (through infective L3). When the free-living adult males mate, all the progeny inherit the paternal X chromosome and thereby all the progeny are XX females. Host conditions and, in particular, host immune response influence the sex ratio of the progeny of parasitic females, with the sex ratio becoming more male-biased in hosts mounting an anti-*S. ratti* immune response (Harvey et al. 2000).

Oxyuroid nematodes exhibit haplodiploidy, where males are haploid and arise by partial parthenogenesis via unfertilized eggs, while females are diploid and develop from fertilized eggs (Adamson 1989). This may

result in a high degree of inbreeding and a decrease in genetic diversity compared to gonochoric species (Mueller-Graf et al. 1999).

Traumatic insemination occurs in oxyuroid nematodes such as *Passalurus ambiguus* in rabbits with males injecting sperm through the female larvae's cuticle (Fig. 2). Females have developed specialized internal structures for sperm storage and transfer to the reproductive system when mature (Chabaud et al. 1983; Hugot et al. 1982) (Fig. 2).

Protandrous hermaphrodite forms are recognized within the Muspiceoidea (*Muspicea*, *Riouxgolvania*, *Lukonema*).



**Fig. 2.** A. Mating between an adult male (large worm) and immature female (stage 4 larvae) of *Hilgertia seurati*; B. Transversal section showing traumatic pore (tp) and sperm vesicle (sv) in larval female of *Passalurus ambiguus*; C-D. Traumatic insemination pores in larval female of *Passalurus ambiguus* (modified after Hugot 1982; Hugot et al. 1992)

## 4 Nematodes as laboratory models

Very few species of nematodes have served as laboratory models to investigate host-parasite interactions and diseases that affect humans or domestic animals. Most of our knowledge comes from these nematodes and among them are the following:

- *Trichinella spiralis*, which is responsible for the human disease trichinellosis, is maintained in laboratory rodents. This unique macroparasite infects epithelial cells of the small intestine.

- *Trichuris muris* is a mouse model for the human parasite *T. trichiura*, highly prevalent in many parts of the developing world. This parasite lives within host gut epithelial cells just as *Trichinella spiralis* does. The adult nematode manages to penetrate the epithelial cells without immediately inducing necrosis and death and to suppress immune responses.

- *Heligmosomoides polygyrus* is used as a model for nematode diseases in domestic animals (strongyloids of livestock), and also serves to investigate host immune responses.

- *Nippostrongylus brasiliensis* is a parasite of rodents and used as a model for hookworm disease.

- *Strongyloides spp.* (used as a model for human strongyloidiasis) and *Parastrongyloides spp.* have the ability to live as free-living or as parasitic worms within some small mammals (rodents, marsupials). Manipulation of culture conditions and host physiology may influence the nematode's life span and whether it is free-living or as parasitic. These nematode models are useful to study genes that are required for parasitism or that contribute to longevity (Mitreva et al. 2004).

- *Litomosoides carinii* is a rodent filarioid nematode used as a model for human filariasis (*Wuchereria bancrofti*, *Brugia malayi*, *Onchocerca volvulus*).

## 5 Evolution of life history traits

Adaptation to parasitism imposes some constraints on the parasites. For example, co-variation of host and parasite body sizes has been observed in oxyuroids of vertebrates, with large mammals harbouring large-sized nematodes, even after controlling for confounding phylogenetic effects (Morand et al. 1996; Morand and Poulin 2002). The studies of Morand (1996) and Morand and Sorci (1998) have emphasized that the evolution of life history traits of nematode parasites are similar to those of free-living nematodes with the habitat-specific mortality driving the evolution of life

traits in both free-living and parasitic forms. Morand (1996) compiled life history traits information (body size, life expectancy of adult stage and free-living stage, maturation time or time to patency, total reproductive output) of free-living, as well as plant, insect and vertebrate parasitic nematodes. Most of the correlations between life traits, although confirming the previous study of Skorping et al (1991), enabled him to propose a causal chain of life history evolution in parasitic nematodes with the key parameter being the adult age-dependent mortality.

Nematode maturation within the host presumably occurs at the time that maximizes reproductive success and depends on age-dependent mortality. Time until maturation in the host, i.e. time to patency, is a determinant of body size, which positively correlates with reproductive output in parasitic nematodes (Morand 1996; Morand and Poulin 2000) and also in parasitic platyhelminths (Trouvé and Morand 1998; Trouvé et al. 1998).

Adult nematode mortality rate, which results from host mortality and host-induced mortality, should favour advanced or delayed time to patency. High mortality rate should favour advanced time to patency in order to reach sexual maturity earlier, whereas low mortality rate should favour delayed time to patency in order to achieve a large body size at sexual maturity (and hence large total reproductive output).

Read and Skorping (1995) showed that tissue migration is a trait selectively advantageous for some nematodes. Species that undertake migration in host tissues during their larval development delay their maturation and tend to grow larger than those that develop directly in the gut.

The first comparative test was provided by Sorci et al. (1997), who showed a significant relationship between host longevity and adult parasite body size, using the primate-oxyurid system, supporting the hypothesis that long-living hosts select large body-sized nematodes. The second test was based on an optimality modelling approach (Morand and Poulin 2000). The optimality model derived a relationship between the time to patency and the inverse of the sum of parasite mortality and host mortality. A comparative test was then performed and the slope of this relationship based on collected data was found to be consistent with the slope expected by the optimality model. Hence, high levels of parasite mortality select for a reduction in time to patency, whereas greater host longevity favours delayed parasite maturity (Morand and Poulin 2000). Although these results contrast with those of Gemmill et al. (1999), they give strong support to the comparative study of Sorci et al. (1997) on the co-variation of parasite and host life-history traits.

## 6 Effect of nematodes on host dynamics

Macroparasites have been reported to influence behaviour, energetic demands, reproduction, survival and mate choice of their hosts. Several studies have demonstrated experimentally the detrimental effects that parasites can have on fecundity and survival in wild small mammal populations. For example, *Obeliscoides cuniculi* reduced survival of the snowshoe hare *Lepus californicus*. If these parasites reduce host fecundity or survival, it is then theoretically possible that they might regulate host numbers (Tompkins and Begon 1999).

The best evidence that the impact of nematodes can reduce host populations comes from laboratory and enclosure experiments. However, the possibility that these nematodes may regulate host populations has been investigated in very few studies. Scott (1987) conducted the first experimental study that demonstrated the ability of a nematode to regulate the abundance of a mammal population. She performed a free-running experimental investigation using mice and the directly transmitted nematode *H. polygyrus*. In the absence of the parasite, the uninfected-mouse population achieved an equilibrium size 20-times larger than that of the infected mouse population. Removal of the parasite from infected mouse populations allowed them to recover similar equilibrium densities as non-infected mouse populations.

Singleton and Spratt (1986) showed that *C. hepatica* induces reduction of natality and survival in laboratory mice. Singleton and McCallum (1990) reported that *C. hepatica* has the potential to control house mouse plagues in Australia. This nematode has the distinctive feature of dependence on the death of its host for transmission (see above). Using a mathematical model, McCallum and Singleton (1989) found that the necessity of host death to ensure the parasite transmission has a destabilizing influence on the host dynamics, leading to oscillations in the mouse population. The model suggested that the parasite could maintain host density far below the carrying capacity. However, manipulative field experiments did not corroborate the efficiency of this parasite in controlling the mouse populations (Singleton and Chambers 1996).

Sub-lethal nematodes have the potential to induce changes in the life history optima of their hosts. Recently, Kristan (2004) investigated the effects of *H. polygyrus* on the house mouse *Mus musculus* and found that reproduction investment was increased when female mice were infected, with parasitized females having larger offspring than unparasitized females. Moreover, she showed the existence of maternal effects. Only offspring from parasitized females were able to eliminate their own infection.

Consequently, offspring susceptibility to *H. polygyrus* could be modified by maternal parasite infection. One possible mechanism for this might include interactions of the maternal antibodies with the offspring's immune system.

## 7 Effect of nematodes on host behaviour

Nematodes can also alter the behaviour of their hosts. Kavaliers and Colwell (1995) showed that female mice could discriminate between the odours of parasitized and non-parasitized male mice. In particular, female mice discriminated between the chemical signals of uninfected males and males infected with *H. polygyrus*. Females preferentially choose uninfected males as they find the odours of uninfected males more attractive than those of infected males.

## 8 Concluding remarks

Nematodes are greatly diverse in terms of species number but also in various kinds of life-cycle, modes of infection and life-history traits. This diversity is far from being completely known. Hence, recently, Clarke et al. (2004) presented evidence that an un-described nematode parasite of the very well investigated wood mouse *Apodemus sylvaticus* may be sexually transmitted. These authors found larval nematodes in the epididymides of males, which suggests that they would be transmitted to females during ejaculation.

In order to better understand the origins of all these facets of nematode biodiversity, we need a more detailed phylogenetic framework of this phylum. By mapping parasite traits onto the nematode phylogeny, we will better estimate the phylogenetical constraints and the ecological adaptation that may have shaped the diversity of nematodes, and particularly their interactions with small mammals.

Although rarely causing the death of their hosts, nematodes have the capacity to alter both the physiology and the behaviour of their hosts. Nematodes can regulate the population dynamics of their hosts, and this may contribute to the extinction spiral of small host populations (see Christe et al. in this volume), although much more experimental and theoretical work is needed. Finally, if nematodes are a threat to biodiversity, they are also of great concern with regards to human health (see Casanova and Ribas; Leirs and Singleton in this volume).

## References

- Adamson ML (1986) Modes of transmission and evolution of life histories in zoo-parasitic nematodes. *Can J Zool* 64:1375–1384
- Adamson ML (1989) Evolutionary biology of the Oxyurida (Nematoda): Biofacies of a haplodiploid taxon. *Adv Parasitol* 28:175–228
- Anderson RC (1988) Nematode transmission patterns. *J Parasitol* 74:30–45
- Anderson RC (1999) Nematode parasites of vertebrates. Their development and transmission. CABI, Wallingford
- Anderson RC, Chabaud AG, Willmott S (eds) (1974-1983) CIH keys to the nematode parasites of vertebrates. Commonwealth Agricultural Bureaux, Farnham Royal
- Aguinaldo AM, Turbeville JM, Linford LS, Rivera MC, Garey JR, Raff RA, Lake JA (1997) Evidence for a clade of nematodes, arthropods and other molting animals. *Nature* 387:489–493
- Behnke JM, Parish HA (1979) *Nematospiroides dubius*: Arrested development of larvae in immune mice. *Exp Parasitol* 47:116–127
- Blaxter ML, de Ley P, Garey JR, Liu LX, Scheldeman P, Vierstraete A, Vanfleteren JR, Mackey LY, Dorris M, Frisse LM, Vida JT, Thomas WK (1998) A molecular evolutionary framework for the phylum Nematoda. *Nature* 392:71–75
- Chabaud AG (1955) Essai d'interprétation phylétique des cycles évolutifs chez nematodes parasites des vertébrés. *Ann Parasitol Hum Comp* 30:83–126
- Chabaud A, Bain O, Hugot J-P, Rausch RL, Rausch VR (1983) Organe de Man et insémination traumatique. *Rev Nematol* 6:127–131
- Clarke JR, Anderson TJC, Bandi C (2004) Sexual transmission of a nematode parasite of wood mice (*Apodemus sylvaticus*)? *Parasitology* 128: 561–568
- De Ley P, Blaxter ML (2002) Systematic position and phylogeny. In: Lee D (ed) *The biology of nematodes*. Harwood Acad Publ, Reading, pp 1–30
- Gemmill AW, Skørping A, Read AF (1999) Optimal timing of first reproduction in parasitic nematodes. *J Evol Biol* 12:1148–1156
- Hammond PM (1992) Species inventory. In: Groombridge B (ed) *Global diversity, status of the earth's living resources*. Chapman and Hall, London, pp 17–39
- Harvey SC, Gemmill AW, Read AF, Viney ME (2000) The control of morph development in the parasitic nematode *Strongyloides ratti*. *Proc R Soc Lond B* 267:2057–2063
- Hernandez AD, Sukhdeo MVK (1995) Host grooming and the transmission strategy of *Heligmosomoides polygyrus*. *J Parasitol* 81:856–869
- Hugot J-P (1982) Sur le genre *Hilgertia* (Oxyuridae, Nematoda) parasite de rongeurs Ctenodactylidae. *Bull Mus Hist Nat Paris* 4: 419–431
- Hugot J-P, Bain O, Cassone J (1982). Insémination traumatique et tube de ponte chez l'oxyure parasite du lapin domestique. *C R Acad Sci Paris* 294:707–710
- Hugot J-P, Baujard P, Morand S (2001) Biodiversity in helminths and nematodes as a field of study: An overview. *Nematology* 3:1–10

- Kavaliers M, Colwell DD (1995) Odours of parasitized males induce adverse responses in female mice. *Anim Behav* 50:1161–1169
- Kavaliers M, Choleris E, Pfaff DW (2005) Genes, odours and the recognition of parasitized individuals by rodents. *Trends Parasitol* 21:423–429
- Kristan DM (2004) Intestinal nematode infection affects host life history and offspring susceptibility to parasitism. *J Anim Ecol* 73:227–238
- Maupas EF (1900) Modes et formes de reproduction des nématodes. *Arch Zool Exp Gen* 7:563–628
- May RM (1988) How many species are there on the Earth? *Science* 241:1441–1449
- McCallum HI, Singleton GR (1989) Models to assess the potential of *Capillaria hepatica* to control outbreaks of house mice. *Parasitology* 98:425–437
- Mitreva M, McCarter JP, Martin J (2004) Comparative genomics of gene expression in the parasitic and free-living nematodes *Strongyloides stercoralis* and *Caenorhabditis elegans*. *Genome Res* 14:209–220
- Morand S (1996) Life-history traits in parasitic nematodes: A comparative approach for the search of invariants. *Funct Ecol* 10:210–218
- Morand S, Poulin R (2000) Optimal time to patency in parasitic nematodes: Host mortality matters. *Ecol Lett* 3:186–190
- Morand S, Poulin R (2002) Body size-density relationships and species diversity in parasitic nematodes: Patterns and likely processes. *Evol Ecol Res* 4:951–961.
- Morand S, Sorci G (1998) Determinants of life-history evolution in nematodes. *Parasitol Today* 14:193–196
- Morand S, Legendre P, Gardner SL, Hugot J-P (1996) Body size evolution of oxyurid parasites: The role of hosts. *Oecologia* 107:274–282
- Mueller-Graf C, Durand P, Feliu C, Hugot J-P, Renaud F, Santalla F, Morand S (1999) Genetic variability and epidemiology of two species of nematodes (*Heligmosomoides polygyrus* and *Syphacia stroma*) of the same host (*Apodemus* sp.) *Parasitology* 118:425–432
- Murray DL, Cary JR, Keith LB (1997) Interactive effects of sublethal nematodes and nutritional status on snowshoe hare vulnerability to predation *J Anim Ecol* 66:250–264
- Poulin R, Morand S (2000) The diversity of parasites. *Q Rev Biol* 75:277–293
- Prociv, P (1989) *Toxocara pteropodis* and visceral larva migrans. *Parasitol Today* 5:106–109
- Read AF, Skørping A (1995) The evolution of tissue migration by parasitic nematode larvae. *Parasitology* 111:359–371
- Scott ME (1987) Regulation of mouse colony abundance by *Heligmosomoides polygyrus*. *Parasitology* 95:111–124
- Singleton GR, Chambers LK (1996) A manipulative field experiment to examine the effect of *Capillaria hepatica* (Nematoda) on wild mouse populations in southern Australia. *Int J Parasit* 26:383–398
- Singleton GR, McCallum HI (1990) The potential of *Capillaria hepatica* to control mouse plagues. *Parasitol Today* 6:190–193



- Singleton GR, Spratt DM (1986) The effects of *Capillaria hepatica* (Nematoda) on natality and survival to weaning in BALB/c mice. *Aust J Zool* 34:687–681
- Skørping A, Read AF, Keymer AE (1991) Life history covariation in intestinal nematodes of mammals. *Oikos* 60:365–372
- Sorci G, Morand S, Hugot J-P (1997) Host-parasite coevolution: Comparative evidence for covariation of life history traits in primates and oxyurid parasites. *Proc R Soc Lond B* 264:285–289
- Tompkins DM, Begon M (1999) Parasites can regulate wildlife populations. *Parasitol Today* 15:311–313
- Trouvé S, Morand S (1998) The evolution of parasites' fecundity. *Int J Parasitol* 28:1817–1819
- Trouvé S, Sasal P, Jourdane J, Renaud F, Morand S (1998) Revisited views on the evolution of life-history traits in parasitic and free-living platyhelminthes. *Oecologia* 115:370–378
- White MJD (1973) *Animal cytology and evolution*. Cambridge Univ Press, New York