Brown, M; Mawa, PA; Kaleebu, P; Elliott, AM; (2006) Helminths and HIV infection: epidemiological observations on immunological hypotheses. Parasite immunology, 28 (11). pp. 613-623. ISSN 0141-9838 DOI: https://doi.org/10.1111/j.1365-3024.2006.00904.x

Downloaded from: http://researchonline.lshtm.ac.uk/id/eprint/10841/

DOI: https://doi.org/10.1111/j.1365-3024.2006.00904.x

Usage Guidelines:

Please refer to usage guidelines at https://researchonline.lshtm.ac.uk/policies.html or alternatively contact researchonline@lshtm.ac.uk.

Available under license: http://creativecommons.org/licenses/by-nc-nd/2.5/
Helminths and HIV infection: epidemiological observations on immunological hypotheses

M. BROWN, P. A. MAWA, P. KALEEBU & A. M. ELLIOTT

SUMMARY
Parasitic helminths have co-evolved with the mammalian immune system. Current hypotheses suggest that immunological stimulation in the presence of helminths is balanced by immuno-regulation and by the broad spectrum of mechanisms possessed by helminths for countering the host immune response. The degree to which this balance is perfected, and the mechanisms by which this is achieved, vary between helminth species; we suggest that this is reflected not only in the degree of pathology induced by helminths but also in a variety of relationships with HIV infection and HIV disease. Available epidemiological data regarding interactions between helminths and HIV are largely observational; results are variable and generally inconclusive. Well designed, controlled intervention studies are required to provide definitive information on the species-specific nature of these interactions and on the advantages, disadvantages and optimal timing of de-worming in relation to HIV infection.

Keywords helminth, HIV, immuno-regulation

INTRODUCTION
Helminth and Human Immunodeficiency Virus (HIV) infection have major effects on the host immune response and co-infection is widespread (1). They are, however, quite different in respects that are important to their interactions.

First, helminth infections are caused by diverse species from three phyla: generalizations regarding the mechanism and nature of their effects may not be appropriate. HIV is essentially a single entity.

Second, helminth infection may be, in a sense, normal to the mammalian immune system. The association between mammals and helminths is ancient: some species probably co-evolved with primates and humans; others, co-evolved with other mammals, may have crossed and adapted to humans following exposure through domestication of animals. In some host–helminth relationships adaptation appears almost perfect. Most people with helminths are unaware of their infection: the persistence of widespread infection, despite disease caused by some high intensity infections, is compatible even with a selective advantage of low intensity infection to the host. By contrast, HIV infection is not normal; it has attained a significant prevalence in humans only in the last 25 years and is universally fatal.

Third, helminths modulate the immune system, but HIV destroys it. Immune modulation by helminths may have both beneficial and detrimental effects in relation to human disease. There is evidence for benefit of helminth infection in relation to atopic disease (2,3) and to the inflammatory pathology of autoimmune disease (4–6). Studies of co-infection with helminths and malaria have produced conflicting results and interpretation of the findings varies, but it is possible that helminths may be associated with some protection against cerebral malaria, although control of replication of the parasite may be impaired (7,8). On the
other hand, for bacterial and viral infections, impaired control of replication and elimination of infection may generally lead to a detrimental outcome (9–12). That HIV infection is detrimental to the immune response to many pathogens is quite clear and poor regulation of the immune system in advanced HIV infection is illustrated by an increased incidence of hypersensitive drug reactions (13,14).

**IMMUNOLOGICAL HYPOTHESES**

During the 1990s it was proposed that helminths might impair the immune response to HIV, leading to greater susceptibility to HIV acquisition and more rapid HIV progression (15). This hypothesis was based on the concept that a T helper (Th)2 bias, induced by helminths, was a form of immune ‘dysregulation’ that might be detrimental in several ways. These included promotion of a Th2 bias with suppression of protective, Th1 responses to HIV; and expansion of a population of Th2 lymphocytes that were more susceptible to HIV infection (16); cells might also be more susceptible to HIV infection due to increased HIV coreceptor expression in response to immune activation (17,18). However, the apparent health of many helminth-infected people reflects the fact that pathways activated by helminth infection tend to be balanced by regulatory mechanisms, with recent interest focused particularly on the role of regulatory CD4+CD25+ T cells, interleukin (IL)-10 and transforming growth factor (TGF)-β (2,19). The degree to which this balance is perfected, allowing long-term parasite survival with minimal damage to the host, varies and may be enhanced in individuals born to helminth-infected mothers compared to those first exposed later in life (20,21). Thus the sequelae of infection range from an apparently healthy host despite heavy intensity infection (as with the filarial parasite, *Mansonella perstans*, and the intestinal parasite, *Enterobius vermicularis*) to the severe disease manifestations of advanced schistosomiasis; this spectrum attests to the complex interactions between effective and regulated immune responses and destructive immunopathology, which continue to mould the ecological relationship between humans and helminths. With the recent introduction of HIV into these long-established systems, pathways involved in both pro-inflammatory and regulatory responses may influence the outcome of HIV or of helminth exposure and infection.

Helminth-induced immuno-regulatory mechanisms that suppress protective responses to HIV could be detrimental. Although the function, phenotype and antigen-specificity of CD4+CD25+ regulatory T cells is not yet well defined, they have been implicated in the modulation of immune responses to bystander antigens (22) and could suppress HIV-specific CD4+ - and CD8+ -derived cytokine production and lymphocyte proliferation, suggesting that they may play a role in suppressing antiviral immune responses (23–28). On the other hand, regulatory activity could have benefits: replication of proviral DNA depends on activation of host cell transcription factors (29), so helminth-induced regulatory activity that suppresses such transcription could be beneficial, particularly in relation to HIV progression (30).

Conversely, a reduction in numbers or function of regulatory T cells has been observed in advanced HIV disease (31,32) and high foxp3 expression (indicative of regulatory T cells) has been found to correlate inversely with markers of immune activation, suggesting that loss of these cells may reduce suppression of immune activation. Regulatory T cells express the HIV coreceptor CCR5 and are readily infected by HIV in vitro (31): perhaps they are preferentially eliminated by direct HIV infection leading to uncontrolled immune activation and dysfunction. This might have important implications for the host–parasite interaction: could preferential depletion of regulatory cells, for example, create an environment imimical to parasite survival and reproduction?

Thus immunological data now suggest a range of scenarios in which helminths and HIV may each either promote or oppose acquisition or progression of the other condition.

**EPIDEMIOLOGICAL OBSERVATIONS**

Initial hypotheses regarding helminths and HIV were developed largely in the absence of epidemiological data to indicate whether substantial effects occurred, and amid controversy as to whether HIV progression was actually more rapid in regions where helminth prevalence was high (33). Several studies have now been conducted. To date, only one randomised trial of the effects of treatment (34) has yet been reported. It must be anticipated that effects are bi-directional: the effects of helminths on the immune system may influence the outcome of exposure to and infection with HIV, and the effects of HIV on the immune system may influence the outcome of exposure to and infection with helminths. Further, particularly in the case of cross-sectional and observational studies, results must be interpreted in the light of potential confounding, and of the progressive nature of HIV disease.

**Effects of helminths on HIV**

*Effects of helminths on susceptibility to HIV infection*

Studies that have examined co-prevalence of HIV and helminth infections are summarized in Table 1. The findings are pertinent to whether helminths increase susceptibility to HIV, or HIV increases susceptibility to helminths. In either case, a higher prevalence of HIV might occur in individuals with helminths.
Table 1  Associations between helminth infections and HIV status

| Worm species | Helminth prevalence observed by HIV status | Country (ref) | Comment |
|--------------|-------------------------------------------|---------------|---------|
|              | HIV-positive | HIV-negative | P  |                  |
| *S. haematobium*  |           |              |    |                  |
| in urine       | n = 134     | n = 345      |    | Zimbabwe (35)    |
| in Papanicolaou smear | 45%       | 37%          |     | Study in women only |
| in any genital specimen | 10%       | 5%           | 0·04|                   |
| *Wuchereria bancrofti* | n = 83     | n = 166      |    | Kenya (36)       |
| Schistosomiasis | 29/80 (36%) | 22/155 (14%) | < 0·001 | Case control study in pregnant women |
| Intestinal helminths* | 5/63 (8%)  | 12/122 (10%) | NS |                  |
| Strongyloides | 24/57 (42%) | 43/89 (48%)  | NS |                  |
| hookworm      | n = 100     | n = 85#      |    | Brazil (37)      |
| *S. haematobium* | n = 407     | n = 1138     |    | Zimbabwe (38)    |
| *S. mansoni*   | n = 78      | n = 78       |     | Thailand (39)    |
| Opisthorchis   | n = 78      | n = 26       |    | Ethiopia (40)    |
| *Ascaris*      | 18%         | 8%           | < 0·05 | All participants had diarrhoea |
| *Strongyloides* | 19%        | 19%          | NS  |                  |
| hookworm      | n = 365     | n = 5243     |    | Brazil (42)      |
| *Ascaris*      | 12%         | 9%           | NS  |                  |
| Trichurus      | 5%          | 6%           | NS  |                  |
| hookworm      | 4%          | 4%           | NS  |                  |
| *S. mansoni*   | 10%         | 7%           | NS  |                  |
| *Strongyloides* | 2%         | 2%           | NS  |                  |
| *Trichurus*    | 6%          | 8%           | NS  |                  |
| hookworm      | 3%          | 4%           | NS  |                  |
| *Strongyloides* | 3%         | 4%           | NS  |                  |
| *S. mansoni*   | 27%         | 28%          | NS  |                  |
| *S. haematobium & mansoni* | 9% | 8% | NS | |
| *Opisthorchis* | n = 211     | n = 213      |    | Brazil (41)      |
| *Ascaris*      | 10%         | 6%           | NS  |                  |
| *Strongyloides* | 2%         | 5%           | NS  |                  |
| *Ascaris*      | n = 365     | n = 5243     |    | Brazil (42)      |
| *Trichurus*    | 12%         | 9%           | NS  |                  |
| hookworm      | 5%          | 6%           | NS  |                  |
| *S. mansoni*   | 4%          | 4%           | NS  |                  |
| *Strongyloides* | 6%         | 1%           | < 0·001 | |
| *S. mansoni*   | 25%         | 32%          | NS  |                  |
| *Trichurus*    | n = 52      | n = 1187     |    | Ethiopia (43)    |
| hookworm      | n = 48      | n = 48       |    | Honduras (44)    |
| *Strongyloides* | 2%         | 21%          | 0·003 | |
| *Ascaris*      | 2%          | 2%           | NS  |                  |
| *Onchocerca*   | n = 93      | n = 2093     | 0·015 | |
| *Ascaris*      | n = 112     | n = 239      | 0·04 | |
| *Strongyloides* | 10%        | 1%           | < 0·001 | |
| hookworm      | n = 49      | n = 846      |    | Congo (47)       |
| *S. haematobium* | n = 112     | n = 48       |    | Honduras (44)    |
| by serology   | 16%         | 26%          | NS  |                  |
| by egg count in urine | 10%   | 18%          | NS  |                  |

*S. mansoni: Schistosoma mansoni; S. haematobium: Schistosoma haematobium. NS: no statistically significant effect.
Until recently, published studies consistently indicated a lack of epidemiological association between schistosomiasis and HIV. This was particularly surprising for *Schistosoma haematobium*, where the presence of female genital lesions and of blood and leucocytosis in seminal fluid (48) were expected to promote transmission, regardless of possible immunological effects (49). However, a recent study among rural Zimbabwean women showed a significant association between HIV and the presence of *S. haematobium* ova in genital samples, supporting the hypothesis of a specific effect on susceptibility to HIV when genital lesions are present (35).

Among nematodes, apart from one study in pregnant women indicating an association between HIV and *Wuchereria bancrofti* (36), the only evidence of a positive association is for *Strongyloides stercoralis* (39,42,46). *Strongyloides* is unusual among helminths in that it is able to complete its life-cycle and replicate in an individual human host, and this may be facilitated by immunosuppression, as discussed below. Given the lack of observed associations between HIV and other intestinal nematodes, a permissive effect of HIV on *Strongyloides* may be the most likely direction of effect.

Other studies suggest a negative association between HIV and nematode infection (44,46), which could be consistent either with a protective effect of nematodes against HIV infection or with the generation, by advancing HIV infection, of an environment that is inimical to establishment of nematode infection, nematode development, or the production of eggs (or microfilariae). In other words, HIV might ‘protect’ against the establishment or survival of a mature nematode infection, or might lead to under-diagnosis due to reduced fecundity. This possibility has been examined in relation to schistosomiasis, as discussed below, but has not yet been examined in relation to nematodes. Alternatively, the explanation may lie in unexplored confounding factors such as age and poverty.

An increase in susceptibility to HIV infection caused by helminths could be obscured in co-prevalence studies if helminths were also associated with increased HIV progression rates and hence mortality, balancing or outweighing increased incidence through loss of co-infected individuals. In this case, increased HIV prevalence in helminth-infected individuals would be more prominent early in an HIV epidemic; but even studies conducted early in the HIV epidemic for their region fail to show a positive association. In a mature epidemic, a positive association might be seen in young age groups, the effect disappearing, or becoming negative with greater age (i.e. longer duration of HIV infection): this possibility has not been examined in reported studies.

Thus co-prevalence studies to date fail to support the hypothesis that helminths generally promote acquisition of HIV infection in adults. This may be, in part, because studies were not designed specifically to address this hypothesis. Prospective studies of the incidence of sexually acquired HIV infection have not generally investigated associations with helminths, and this issue has yet to be studied in animal models in vivo (12). An exception is the recent study on female genital schistosomiasis: after one year of follow-up, seven of 224 women who were HIV-negative at baseline had seroconverted; all of these had *S. haematobium*-related findings at baseline (five with genital lesions, two with ova in urine) compared to 65% of those who did not seroconvert (P = 0.098); this result, although inconclusive, again supports the hypothesis of a specific effect on susceptibility when genital lesions are present (35). One retrospective case-control study has examined the effect of maternal helminths on vertical HIV transmission. In this study 13 of 44 HIV-exposed infants were found to be HIV infected at 12–24 months of age, and a positive association was observed between vertical transmission and maternal lymphatic filariasis (*Wuchereria bancrofti*) (36). If confirmed in further studies and for other helminths, this effect would be of considerable public health importance and might be amenable to intervention by de-worming during pregnancy, which is now advocated (for considerations such as potential effects on maternal anaemia, rather than HIV infection) (50).

**Effects of helminths on HIV disease progression**

Cross-sectional studies of associations between helminth infection and severity of HIV disease, measured by CD4+ T cell count and HIV load, suffer from issues of interpretation that are similar to those for co-prevalence studies. Thus, the hypothesized adverse effect of helminths on HIV progression might predict lower CD4 counts and higher viral loads in co-infected individuals; but higher mortality in co-infected individuals could obscure or invert such an effect, while suppression of helminth development or egg production in individuals with advanced HIV disease could lead to under-diagnosis and a spurious impression of a protective effect of helminths. Confounding with behavioural and socio-economic factors could again provide misleading results.

Most studies so far have presented results for any helminth compared to no helminth infection. Overall, CD4+ T cell counts in co-infected individuals have been higher, or similar, to those in participants with HIV alone and viral load has been similar, at least after adjusting for measured confounding factors (Table 2). Thus, at a simplistic level, results do not support the hypothesis of an adverse effect of co-infection on HIV disease. Individual studies have addressed aspects of these associations in more detail. A potentially important consideration is the effect of intensity of helminth infection. Wolday and colleagues (54) measured intensity by combining egg counts from the helminth species encountered (predominantly *Trichurus* and *Ascaris*) and found that individuals in the lowest 33% for intensity had lower viral load than those
with medium or highest intensity infection (lower, too, than helminth-free participants, although the statistical significance of this difference was not presented). On the other hand, in Uganda, we found no correlation between intensity of S. mansoni infection and viral load (55); and a study in Zambia (predominantly Ascaris and hookworm) showed no statistically significant difference in viral load between moderate-to-high and low intensity infections (51). Another potentially important consideration is the effect of helminth species. Our results in Uganda suggested a possible distinction between species such as hookworm and Mansonella, where CD4+ T cell counts might be higher (and, in the case of Mansonella, viral load lower) and Schistosoma and Strongyloides, where CD4+ T cell counts might be similar (or, for Strongyloides, lower) and viral load higher (52). These observations require confirmation, as effects were, at best, marginally statistically significant, but serve to highlight the potential importance of effects of intensity, and of species-specific differences. Our study, conducted within an existing cohort, allowed a retrospective assessment of the effects of untreated helminths (compared to no helminths) on HIV progression measured by CD4+ T cell decline. No statistically significant effects were observed.

Prospective studies of the effects of treatment of helminths are summarized in Table 3. These require consideration of the progressive nature of HIV disease. So far the presumption that helminths are detrimental has generally led to the view that helminth infections, once identified, should be treated. Lawn and colleagues found that viral load increased progressively over 15 months after successful treatment of schistosomiasis with praziquantel, and that the increase was not related to the degree of decline in egg count or serum circulating cathodic antigen (CCA), suggesting, perhaps, a lack of association with the treatment. However, lack of a comparison group made it impossible to distinguish effects of HIV progression and praziquantel treatment (56). Kallstrup and colleagues addressed this issue by randomising participants with schistosomiasis and HIV infection to immediate vs. delayed praziquantel treatment. At 3 months they found no change in viral load in the treated group, but an increase in the untreated group (34). On the other hand, we have twice observed a significant transient increase in viral load approximately one month after de-worming, in particular, after praziquantel treatment in HIV–Schistosoma co-infection; this could be related to Th2 responses to dying schistosomes and to loss of the anti-inflammatory effects of

Table 2 Associations between helminth infections and CD4+ T cell count and viral load in HIV-positive subjects

| Total number of HIV positive participants | Number infected and helminth species | Effect of co-infection with helminths on CD4+ T cell count | Effect of co-infection with helminths on viral load | Country (ref) | Comments |
|------------------------------------------|-------------------------------------|----------------------------------------------------------|--------------------------------------------------|--------------|----------|
| 111                                      | 54 All species (predominant species: Ascaris and hookworm) | Higher (P = 0·02)                                         | NS                                                | Zambia (51) |          |
| 185                                      | 143 Schistosomiasis                 | NS                                                        | Not done                                         | Zimbabwe (38) | Compared subjects with and without schistosomiasis (NS after adjustment for potential confounding factors) |
| 539                                      | 290 All species                    | NS Higher (P = 0·007)                                      | NS Higher (P = 0·03)                             | Uganda (52) |          |
|                                           | Hookworm                           | NS                                                        | NS                                               |              |          |
|                                           | S. mansoni                          | NS                                                        | Higher (P = 0·007)                                |              |          |
|                                           | Strongyloides                       | NS                                                        | Higher (P = 0·03)                                |              |          |
|                                           | Mansonella                          | Higher (P = 0·04)                                         | NS                                               |              |          |
| 108                                      | 39 All species (predominant species: S. mansoni and hookworm) | Higher (P = 0·005)                                         | NS                                                | Uganda (53) |          |
| 56                                       | 31 All species (predominant species: Trichuris and Ascaris) | NS                                                        | NS                                                | Ethiopia (54) |          |
| 365                                      | 161 All species (predominant species: Ascaris, Strongyloides, Trichuris and hookworm) | NS                                                        | Lower (P = 0·02)                                 | Brazil (42) |          |

S. mansoni: Schistosoma mansoni; S. haematobium: Schistosoma haematobium. NS: no statistically significant effect.

© 2006 The Authors
Journal compilation © 2006 Blackwell Publishing Ltd, Parasite Immunology, 28, 613–623
### Table 3: Associations between helminths and worm infections: prospective studies of treatment

| Number of participants and helminth species | Treatment | Follow-up time | Comparison made | Change in CD4 with treatment | Change in viral load (VL) with treatment | Country (ref) | Comments |
|--------------------------------------------|-----------|----------------|----------------|------------------------------|------------------------------------------|--------------|----------|
| 130 participants with *S. mansoni* and/or *S. haematobium* | Prazi 40 mg/kg | 3 months | Untreated vs. treated | No significant change in either group | No change in treated group; increase in untreated group | Zimbabwe (34) | $P = 0.03$ for difference in change in viral load between treated and untreated groups |
| 54 participants (predominantly Ascaris and hookworm) | Two treatments, 1 mth apart, with alb (3 days, 400, 200, 200 mg) and prazi (40 mg/kg, divided) | 9 weeks | Uninfected vs. infected | No significant change in either group | No significant change in either group | Zambia (51) | VL declined after treatment in 6 people with high intensity infection |
| 234 participants with helminths | Alb 400 mg stat | 6 months | Successfully treated vs. persistently infected | NS | NS | Uganda (52) | 

97 Hookworm | Alb 400 mg stat | NS | NS | NS |

159 *S. mansoni* | Prazi 40 mg/kg | Larger decrease if cleared ($P = 0.05$) | NS | NS |

53 *Strongyloides* | Alb 400 mg bd 3/7 | NS | NS |

40 *Mansonella* | None | Increase if cleared, decrease if persisted ($P = 0.005$) | NS |

31 participants with helminths (predominantly Trichuris and Ascaris) | Three treatments, 3 mth apart, with alb 200 mg daily, 3 days; plus prazi (40 mg/kg, divided, for schistosomiasis) | 6 months | Uninfected vs. successfully treated vs. persistently infected | No change in any group | Decrease in successfully treated group; increase in uninfected and persistently infected groups ($P = 0.04$)$^b$ | Ethiopia (54) | $^b$P-value for comparison with successfully treated group. |

30 men with *S. mansoni* | Single dose of prazi 40 mg/kg | 1–15 months | None | Not reported | Increased | Kenya (56) | No correlation between change in VL and change in egg count or CCA concentration |

*S. mansoni*: Schistosoma mansoni; *S. haematobium*: Schistosoma haematobium. Alb: albendazole. prazi: praziquantel. NS: no statistically significant difference between the groups compared.
schistosome-induced IL-10 (53,55). This may be important with regard to the treatment of helminths in HIV-infected women during pregnancy, as a transient rise in viral load might have the reverse of the desired effect on vertical HIV transmission. Modjarrad and colleagues compared changes in CD4 counts and viral load over an approximately 9-week period between participants who were treated for helminths (predominantly hookworm and Ascaris) and participants without helminths, who were untreated. They found little change in CD4 count or viral load in either group (51). In other studies, comparisons have been made, within helminth-infected groups, between those treated successfully and those with persistent infection. Wolday and colleagues (Ascaris and Trichuris) observed a decrease in viral load following successful treatment, and an increase with persistent infection (54), but no such effect was observed for the common species (S. mansoni, hookworm, Strongyloides and Mansonella) in our study in Uganda. In fact, in Uganda, particular interest again attached to Mansonella. This species was not susceptible to the treatments given, and, being regarded as non-pathogenic, was not specifically treated. Persistence of infection was associated with a decline in viral load, and spontaneous clearing of infection with an increase (52).

Thus cross-sectional, retrospective and prospective data to date fail to support the hypothesis that helminth infection, in general, promotes HIV progression, but the findings reported by Kallestrup and colleagues, together with studies in a macaque model, point to a detrimental effect of schistosomiasis (12,34). In the macaque, effects were observed principally in association with initial viral inoculation and with the development of adult worms and egg-laying following new or renewed schistosome infection; this is perhaps in keeping with the tendency of schistosome eggs to induce pathological inflammatory responses. Further, there is some evidence that schistosomiasis may be associated with increased susceptibility to tuberculosis in people with HIV infection (57): if this is the case, schistosomiasis could promote HIV progression indirectly, by increasing susceptibility to additional co-infections with a more potent influence on viral replication (58,59). Schistosomiasis aside, there are some hints that high intensity infections with certain helminth species may be associated with higher viral loads, which may decline with treatment, but, to be convincing, these findings would need to be confirmed in larger studies. The vast majority of HIV-infected adults with helminths have low intensity infections, so the effects, if any, of low-intensity infections are pertinent. As suggested by Modjarrad and colleagues, the effects of high intensity helminth infections may be best explored, and most relevant, among children with HIV, where both worm burden and viral load tend to be high (51). There are hints, too, of differences in effect between helminth species, and even of possible benefits of helminth infection; these need to be investigated in more focused, prospective studies; uncertainty regarding the advantages and disadvantages of treatment suggest that placebo-controlled trials would be justified.

Effects of helminths on vaccination against HIV

No vaccine against HIV is yet ready for implementation (60), but there is evidence that helminth infection can alter both cellular and antibody responses to other, existing vaccines (61–69); suppression of responses and switching to a Th2 profile have both been observed. Effects may differ for vaccines given orally (where effects of intestinal helminths on the mucosa may suppress the development of the response (66,67)), compared with parenteral vaccines; and for live vectors (viral vectors, Salmonella or Bacille Calmette Guérin (BCG)), where there could be effects on the replication of the vector and hence the dose of vaccine antigen experienced (69). Results of on-going studies of interactions between helminths and existing vaccines, including the role and timing of de-worming in determining vaccine efficacy, are likely to be pertinent as HIV vaccines are developed, tested and implemented; however, it is unlikely that helminth infection accounts for the poor immunogenicity of vaccine candidates tested in Africa to date; recent phase I trials of DNA/modified vaccinia Ankara (MVA) vaccines showed poor immunogenicity in both Africa and Europe (70–72).

Effects of HIV on helminths

HIV-induced CD4+ T-lymphocyte depletion, immune activation and changes in Th1/Th2 and regulatory responses should, in theory, affect the epidemiology of helminth-associated disease in co-infected individuals. Anticipated effects might include changes in immunopathology, reduced efficacy of treatment and impaired resistance to infection or re-infection. However, to date, there is surprisingly little evidence of effects of HIV on these parameters. Most information available is from Schistosoma, Onchocerca and Strongyloides infections, as follows.

Animal models of immunosuppression suggest that granuloma formation and consequently schistosome egg excretion might be reduced in HIV infection (73). Initial studies in humans supported this hypothesis (47,74,75) with evidence of reduced egg excretion in HIV-infected subjects. Recent case reports describe symptomatic schistosomal infection as an immune reconstitution phenomenon following antiretroviral therapy: these also imply that pathological responses to schistosomes and schistosome eggs are suppressed in advanced HIV disease and recover with reconstitution of the immune response (76,77). However, other studies have failed to demonstrate an effect of HIV on egg excretion or liver
fibrosis (38,43,55,78). Similarly, efficacy of praziquantel, which is considered to act, in part, by exposing worms to immunologically mediated killing (79), has not been found to be impaired in HIV-infected people (75,80). Karanja and colleagues demonstrated a small effect of HIV on the acquisition of resistance to re-infection in heavily exposed Kenyan adults, which may in part be explained by suppression of post-treatment S. mansoni-specific cytokine and antibody responses (81–83).

Studies from Uganda have explored associations between Onchocerca volvulus infection and HIV status. Reduced Onchocerca-specific cytokine and antibody responses were found in HIV-co-infected individuals, which were more marked in subjects with lower CD4+ counts, but skin microfilarial densities were marginally lower in HIV-positive subjects and it is difficult to exclude confounding by differences in exposure, or reduced onchocercal fecundity in the presence of HIV (84–86). Kipp and colleagues found more severe onchocercal skin disease in co-infected patients, but this finding was based on only six HIV-infected subjects (87). There was no effect of HIV on ivermectin efficacy (85).

The effect of HIV on Strongyloides infection is of particular interest because of the severe manifestations of disseminated S. stercoralis infection seen following immunosuppression by corticosteroids, malignancy and HTLV-1 infection. Although well described in HIV-infected subjects without evidence of other mechanisms of immunosuppression, the syndrome is less common than might be expected in regions of high co-prevalence (88). Animal models suggest that host immunosuppression facilitates dissemination by promoting a switch towards direct development of Strongyloides larvae into infective L3 larvae, thereby by-passing the free-living adult stage and allowing auto-infection of the host (89). Following on from this work, we studied Strongyloides development among HIV-infected adults in Uganda (90). Charcoal stool cultures positive for Strongyloides were dissected and the ratio of infective L3 larvae to free-living adults was assessed. We expected that subjects with lower CD4+ counts would have a higher proportion of infective L3 larvae, in keeping with animal models. In fact, the opposite was found, with a positive correlation between direct development and CD4+ count. This may explain the low incidence of hyperinfection in HIV-infected adults, and attests to differences in the nature of the immune deficit between advanced HIV infection and other immunosuppressive states: corticosteroid-induced immunosuppression is associated with prominent expression of regulatory cytokines, such as IL-10 (91), and HTLV-1 infection with depletion of type 2 cytokines (92), but in HIV infection, regulatory T cells may be preferentially destroyed (31) and type 2 cytokine responses may be relatively preserved (93). There was no association between CD4+ count and total number of larvae per culture in the Ugandan study (MB, unpublished observations), which further argues against either an increase in Strongyloides fecundity or burden. Thus although the association between Strongyloides and HIV observed in some co-prevalence studies may be due to increased susceptibility to Strongyloides, this may be mediated by a mechanism other than auto-infection. Recent case reports of symptomatic strongyloidiasis presenting as an immune reconstitution syndrome after initiation of antiretroviral therapy (ART) suggest a protective effect of HIV-induced immunosuppression on some aspects of Strongyloides pathogenesis (94–96).

Thus results to date indicate that effects of HIV on the pathological consequences of, and susceptibility to, helminth infections may be minor compared with effects on viral, bacterial and fungal infections, where a major component of the increased susceptibility is loss of control of replication: these organisms, unlike most helminths, complete their life-cycle within the host. The hypothesis, suggested above, that progressive impairment of immune regulation in HIV disease can render the host environment less conducive to the maintenance of parasitic helminth infections has not yet been investigated.

**CONCLUSIONS**

Early hypotheses on potential mechanisms for helminth–HIV interactions were inspired by the Th1/Th2 hypothesis. These must now be superseded by models that take account of regulatory mechanisms which are being shown to have a potent effect on helminth-induced responses and, it emerges, on HIV.

There is epidemiological evidence for a bi-directional interaction between helminths and HIV; the direction of effects is not easy to disentangle in observational studies and there is a pressing need for well-designed, randomised, controlled intervention trials. These must take into account the possibility of differences in effect between helminth species, stage and intensity of infection; between effects on the acquisition, and effects on the progression, of HIV infection; and perhaps indirect effects of helminths mediated by a possible increase in susceptibility to additional co-infections such as malaria (7,8) and tuberculosis (11,57–59,68).

Consider the following suggestion. Host–parasite relationships (exemplified by Mansonella, perhaps also hookworm) that are characterized by minimal pathology, implying balanced interactions between inflammatory and regulatory responses, might not promote viral replication; their effect might be neutral or even protective with regard to HIV progression; their removal might promote viral replication by reducing regulatory control of transcription. They might, however, be associated with less effective immune responses after initial inoculation of virus or vaccine. Conversely, their
host–parasite balance might be vulnerable to selective loss of components of the immune response during HIV progression, leading to lower prevalence with advancing HIV disease. Host–parasite interactions such as schistosomiasis, where inflammatory responses have persisted through evolution, perhaps due to a selective advantage for parasite egg excretion, may be more detrimental with regard to HIV infection and treatment may be beneficial in most circumstances.

The past decade has brought to light the interest and complexity of helminth–HIV interactions. The next decade provides opportunities for definitive studies.

ACKNOWLEDGEMENTS

We acknowledge the support of the Wellcome Trust, who funded our work in Uganda through fellowships awarded to MB and AME.

REFERENCES

1 Bundy D, Sher A & Michael E. Good worms or bad worms: do worm infections affect the epidemiological patterns of other diseases? Parasitol Today 2000; 16: 273–274.

2 Maizels RM. Infections and allergy – helminths, hygiene and host immune regulation. Curr Opin Immunol 2005; 17: 656–661.

3 Elliott AM, Mpairwe H, Quigley M et al. Helminth infection during pregnancy and development of infantile eczema. JAMA 2005; 294: 2032–2034.

4 Cooke A, Tonks P, Jones FM et al. Infection with Schistosoma mansoni prevents insulin dependent diabetes mellitus in non-obese diabetic mice. Parasite Immunol 1999; 21: 169–176.

5 Summers RW. Elliott DE Urban JF Jr, Thompson RA & Weinstock JV. Trichuris suis therapy for active ulcerative colitis: a randomized controlled trial. Gastroenterology 2005; 128: 825–832.

6 Summers RW, Elliott DE, Urban JF Jr, Thompson R & Weinstock JV. Trichuris suis therapy in Crohn's disease. Gut 2005; 54: 87–90.

7 Nacher M. Interactions between worm infections and malaria. Clin Rev Allergy Immunol 2004; 26: 85–92.

8 Druilhe P Adama J & Sokhna C. Worms can worsen malaria: towards a new means to roll back malaria. Trends Parasitol 2005; 21: 359–362.

9 Acker J Sharai M Kumberg M Buller R Sher A & Berzofsky J. Helminth infection results in decreased virus-specific CD8+ cytotoxic T-cell and Th1 cytokine responses as well as delayed virus clearance. Proc Natl Acad Sci USA 1993; 90: 948–952.

10 Brady MT O'Neill SM Dalton JP & Mills KH. Fasciola hepatica suppresses a protective Th1 response against Bordetella pertussis. Infect Immun 1999; 67: 5372–5378.

11 Elias D Akuffo H Thors C Pawlowski A & Britton S. Low dose chronic Schistosoma mansoni infection increases susceptibility to Mycobacterium bovis BCG infection in mice. Clin Exp Immunol 2005; 139: 398–404.

12 Chenine A-L, Buckley KA, LiP-L et al. Schistosoma mansoni promotes SVIV clade C replication in rhesus macaques. AIDS 2005; 19: 1793–1797.
NF-κB sites in the long terminal repeat. Proc Natl Acad Sci USA 1989; 86: 5974–5978.

30 Schotteius AJ, Mayo MW, Sartor RB & Baldwin AS Jr. Interleukin-10 signaling blocks inhibitor of κB kinase activity and nuclear factor κB DNA binding. J Biol Chem 1999; 274: 31868–31874.

31 Oswald-Richter K, Grill SM, Shariat N et al. HIV infection of naturally occurring and genetically reprogrammed human regulatory T-cells. PLoS Biol 2004; 2: 955–966.

32 Tsunemi S, Iwasaki T, Imado T et al. Relationship of CD4+CD25+ regulatory T cells to immune status in HIV-infected patients. AIDS 2005; 19: 879–886.

33 Morgan D & Whitworth J. The natural history of HIV-1 infection in Africa. Nature Med 2001; 7: 143–145.

34 Kjetland EF, Ndhlovu PD, Gomo E et al. Schistosomiasis and HIV-1 infection in rural Zimbabwe: effect of treatment of schistosomiasis on CD4 cell count and plasma HIV-1 RNA load. J Infect Dis 2005; 192: 1956–1961.

35 Kettlefield EF, Ndhlouvou PD, Gomo E et al. Association between genital schistosomiasis and HIV in rural Zimbabwean women. AIDS 2006; 20: 593–600.

36 Gallagher M, Malhotra I, Mungai PL et al. The effects of maternal malaria and helminth infections on mother-to-child HIV transmission. AIDS 2005; 19: 1849–1855.

37 Da Silva CV, Ferreira MS, Borges AS & Costa-Cruz JM. Intestinal parasitic infections in HIV/AIDS patients: experience at a teaching hospital in central Brazil. Scand J Infect Dis 2005; 37: 211–215.

38 Kallestrup P, Zinyama R, Gomo E et al. Schistosomiasis and HIV-1 infection in rural Zimbabwe: implications of coinfection for excretion of eggs. J Infect Dis 2005; 191: 1311–1320.

39 Pinlar S, Mootskapun P, Pinlar P, Pipitgool V & Tuangnadee R. Detection of opportunistic and non-opportunistic intestinal parasites and liver flukes in HIV-positive and HIV-negative subjects. Southeast Asian J Trop Med Public Health 2005; 36: 841–845.

40 Hailemariam G, Kassu A, Abebe G et al. Intestinal parasitic infections in HIV/AIDS and HIV seronegative individuals in a teaching hospital, Ethiopia. Jpn J Infect Dis 2004; 57: 41–43.

41 Marchi Blatt J & Cantos GA. Evaluation of techniques for the diagnosis of Strongyloides stercoralis in human immunodeficiency virus (HIV) positive and HIV negative individuals in the city of Itajai, Brazil. Braz J Infect Dis 2003; 7: 402–408.

42 Feitosa G, Bandeira AC, Sampaio DP, Badaró R & Brites C. High prevalence of giardiasis and strongyloides among HIV-infected patients in Bahia, Brazil. Braz J Infect Dis 2001; 5: 339–344.

43 Fontanet AL, Woldemichael T, Sahlu T et al. Epidemiology of HIV and Schistosoma mansoni infections among sugar-estate residents in Ethiopia. Ann Trop Med Parasitol 2000; 94: 145–155.

44 Lindo JF, Dubon JM, Ager AL et al. Intestinal parasitic infections in human immunodeficiency virus (HIV)-positive and HIV-negative individuals in San Pedro Sula, Honduras. Am J Trop Med Hyg 1998; 59: 431–435.

45 Fischer P, Kipp W, Kabwa P & Buttner DW. Onchocerciasis and human immunodeficiency virus in western Uganda: prevalence and treatment with ivermectin. Am J Trop Med Hyg 1995; 53: 171–178.

46 Gomez Morales MA, Atzori C, Ludovisi A, Rossi P, Scaglia M & Pozio E. Opportunistic and non-opportunistic parasites in HIV-positive and negative patients with diarrhoea in Tanzania. Trop Med Parasitol 1995; 46: 109–114.

47 N’Zoukoudi-N’Doundou MY, Dirat I, Akouala JJ, Penchenier L, Makuwa M & Rey JL. Bilharziasis and human immunodeficiency virus infection in Congo. Med Trop (Mars) 1995; 55: 249–251.

48 Leutscher PD, Pedersen M, Raharisoa C et al. Increased prevalence of leukocytes and elevated cytokine levels in semen from Schistosoma haematobium infected individuals. J Infect Dis 2005; 191: 1639–1647.

49 Feldmeier H, Krantz I & Poggensee G. Female genital schistosomiasis as a risk factor for the transmission of HIV. Int J STD AIDS 1994; 5: 368–372.

50 Allen HE, Crompton DWT, de Silva N, LoVerde PT & Olds GR. New policies for using anthelminthics in high risk groups. Trends Parasitol 2002; 18: 381–382.

51 Modjarrad K, Zulu I, Redden DT et al. Treatment of intestinal helmiths does not reduce plasma concentrations of HIV-1 RNA in co-infected Zambian adults. J Infect Dis 2005; 192: 1277–1283.

52 Brown M, Kizza M, Watera C et al. Helminth infection is not associated with faster HIV disease progression in co-infected adults in Uganda. J Infect Dis 2004; 190: 1869–1879.

53 Elliott AM, Mawa PA, Joseph S et al. Associations between helminth infection and CD4+ T cell count, viral load and cytokine responses in HIV-1 infected Ugandan adults. Trans Roy Soc Trop Med Hyg 2003; 97: 103–108.

54 Wolday D, Mayaan S, Mariam ZG et al. Treatment of intestinal worms is associated with decreased HIV plasma viral load. J Acquired Immune Defic Syndr 2002; 31: 56–62.

55 Brown M, Mawa P, Joseph S et al. Treatment of Schistosoma mansoni increases helminth-specific type 2 cytokines and HIV-1 RNA concentrations in co-infected Ugandan adults. J Infect Dis 2005; 191: 1648–1657.

56 Lawn SD, Karanja DMS, Mwinzi P et al. The effect of treatment of schistosomiasis on blood plasma HIV-1 RNA concentration in coinfected individuals. AIDS 2000; 14: 2437–2443.

57 Brown M, Miroy G, Nkurunziza P et al. Schistosoma mansoni, nematode infections and progression to active tuberculosis among HIV-1-infected Ugandans. Am J Trop Med Hyg 2006; 74: 819–825.

58 Goletti D, Weissman D, Jackson RW et al. Effect of Mycobacterium tuberculosis on HIV replication: role of immune activation. J Immunol 1996; 157: 1271–1278.

59 Whalen C, Horsburgh CR, Hom D, Lahart C, Simberko M & Ellner JJ. Accelerated course of human immunodeficiency virus infection after tuberculosis. Am J Respir Crit Care Med 1995; 151: 129–135.

60 Gallo RC. The end or the beginning of the drive to an HIV-preventive vaccine: a view from over 20 years. Lancet 2005; 366: 1894–1898.

61 Kilian HD & Nielsen G. Cell mediated and humoral immune response to tetanus vaccinations in onchocerciasis patients. Trop Med Parasitol 1989; 40: 285–291.

62 Kilian HD & Nielsen G. Cell mediated and humoral immune responses to BCG and tubella vaccinations and to recall antigens in onchocerciasis patients. Trop Med Parasitol 1989; 40: 445–453.

63 Sabin EA, Ilma Araujo M, Carvalho EM & Pearce EJ. Impairment of tetanus toxoid-specific Th1-like immune responses in humans infected with Schistosoma mansoni. J Infect Dis 1996; 173: 269–272.

64 Cooper PJ, Espinel I, Paredes W, Guderian RH & Nutman TB. Impaired tetanus-specific cellular and humoral responses following tetanus vaccination in human onchocerciasis. J Infect Dis 1998; 178: 1133–1138.

65 Malhotra I, Mungai P, Warnachi A et al. Helminth- and Bacillus-
Calmette-Guerin-induced immunity in children sensitized in utero to filariasis and schistosomiasis. *J Immunol* 1999; 162: 6843–6848.

Cooper PJ, Chico ME, Losonsky G et al. Albendazole treatment of children with ascarisiasis enhances the vibriocidal antibody response to the live attenuated oral cholera vaccine CVD 103-HgR. *J Infect Dis* 2000; 182: 1199–1206.

Cooper PJ, Chico M, Sandoval C et al. Human infection with *Ascaris lumbricoides* is associated with suppression of the interleukin-2 response to recombinant cholera toxin B subunit following vaccination with the live oral cholera vaccine CVD 103-HgR. *Infect Immun* 2001; 69: 1574–1580.

Elias D, Wolday D, Akuffo H, Petros B, Bronner U & Britton S. Effect of deworming on human T cell responses to mycobacterial antigens in helminth-exposed individuals before and after bacille Calmette-Guérin (BCG) vaccination. *Clin Exp Immunol* 2001; 123: 219–225.

Elliott AM, Namujju PB, Mawa PA et al. A randomised controlled trial of the effects of albendazole in pregnancy on maternal responses to mycobacterial antigens and infant responses to bacille Calmette-Guerin (BCG) immunisation [ISRCTN32849447]. *BMC Infectious Dis* 2005; 5: 115.

Guimaraes-Walker A, Mackie N, McMichael A et al. Priming with a candidate HIV-1 clade A DNA vaccine followed by booster with HIV-1 clade A MVA vaccine in volunteers at low risk of HIV infection. *AIDS Vaccine* 04, Lausanne, Switzerland 2004; 55 (Abstract).

Jaoko W, Omosa G, Bhatt K et al. Safety and immunogenicity of DNA and MVA HIVA vaccines in phase 1 HIV-1 vaccine trials in Nairobi, Kenya. *AIDS Vaccine* 04, Lausanne, Switzerland 2004; 55 (Abstract).

Nakwagala F, Birungi J, Schmidt C et al. Safety and immunogenicity of HIV-1 clade A vaccines in HIV-uninfected adult Ugandan volunteers. *AIDS Vaccine* 04, Lausanne, Switzerland 2004, Abstract P244.

Doenhoff MJ, Hassounah O, Murare H, Bain J & Lucas S. The schistosome egg granuloma: immunopathology in the cause of host protection or parasite survival? *Trans R Soc Trop Med Hyg* 1986; 80: 503–514.

Karanja DM, Colley DG, Nahlen BL, Ouma JH & Secor WE. Studies on schistosomiasis in western Kenya: I. Evidence for immune-facilitated excretion of schistosomiasis eggs from patients with *Schistosoma mansoni* and human immunodeficiency virus coinfections. *Am J Trop Med Hyg* 1997; 56: 515–521.

Mwanakasale V, Yovantsou P, Sukwa T, Ziba M, Ernest A & Tanner M. Interaction between *Schistosoma haematobium* and human immunodeficiency virus type 1: the effects of coinfection on treatment outcomes in rural Zambia. *Am J Trop Med Hyg* 2003; 69: 420–428.

Fernando R & Miller R. Immune reconstitution eosinophilia due to schistosomiasis. *Sex Transm Infect* 2002; 78: 76.

de Silva S, Walsh J & Brown M. Symptomatic *Schistosoma mansoni* infection as an immune restoration phenomenon in a patient receiving antiretroviral therapy. *Clin Infect Dis* 2006; 42: 303–304.

Mwinzi PNM, Karanja DMS, Kareko I et al. Evaluation of hepatic fibrosis in persons co-infected with *Schistosoma mansoni* and human immunodeficiency virus 1. *Am J Trop Med Hyg* 2004; 71: 783–786.

Sabah AA, Fletcher C, Webbe G & Doenhoff MJ. *Schistosoma mansoni*: reduced efficacy of chemotherapy in infected T-cell-deprived mice. *Exp Parasitol* 1985; 60: 348–354.

Karanja DM, Boyer AE, Strand M et al. Studies on schistosomiasis in western Kenya: II. Efficacy of praziquantel for treatment of schistosomiasis in persons coinfected with human immunodeficiency virus-1. *Am J Trop Med Hyg* 1998; 59: 307–311.

Karanja DM, Hightower AW, Colley DG et al. Resistance to reinfestation with *Schistosoma mansoni* in occupationally exposed adults and effect of HIV-1 co-infection on susceptibility to schistosomiasis: a longitudinal study. *Lancet* 2002; 360: 592–596.

Mwinzi PN, Karanja DM, Colley DG, Orago AS & Secor WE. Cellular immune responses of schistosomiasis patients are altered by human immunodeficiency virus type 1 coinfection. *J Infect Dis* 2001; 184: 488–496.

Joseph S, Jones FM, Laidlaw ME et al. Impairment of the *Schistosoma mansoni*-specific immune responses elicited by treatment with Praziquantel in Ugandans with HIV-1 co-infection. *J Infect Dis* 2004; 190: 613–618.

Sentongo E, Rubaale T, Buttner DW & Brattig NW. T cell responses in coinfection with *Onchocerca volvulus* and the human immunodeficiency virus type 1. *Parasite Immunol* 1998; 20: 431–439.

Fischer P, Kipp W, Kabwa P & Buttner DW. Onchocerciasis and human immunodeficiency virus in western Uganda: prevalence and treatment. *Am J Trop Med Hyg* 1995; 53: 171–178.

Tawill SA, Gallin M, Erttman KD, Kipp W, Bamuhija J & Buttner DW. Impaired antibody responses and loss of reactivity to *Onchocerca volvulus* antigens by HIV-seropositive onchocerciasis patients. *Trans R Soc Trop Med Hyg* 1996; 90: 85–89.

Kipp W, Bamuhija J & Rubaale T. *Simulium neavei*-transmitted onchocerciasis: HIV infection increases severity of onchocercal skin disease in a small sample of patients. *Trans R Soc Trop Med Hyg* 2003; 97: 310–311.

Lucas SB, Hounou A, Peacock C et al. The mortality and pathology of HIV infection in a west African city. *AIDS* 1993; 7: 1569–1579.

Harvey SC, Gemmill AW, Read AF & Viney ME. The control of morph development in the parasitic nematode *Strongyloides ratti*. *Proc R Soc Lond B Biol Sci* 2000; 267: 2057–2063.

Viney ME, Brown M, Omoding NE et al. Why does HIV infection not lead to disseminated strongyloidiasis? *J Infect Dis* 2004; 190: 2175–2180.

Barnes PJ. Anti-inflammatory actions of glucocorticoids: molecular mechanisms. *Clin Sci* 1998; 94: 557–572.

Neve FA, Filho JO, Gam AA et al. Interferon-gamma and interleukin-4 responses in relation to serum IgE levels in persons infected with human T lymphotropic virus type I and *Strongyloides stercoralis*. *J Infect Dis* 1998; 178: 1856–1859.

Clerici M, Hakim FT, Venzon DJ et al. Changes in interleukin-2 and interleukin-4 production in asymptomatic, human immunodeficiency virus-seropositive individuals. *J Clin Invest* 1993; 91: 759–765.

Kim A & Lupatkin HC. *Strongyloides stercoralis* infection as a manifestation of immune restoration syndrome. *Clin Infect Dis* 2004; 39: 439–440.

Lanzafame M, Faggian F, Lattuada E, Antolini D & Vento S. Strongyloidiasis in an HIV-1-infected patient after highly active antiretroviral therapy-induced immune restoration. *J Infect Dis* 2005; 191: 1027.

Brown M, Cartledge JD & Miller RF. Dissemination of *Strongyloides stercoralis* as an immune restoration phenomenon in an HIV-1-infected man on antiretroviral therapy. *Int J STD AIDS* 2006; 17: 000–000 in press.