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Transmission intensity and human immune responses to lymphatic filariasis

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SUMMARY

Our understanding of how the host immune response influences the risk of developing disease has changed dramatically over the past decade. Previously, the spectrum of disease associated with lymphatic filariasis was largely attributed to the nature of the host immune response. Now, we appreciate that the duration and intensity of infection and possibly the direct influence of parasite-derived molecules also determine the risk of disease. Individuals chronically infected with lymphatic filariasis generally have an impaired lymphocyte proliferation response to filarial antigens and favour Th2-type cytokine responses. This ability to down-modulate the host immune response may help protect the host from disease. Defects in antigen-presenting cell (APC) function appear to participate in this acquired immune hyporesponsiveness, although the mechanisms as to how this occurs are poorly understood. Here, we present evidence that repeated exposure to infective stage larvae and their secreted products may stimulate basophils and mast cells to related products that may impair APC function.

Keywords *transmission intensity, filarial nematodes, basophils, IL-4*

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INTRODUCTION

The broad diversity of clinical responses to filarial infection has been generally considered to reflect the intensity, and type of immune response to the parasite or parasite products (1). We now recognize that factors other than the host immune response are likely to contribute to whether an individual develops clinically apparent disease or not. Since the parasite does not replicate within the human host, the cumulative and/or temporal pattern of exposure to infective larvae determines the infection load and may therefore increase the likelihood of developing disease. This implies that parasite themselves, their soluble products and/or their anatomical location may directly affect lymphatic function apart from the host immune response and increase the risk of developing disease. Genetic polymorphisms in the parasite and/or host may also influence the susceptibility to infection and/or disease. It has also been hypothesized that secondary infection by bacteria of already damaged lymphatics by pre-existing *Wuchereria bancrofti* infection may accelerate or exacerbate development of chronic lymphatic disease (2). These hypotheses are probably not mutually exclusive and each, to varying degrees, may contribute to the heterogeneity in infection and disease with lymphatic filariasis infection.

This review examines the interrelationship between the first two hypotheses: the impact of transmission intensity on the host immune response. This link between transmission and host immunity derives from the complex life cycle of lymphatic dwelling filariae and the likelihood that shared antigens exist between the different stages of the parasite (3,4). Similar to other nematodes, *W. bancrofti* has five distinct developmental stages and four of these stages occur within the human host beginning with inoculation of the infective stage larvae, or L3. L3 are deposited on the skin during blood feeding by the mosquito vector. The larvae enter the host at the puncture site and penetrate the dermis to establish residence in the local lymphatics, a tissue niche

that is absolutely essential for their survival and subsequent development (5–7). Nine to 14 days later, and after L3 have shed their cuticle (i.e. moulted), fourth-stage larvae appear and differentiate over 6–9 months into sexually mature adult worms. Once an adequate number of female and male worms accumulate in the lumen of afferent lymphatic vessels, microfilariae are produced and released by fecund female worms. Infective stage larvae release proteolytic enzymes that facilitate the penetration process (8). These molecules can also be highly antigenic and have the potential to influence the type of immune response (9).

IMMEDIATE HYPERSENSITIVITY RESPONSES AND THE TH1/TH2 PARADIGM

Immediate hypersensitivity reactions, characterized by the presence of immunoglobulin (Ig)E antibody, eosinophils, mast cells and basophils, are the hallmark of helminth infections, including lymphatic filariasis. Each of these immediate hypersensitivity responses has been implicated in the resistance to infection and in the various clinical manifestations of disease (10). In spite of the frequently elevated levels of IgE and eosinophilia in patients with lymphatic filariasis, they rarely have clinically apparent allergic reactions to these parasites, although their basophils and mast cells can be highly sensitized with specific antiparasitic IgE (11). This effector arm of the immediate hypersensitivity response is thought, in part, to be modulated by the production of blocking antibodies that are abundant in the serum of filarial infected patients (11,12). These blocking antibodies, by definition, can inhibit IgE-mediated activation of basophils. Blocking antibodies are primarily of the IgG4 isotype (11) and show a pattern of antigen recognition that parallels IgE (13), suggesting that blocking antibodies bind to parasite allergens in the fluid phase, thereby preventing access of the allergens to IgE-coated mast cells. Filarial infected individuals also produce large amounts of polyclonal IgE that does not recognize filarial antigens (12,14). This nonspecific IgE can also bind to the high affinity FcεRI on mast cells and basophils and reduce the amount of filarial-specific IgE bound to the cell surface. Therefore, only large amounts of filarial antigens can cross-link the widely spaced filarial-specific IgE on the cell surface which is necessary for cell activation.

Filarial antigen-specific T cells are thought to regulate the induction and down-modulation of the immediate hypersensitivity response and blocking antibodies (1,15,16). The Th1/Th2 paradigm has been an attractive model to understand this T cell response in human lymphatic filariasis. Typically, filarial infected individuals stimulate an expanded population of antigen-specific T cells that produce varying amounts of interleukin (IL)-4, IL-5, IL-10 and IL-13 (17–21). Most of these cytokines are associated with a Th2-type immune response and participate in the generation of the immediate hypersensitivity responses described above. IL-4 and IL-13 produced by these T cells stimulate polyclonal and antigen-specific IgE and IgG4 (22,23). The cytokine regulation of IgG4, although it can parallel that of IgE, is also distinct (24).

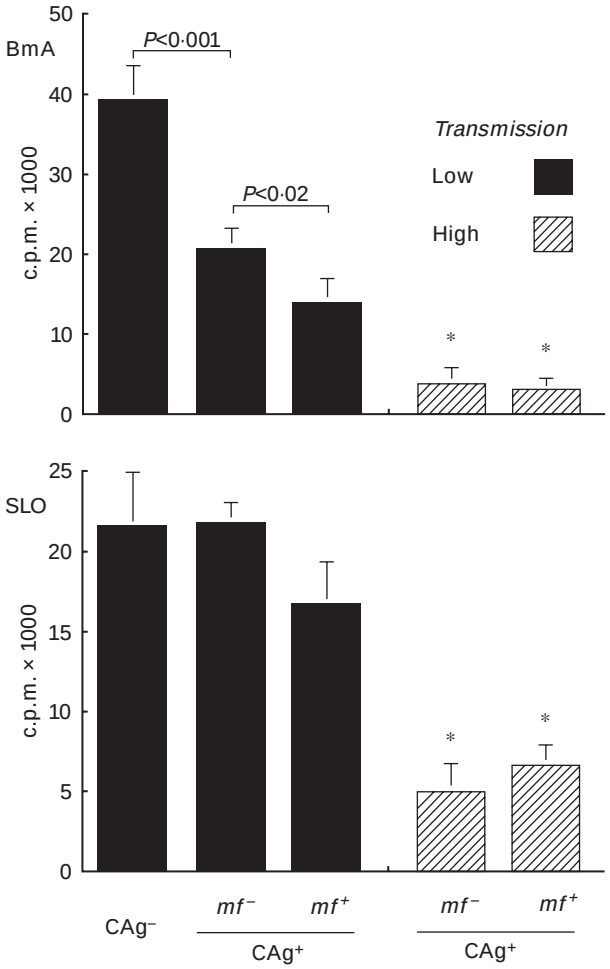

Figure 1 The presence of *W. bancrofti* infection and exposure correlates with impaired lymphocyte proliferation responses by Papua New Guinean study subjects. Solid bars represent individuals from the low transmission village and hatched bars denote residents from the high transmission village. Infection status was determined by measurement of CAg (Og4C3 sandwich ELISA) and peripheral blood microfilaremia (mf) by Nuclepore filtration. Lymphocyte proliferation represents the net proliferative response (antigen induced − spontaneous) of PBMC stimulated with BmA (soluble extract of *Brugia malayi* adults worms) or streptolysin-O. Bars represent the mean ± SEM of the group. The mean c.p.m. for PBMC from residents of the high transmission village was significantly less (denoted by an asterisk) than that of every group from the low transmission village ($P < 0{\cdot}001$–$0{\cdot}01$).

IL-12, for example, can inhibit IgE expression through enhanced interferon (IFN)-γ release by NK cells, but has been shown to augment IgG4 release (25). This is consistent with a model that Th1-type immunity, as defined by increased IL-2 and IFN-γ production by T cells and IL-12 by NK cells and monocytes, can cross-regulate the Th2-type immunity at the T cell level and by enhanced blocking antibody production. Although the Th1/Th2 paradigm has been widely criticized as being too simplistic for understanding the immune response for many diseases (26), the striking Th2-orientation of the immune response to filarial infection continues to make this model attractive. The Th1/Th2 model, however, fails adequately to explain the mechanisms of immune hyporesponsiveness observed in many filarial infection patients (see below) and attention should be paid to specific cytokines, other molecules and a wider range of cell types.

RELATIONSHIP BETWEEN FILARIAL INFECTION AND IMMUNE HYPORESPONSIVENESS

Immunological studies of human lymphatic filariasis throughout endemic areas of the world consistently show that filarial antigen-specific immunity differs according to microfilarial status of the individual. Adults who are microfilaremic have significantly lower adult worm-antigen driven lymphocyte proliferation (27,28) and diminished IFN-γ production (17,29). These studies also established that humoral immune responses, including filarial-specific IgG and IgE, are relatively depressed among microfilaremic individuals (30,31). In contrast, amicrofilaremic persons generally have strong parasite-specific proliferation responses and type-1 immunity (17). More recent observations indicate that impaired lymphocyte proliferation and IFN-γ responses correlate more closely with infection status as defined by the presence of circulating antigen (CAg) detected by *W. bancrofti* specific monoclonal antibody Og4C3, rather than microfilaremia *per se* (29,32). Studies of *W. bancrofti*-infected subjects in Papua New Guinea confirm the association between CAg status and filarial-specific proliferation and IFN-γ responses (Figure 1). The immune hyporesponsiveness in filarial infected subjects from India corresponded to an absolute reduction in the frequency of filarial-specific T and B lymphocyte precursors (33). These studies showed that the frequency of proliferating $CD3^+$ T cells responding to extracts of adult *Brugia malayi* was significantly lower among microfilaremic (1 in 3757) compared to amicrofilaremic subjects (1 in 1513). Similarly, the proportion of B cells producing parasite-specific IgG and IgE was lower in the microfilaremic group.

The mechanism of hyporesponsiveness or partial anergy among infected individuals is in part related to the dominance of the Th2 subset of $CD4^+$ T cells. Using IL-4 as a marker of a Th2-type response (and IFN-γ as an indicator of a Th1-type response), microfilaremic subjects had significantly fewer IFN-γ-secreting cells compared to amicrofilaremic subjects (17). The absolute number of IL-4 secreting cells, however, was equivalent between the two groups. Overall, microfilaremic individuals had eight-fold more filarial-specific IL-4 relative to IFN-γ secreting cells. By contrast, amicrofilaremic individuals had a predominance of cells secreting IFN-γ relative to IL-4. It should be stressed that the absolute number of filarial-specific lymphocytes, both Th1-and Th2-type cells, was diminished in the microfilaremic compared to amicrofilaremic individuals. The relative reduction in Th1-type responses is due partly to IL-10 and/or tumour growth factor (TGF)-β, since in-vitro neutralization of these cytokines partially reversed lymphocyte hyporesponsiveness among microfilaremic subjects as measured by proliferation and cytokine production (15,17,34). To attribute this antigen-specific hyporesponsiveness among infected patients to immune deviation towards Th2 is probably an oversimplification for a number of reasons. First, impaired lymphocyte proliferation should affect both Th1 and Th2 type cells, although it appears that Th1 type cells lymphocytes may be more affected. Second, Th1 and Th2 type cells, as well as monocytes, produce IL-10 and its suppressive effect on lymphocyte proliferation cannot be explained by a simple Th2/Th1 dichotomy. Third, the depressed production of parasite-specific IgE is discordant with increased IL-4 and IgG4 production characteristic of infected individuals.

The mechanisms associated with partial anergy observed in filarial infected patients may be considered in the context of 'central tolerance' verses 'peripheral tolerance'. Central tolerance relates to the selective depletion or anergy that may develop as a consequence of exposure *in utero* to filarial antigens or anti-idiotypic antibodies. This idea has been well addressed elsewhere (33,35,36) and will not be considered further here. Peripheral 'tolerance' may be considered as the effect of persistent or intermittent release of high amounts of antigen by the parasite on the host immune response, the direct effect of the parasite itself or of parasite-derived molecules that may mimic or block host cytokines or receptors (37,38). Peripheral tolerance is likely to be only partial and can be reversed with elimination of the parasite infection after chemotherapy (39,40). Increasing evidence, both from older studies and more recent experiments, indicates that defects in antigen presentation are critical for development of peripheral tolerance (41,42).

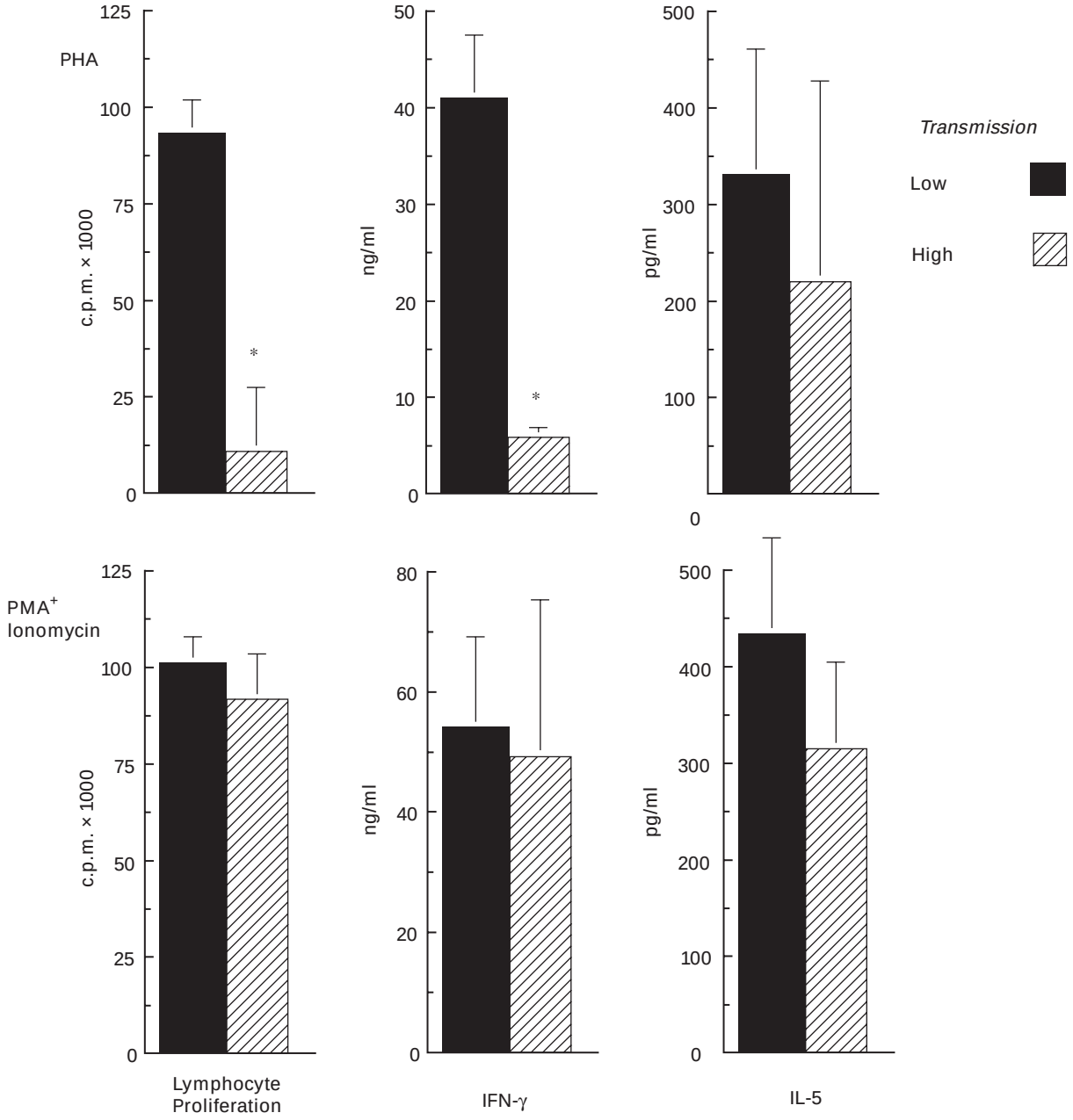

Figure 2 Heavy exposure to infective larvae results in impaired phytohemagglutanin- but not PMA/ionomycin-driven lymphocyte proliferation responses and IFN-γ production suggesting frequent exposure to developing larvae induces a defect in APC function. Solid bars indicate CAg^+ residents of the low transmission village and hatched bars denote residents of the high transmission village. Bars represent mean ± SEM (for lymphocyte proliferation) and geomean ± SEM for cytokine production. *Significant difference between two groups, $P < 0{\cdot}001$ for both comparisons.

EFFECT OF EXPOSURE ON IMMUNE RESPONSES TO LYMPHATIC FILARIASIS

Development of a Th2 bias and suppression of the host proliferative response begins at the earliest stages of infection. Subcutaneous infection of mice with infective stage L3 larvae of *Brugia pahangi* suppresses lymphocyte proliferation and IFN-γ production by splenocytes to mitogens and parasite antigens within 12 days (43). This corresponds to a time when infective larvae have migrated to the lymphatics and begin to undergo their molt to the L4. This active suppression has been shown to involve IL-10

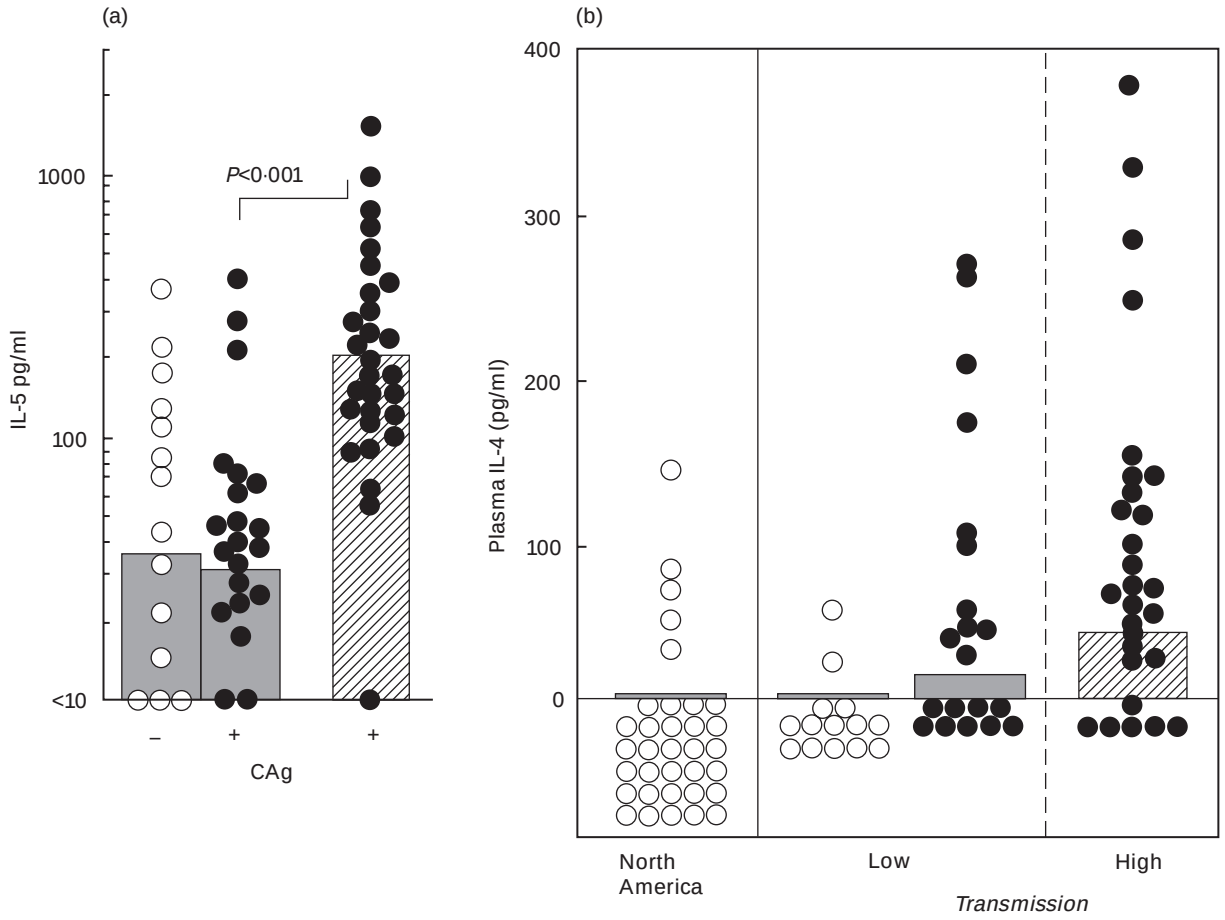

Figure 3 Heavy exposure promotes a Th2 bias indicated by increased filarial antigen-stimulated IL-5 production by PBMC and elevated plasma IL-4 levels among Papua New Guinean residents of the high compared to low transmission villages. (a) Showing net BmA-driven IL-5 production with respect to the presence (CAg^+) or absence of infection (CAg^-) and either comparatively light exposure (shaded bars) or intense exposure (hatched bars). Bars indicate geometric means. Significance difference among infected subjects between the low and high transmission groups is shown within the figure. (b) Showing plasma IL-4 levels determined by immunoassay. Each circle represents the mean value for two or more determinations of serial two-fold dilutions of plasma from one individual. The significance of difference in the mean level for CAg^+ versus CAg^- subjects from the low transmission village and CAg^+ persons from the low versus high transmission village was $P < 0{\cdot}05$.

and resident antigen presenting cells (APC) (44). The animals were not completely unresponsive, however, and they mounted a concomitant Th2 response to the parasite, characterized by elevated levels of IL-4, IL-5 and IL-10 and parasite-specific serum IgG, IgG1, and IgE (43). The production of IL-4 appears within 24 h after L3 injection produced by a population of CD4-CD8-T cells in draining lymph nodes at the infection site (45). To understand better the mechanisms by which L3 larvae produce this immunosuppression, L3 larvae have been implanted in the murine peritoneal cavity. Within 7 days after implantation, peritoneal exudate cells developed a marked capacity to suppress various T cell lines *in vitro* (46). The precise mechanisms by which these cells mediate this immune suppression remains unclear; it requires IL-4 but not IL-10, although IL-4 itself is not directly suppressive (46). In this model, excretory/secretory products from the adult *B. malayi* worms, as well as from other common nematode parasites, also induce this suppression (47). These observations differ from the role of IL-10 and APC in modulating the immunosuppression observed after subcutaneous infection with L3. These models of infection are clearly different, but they may not be mutually exclusive. Overall, these observations indicate that frequent exposure of the mammalian host to developing larvae plays a critical role in the Th2 bias and the development of immune hyporesponsiveness. This is not surprising since L3 stage parasites must also evade immune defenses on penetration of the host.

The murine studies appear to mirror a similar induction of partial immune hyporesponsiveness and Th2 bias in

human filariasis. These studies were performed on Papua New Guineans (PNG) living in remote areas highly endemic for *W. bancrofti*. Here transmission intensity – quantified as the annual transmission potential (the number of L3 to which an individual is theoretically exposed per year) of the local mosquito vector *Anopheles punctulatus* – varies tremendously among nearby villages within same linguistic groups (48). Transmission intensity can vary between 50 and 100-fold between hamlets only several kilometers apart in this rugged and geographically diverse country. Such differences were exploited to compare T cell and cytokine responses among children and adults of two villages within 20 km of each other where transmission intensity of *Wuchereria bancrofti* differed 63-fold (37 versus 2355 L3 per person per year). Residents of the high transmission village had four- to 11-fold lower levels of proliferation (Figure 1) and IFN-γ responses to filarial antigen, even when subjects were matched for the intensity of infection (all study subjects in the high transmission were infected with *W. bancrofti*). Residents of the high transmission village also had markedly impaired lymphocyte proliferation and IFN-γ production to the nonparasite antigen streptolysin-O (Figure 1) and to APC-dependent mitogen, phytohemagglutinin (Figure 2). By contrast, lymphocyte proliferation and IFN-γ production in response to the mitogens PMA + ionomycin (which directly activates protein kinase C and facilitates influx of Ca^{2+} into the cell and does not require APC help) was similar between residents of the high and low transmission villages (Figure 2). Moreover, purified $CD4^+$ cells from residents of the high transmission village could also be activated with immobilized anti-CD3 that cross-links the T cell receptor and anti-CD28, which provides an important costimulatory requirement. These results suggest that the incoming and developing larvae nonspecifically depress lymphocyte proliferation and IFN-γ production, analogous to that observed in murine models. Because T cells are capable of full activation if the requirement for APC costimulation is bypassed, this suggests that the larvae or their excretory/secretory products impair APC function. Further investigation of this issue will require isolation of APC from the skin of infected individuals and assessment of their level of activation and expression of costimulatory molecules such as CD40, CD80 and CD86. It may also be informative to determine whether filarial larvae themselves, or molecules released during the moulting process, modify the function of APC isolated from the dermis of uninfected individuals.

This ability of the parasite to modify the host immune response has obvious advantages to the parasite to enhance its survival. However, the impact that impaired APC function might have on the host response to other infections has not been well investigated. Other filarial infections, particularly human onchocerciasis, have also been shown to modulate suppression of lymphocyte proliferation and IFN-γ production in response to mitogen and nonparasite antigens (49–52). Although these studies did not correlate transmission intensity to levels of immune hyporesponsiveness, microfilariae of *Onchocerca volvulus*, infective to the insect vector, persist in the skin where their excretory/secretory production may also modify the host immune response in a manner analogous to that of the infective larvae of lymphatic filarial worms.

In the PNG study, frequent exposure to infective stage larvae enhanced the Th2-type immune response. Filarial antigen-driven IL-5 production was 5·5-fold greater ($P < 0{\cdot}001$) and plasma IL-4 levels were elevated among more heavily exposed individuals (Figure 3). IL-4 and IL-10 responses by peripheral blood mononuclear cells (PBMC) differed little according to village, however. Furthermore, we observed that increased production of the counter-regulatory cytokines IL-10 or TGF-β did not correlate with weak proliferation and IFN-γ responses. Plasma IL-5, IFN-γ, IL-10 and TGF-β levels were similar in the two villages. This observation contrasts with a previous report, which showed that IL-10 and TGF-β contribute to lymphocyte hyporesponsiveness in mf^+ subjects (17), although other studies have also failed to demonstrate that IL-10 modulates T-cell responses to filariae (53). These studies indicate that suppression of lymphocyte proliferation and IFN-γ production as a consequence of heavy exposure to developing larvae may differ from that observed with chronic infection.

The molecular basis of the propensity for filariae and other helminths to induce a bias toward type 2 immunity is poorly understood. Helminths have abundant 'ladder' proteins with amino acid repeat sequences similar to those of environmental and venom allergens (54). They also contain carbohydrates that preferentially induce IL-10 production by innate immune cells and upregulate CD28-CTLA4 or other costimulatory pathways that favour type 2 T-cell differentiation (55,56). In this context, a secreted product (denoted ES-62) of the animal filarial parasite *Acanthocheilonema viteae* has been reported to signal murine dendritic cells to drive differentiation of ovalbumin-specific TCR transgenic T-cells to the type 2 cytokine phenotype (57).

An additional biological feature of human filariasis that may predispose to the establishment of a type 2 bias relates to the temporal profile of exposure to parasite antigen in the skin. Prolonged and continuous administration of soluble antigen into the subcutaneous tissue of genetically predisposed mice resulted in preferential induction of $CD4^+$ Th2 cells (58,59). Persistent infection with *W. bancrofti* may parallel these studies in the pattern of chronic antigenic

exposure in the skin, subcutaneous tissues and draining lymphatics.

L3 ACTIVATION OF BASOPHILS IN THE DEVELOPMENT OF TH2 IMMUNE BIAS AND IMMUNE HYPORESPONSIVENESS

A striking finding of the PNG studies was the elevated plasma levels of IL-4 in infected subjects compared to uninfected individuals from PNG (Figure 3b). Overall, plasma IL-4 levels were more than two-fold higher in the high transmission village compared to the low transmission village. Particular care must be made in the interpretation of IL-4 in plasma, because it has a short in-vivo half-life (IL-4 is a T-cell growth factor and may thus be rapidly consumed). In addition, much of the IL-4 may be bound to soluble IL-4 receptors and therefore interfere with its measurement by ELISA or alter its biological activity. We therefore confirmed that plasma IL-4 detected by the two-site ELISA was able to drive the proliferation of an IL-4-dependent human T-cell clone.

An important source of this IL-4 is likely to derive from mast cells and basophils in the dermis. Both cell types are present in low numbers in peripheral blood but plentiful in dermal tissues where L3 are inoculated and larval development subsequently takes place. Persons exposed repeatedly to large numbers of L3 and pre-adult *W. bancrofti* may thus experience sustained increases in IL-4 production by activation and degranulation of cells located in the dermis, particularly mast cells bearing cytophilic filarial-specific IgE bound to FcεRI. This possibility is supported by the observation that soluble antigens from L3 larvae preferentially stimulate basophils, the circulating counterpart of the mast cell, enriched from peripheral blood (Figure 4). More than 80% of individuals released IL-4 in response to L3 antigens compared to 50% and 36% of individuals that produced these same molecules in response to adult or microfilarial antigens, respectively. Histamine was also preferentially produced by basophils in response to L3 antigens. This production of IL-4 by $FceR^+$ cells may contribute to the Th2 bias observed among heavily exposed individuals. Basophils and mast cells release other mediators such as prostaglandin D_2 that has also been shown to participate in development of a Th2-type inflammatory response (60).

Mast cells and basophils play a critical role in host defense, particularly across epithelial barriers such as the skin. It has been increasingly recognized that these cells also regulate the local inflammatory responses, both by perpetuating local allergic inflammatory responses and by modulating this inflammation (61). The role of these cells in regulating host inflammatory response to filarial

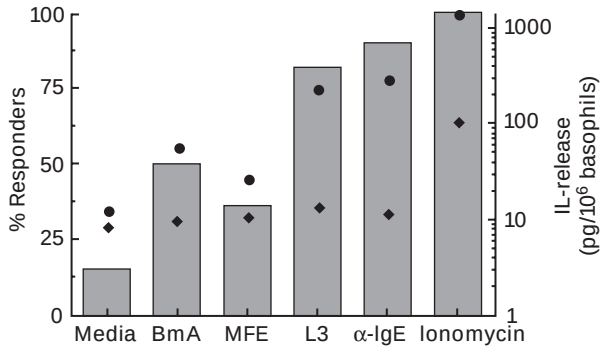

Figure 4 Infective stage larvae preferentially stimulate IL-4 release by basophils among filarial-infected subjects in Papua New Guinea. Basophils were enriched from PBMC by Percoll-gradient centrifugation and adjusted to 10^6 basophils per ml. Cultures were stimulated with the amount of soluble stage-specific filarial antigen previously determined to stimulate the optimal amount of IL-4 release after 4 h of incubation by immunoassay (e.g. 30 μg/ml of BmA, 10 μg/ml of MFE and 1 μg/ml of L3). These antigens stimulated no IL-4 release from enriched basophils from North American or Papua New Guineans who resided in an area not endemic for lymphatic filariasis ($n = 13$). Bars show the percentage of filarial infected adults (all CAg^+ males >20 years of age, $n = 20$) that produced detectable IL-4 and the high (circles) and low (diamonds) range of IL-4 produced in the culture supernatants. Stimulation with anti-IgE and ionomycin in parallel cultures served as positive controls.

infections has been less well appreciated. Histamine release, for example, causes a local increase in blood flow and vascular permeability to promote accumulation of host inflammatory cells. Histamine may also modulate this local inflammatory response. It can suppress pro-inflammatory mediators such as tumour necrosis factor-α (62) and has been shown to quell lymphocyte proliferation in human filariasis (63). Basophils and mast cells also express CD40L (64) and, along with their release of IL-4 and IL-13 (65), may induce B cells to generate polyclonal IgE. This may be an important source of the extremely high levels of polyclonal IgE observed in filarial infected individuals. This polyclonal IgE, as indicated above, may act to downregulate further activation of these cells types by displacing parasite-specific IgE on the cell surface. Furthermore, even if only a small percentage of basophils and mast cells had sufficient levels of antigen-specific IgE to trigger cell activation with antigen exposure, these cells are likely to far exceed the number of antigen-specific T cells capable of making the same cytokine (66).

If the intensity or cumulative degree of exposure to L3 and developing larvae in the dermal lymphatics is an important determinant of the strength of type 2 immunity in human filariasis, such responses should wane following sustained reduction in transmission. Comparison of plasma IL-4 levels and T-cell cytokine responses before and after

reduction in transmission intensity should allow this hypothesis to be tested. Given the existing global plan to control lymphatic filariasis through mass chemotherapy that reduces or even eliminates mosquito-borne transmission of *W. bancrofti* (67), such studies may be feasible in the near future. Although the interruption of transmission is the desired goal in the control of lymphatic filariasis, the absence of infection and lack of exposure would eliminate those factors that contribute to a suppressed host immune response. Subsequent reinfection may trigger a more vigorous host responses and increase the risk for disease. Clearly, a better understanding of the pathogenesis of this disease remains an important objective even as a worldwide program to eliminate this disease begins.

REFERENCES

1 King CL, Nutman TB. Regulation of the immune response in lymphatic filariasis and onchocerciasis. *Immunol Today* 1991; **12**: A54–A58.

2 Dreyer G, Piessens WF. In *Lymphatic Filarisis*, ed. Nutman TB. London: Imperial College Press; 2000: 245–264.

3 Philipp M, Maizels RM, McLaren DJ, Davies MW, Suswillo R, Denham DA. Expression of cross-reactive surface antigens by microfilariae and adult worms of *Brugia pahangi* during infections in cats. *Trans Royal Soc Trop Med Hygiene* 1986; **80**: 385–393.

4 Rao UR, Nasarre C, Coleman SU *et al.* Cellular immune responses of jirds to extracts of life cycle stages and adult excretory secretory products during the early development of *Brugia pahangi*. *Exp Parasitol* 1996; **82**: 255–266.

5 Suswillo RR, Denham DA, McGreevy PB. The number and distribution of *Brugia pahangi* in cats at different times after a primary infection. *Acta Trop* 1982; **39**: 151–156.

6 Nelson FK, Greiner DL, Shultz LD, Rajan TV. The immunodeficient scid mouse as a model for human lymphatic filariasis. *J Exp Med* 1991; **173**: 659–663.

7 Scott AL. In *Lymphatic Filarisis*, ed. Nutman TB. London: Imperial College Press; 2000: 5–39.

8 Petralanda I, Yarzabal L, Piessens WF. Studies on a filarial antigen with collagenase activity. *Mol Biochem Parasitol* 1986; **19**: 51–59.

9 Aalberse RC. Structural biology of allergens. *J Allergy Clin Immunol* 2000; **106**: 228–238.

10 Ottesen EA. Immediate hypersensitivity responses in the immunopathogenesis of human onchocerciasis. *Rev Infect Dis* 1995; **7**: 796–801.

11 Hussain R, Poindexter R, Ottesen EA. Control of allergic reactivity in human filariasis. Predominant localization of blocking antibody to the IgG4 subclass. *J Immunol* 1992; **148**: 2731–2737.

12 Hussain R, Ottesen E. IgE responses in human filariasis. II. Qualitative characterization of filaria-specific IgE. *J Immunol* 1983; **131**: 1516–1521.

13 Hussain R, Ottesen EA. IgE responses in human filariasis. IV. Parallel antigen recognition by IgE and IgG4 subclass antibodies. *J Immunol* 1986; **136**: 1859–1863.

14 Hussain R, Hamilton R, Kumaraswami V, Adkinson NJ, Ottesen EA. IgE responses in human filariasis. I Quantitation of filaria-specific IgE. *J Immunol* 1981; **127**: 1623–1629.

15 Mahanty S, Nutman TB. Immunoregulation in human lymphatic filariasis: the role of interleukin 10. *Parasite Immunol* 1995; **17**: 385–392.

16 Piessens WF, Wadee AA, Kurniawan L. Regulation of immune responses in lymphatic filariasis. *Ciba Found Symp* 1987; **127**: 164–179.

17 King CL, Mahanty S, Kumaraswami V *et al.* Cytokine control of parasite-specific anergy in human lymphatic filariasis. Preferential induction of a regulatory T helper type 2 lymphocyte subset. *J Clin Invest* 1993; **92**: 1667–1673.

18 Mahanty S, King CL, Kumaraswami V *et al.* IL-4- and IL-5-secreting lymphocyte populations are preferentially stimulated by parasite-derived antigens in human tissue invasive nematode infections. *J Immunol* 1993; **151**: 3704–3711.

19 de Almeida AB, Silva MC, Braga C, Freedman DO. Differences in the frequency of cytokine-producing cells in antigenemic and nonantigenemic individuals with bancroftian filariasis. *Infect Immun* 1998; **66**: 1377–1383.

20 Mahanty S, Mollis S, Ravichandran M *et al.* High levels of spontaneous and parasite antigen-driven interleukin-10 production are associated with antigen-specific hyporesponsiveness in human lymphatic filariasis. *J Infect Dis* 1996; **173**: 769–773.

21 de Boer BA, Fillie YE, Kruize YC, Yazdanbakhsh M. Antigen-stimulated IL-4, IL-13 and IFN-gamma production by human T cells at a single-cell level. *Eur J Immunol* 1998; **28**: 3154–3160.

22 King CL, Ottesen EA, Nutman TB. Cytokine regulation of antigen-driven immunoglobulin production in filarial parasite infections in humans. *J Clin Invest* 1990; **85**: 1810–1815.

23 Garraud O, Nkenfou C, Bradley J, Perler F, Nutman TB. Identification of recombinant filarial proteins capable of inducing polyclonal and antigen-specific IgE and IgG4 antibodies. *J Immunol* 1995; **155**: 1316–1325.

24 Garraud O, Nkenfou C, Bradley JE, Nutman TB. Differential regulation of antigen-specific IgG4 and IgE antibodies in response to recombinant filarial proteins. *Int Immunol* 1996; **8**: 1841–1848.

25 de Boer BA, Kruize YC, Rotmans PJ, Yazdanbakhsh M. Interleukin-12 suppresses immunoglobulin E production but enhances immunoglobulin G4 production by human peripheral blood mononuclear cells. *Infect Immun* 1997; **65**: 1122–1125.

26 Allen JE, Maizels RM. Th1-Th2: reliable paradigm or dangerous dogma? *Immunol Today* 1997; **18**: 387–392.

27 Ottesen EA, Weller P, Heck L. Specific cellular immune unresponsiveness in human filariasis. *Immunology* 1977; **33**: 413–421.

28 Piessens WF, Ratiwaytano S, Tuti S *et al.* Antigen-specific suppressor cells and suppressor factors in human filariasis with. *Brugia Malayi New Engl J Med* 1980; **302**: 833–837.

29 Dimock K, Eberhard M, Lammie P. Th1-like antifilarial immune responses predominate in antigen-negative persons. *Infect Immun* 1996; **64**: 2962–2967.

30 Nutman TB, Kumaraswami V, Pao L, Narayanan P, Ottesen EA. An analysis of in vitro B cell immune responsiveness in human lymphatic filariasis. *J Immunol* 1987; **138**: 3954–3959.

31 Marley SE, Lammie PJ, Eberhard ML, Hightower AW. Reduced antifilarial IgG4 responsiveness in a subpopulation of microfilaremic persons. *J Infect Dis* 1995; **172**: 1630–1633.

32 de Almedia AB, Maia e Silva M, Maciel MA, Freedman DO. The presence or absence of active infection, not clinical status, is most closely associated with cytokine responses in lymphatic filariasis. *J Infect Dis* 1996; **173**: 1453–1459.

33 King CL, Kumaraswami V, Poindexter R *et al.* Immunologic tolerance in lymphatic filariasis. Diminished parasite-specific T

and B lymphocyte precursor frequency in the microfilaremic state. *J Clin Invest* 1992; **89**: 1403–1410.

34 Ravichandran M, Mahanty S, Kumaraswami V, Nutman TB, Jayaraman K. Elevated IL-10 mRNA expression and down-regulation of Th1-type cytokines in microfilaraemic individuals with *Wuchereria bancrofti* infection. *Parasite Immunol* 1997; **19**: 69–77.

35 Maizels RM, Lawrence RA. Immunological tolerance: the key feature in human filariasis? *Parasitol Today* 1991; **7**: 271–276.

36 Steel C, Guinea A, McCarthy J, Ottesen EA. Long-term effect of prenatal exposure to maternal microfilaraemia on immune responsiveness to filarial parasite antigens. *Lancet* 1994; **343**: 890–893.

37 Zinkernagel RM. Immunology taught by viruses. *Science* 1996; **271**: 173–178.

38 Gomez-Escobar N, Lewis E, Maizels RM. A novel member of the transforming growth factor-beta (TGF-beta) superfamily from the filarial nematodes *Brugia malayi* and *B. pahangi*. *Exp Parasitol* 1998; **88**: 200–209.

39 Piessens WF, Tratiwayanto S, Piessens PW *et al.* Effect of treatment with diethylcarbamazine on immune responses to filarial antigens in patients infected with *Brugia malayi*. *Acta Tropica* 1981; **38**: 227–234.

40 Sartono E, Kruize Y, Kurniawan A *et al.* Elevated cellular immune responses and interferon-gamma release after long-term diethylcarbamazine treatment of patients with human lymphatic filariasis. *J Infect Dis* 1995; **171**: 1683–1687.

41 Ottesen EA. Modulation of the host response in human schistosomiasis. I. Adherent suppressor cells that inhibit lymphocyte proliferative responses to parasite antigens. *J Immunol* 1979; **123**: 1639–1644.

42 MacDonald AS, Loke P, Allen JE. Suppressive antigen-presenting cells in helminth infection. *Pathobiology* 1999; **67**: 265–268.

43 Osborne J, Hunter SJ, Devaney E. Anti-interleukin-4 modulation of the Th2 polarized response to the parasitic nematode *Brugia pahangi*. *Infect Immun* 1996; **64**: 3461–3466.

44 Osborne J, Devaney E. Interleukin-10 and antigen-presenting cells actively suppress Th1 cells in BALB/c mice infected with the filarial parasite *Brugia pahangi*. *Infect Immun* 1999; **67**: 1599–1605.

45 Osborne J, Devaney E. The L3 of *Brugia* induces a Th2-polarized response following activation of an IL-4-producing CD4–CD8-alphabeta T cell population. *Int Immunol* 1998; **10**: 1583–1590.

46 MacDonald AS, Maizels RM, Lawrence RA, Dransfield I, Allen JE. Requirement for in vivo production of IL-4, but not IL-10, in the induction of proliferative suppression by filarial parasites. *J Immunol* 1998; **160**: 1304–1312.

47 Allen JE, MacDonald AS. Profound suppression of cellular proliferation mediated by the secretions of nematodes. *Parasite Immunol* 1998; **20**: 241–247.

48 Bockarie M, Kazura J, Alexander N *et al.* Transmission dynamics of *Wuchereria bancrofti* in East Sepik Province, Papua New Guinea. *Am J Trop Med Hyg* 1996; **54**: 577–581.

49 Burchard GD, Brattig NW, Kruppa TF, Horstmann RD. Delayed-type hypersensitivity reactions to *Onchocerca volvulus* antigens in exposed and non-exposed African individuals. *Trans Royal Soc Trop Med Hygiene* 1999; **93**: 103–105.

50 Elkhalifa MY, Ghalib HW, Dafa'Alla T, Williams JF. Suppression of human lymphocyte responses to specific and non-specific stimuli in human onchocerciasis. *Clin Exp Immunol* 1991; **86**: 433–439.

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

52 Greene BM, Fanning MM, Ellner JJ. Non-specific suppression of antigen-induced lymphocyte blastogenesis in *Onchocerca volvulus* infection in man. *Clin Exp Immunol* 1983; **52**: 259–265.

53 Sartono E, Kruize YC, Partono F, Kurniawan A, Maizels RM, Yazdanbakhsh M. Specific T cell unresponsiveness in human filariasis: diversity in underlying mechanisms. *Parasite Immunol* 1995; **17**: 587–594.

54 Maizels RM, Gregory W, Kwan-Lim G, Selkirk M. Filarial surface antigens: the major 29 kilodalton glycoprotein and a novel 17–200 kilodalton complex from adult *Brugia malayi* parasites. *Mol Biochem Parasitol* 1989; **32**: 213–227.

55 Palanivel V, Posey C, Horauf AM, Solbach W, Piessens WF, Harn DA. B-cell outgrowth and ligand-specific production of IL-10 correlate with Th2 dominance in certain parasitic diseases. *Exp Parasitol* 1996; **84**: 168–177.

56 Harnett W, Deehan MR, Houston KM, Harnett MM. Immunomodulatory properties of a phosphorylcholine-containing secreted filarial glycoprotein. *Parasite Immunol* 1999; **21**: 601–608.

57 Whelan M, Harnett MM, Houston KM, Patel V, Harnett W, Rigley KP. A filarial nematode-secreted product signals dendritic cells to acquire a phenotype that drives development of Th2 cells. *J Immunol* 2000; **164**: 6453–6460.

58 Guery JC, Galbiati F, Smiroldo S, Adorini L. Selective development of T helper (Th) 2 cells induced by continuous administration of low dose soluble proteins to normal and beta (2)-microglobulin-deficient BALB/c mice. *J Exp Med* 1996; **183**: 485–497.

59 Foucras G, Gapin L, Coureau C, Kanellopoulos JM, Guery JC. Interleukin 4-producing CD4 T cells arise from different precursors depending on the conditions of antigen exposure in vivo. *J Exp Med* 2000; **191**: 683–694.

60 Matsuoka T, Hirata M, Tanaka H *et al.* Prostaglandin D2 as a mediator of allergic asthma. *Science* 2000; **287**: 2013–2017.

61 Nolte H. The role of mast cells and basophils in immunoregulation. *Allergy Asthma Proc* 1996; **17**: 17–21.

62 Vannier E, Miller LC, Dinarello CA. Histamine suppresses gene expression and synthesis of tumor necrosis factor alpha via histamine H2 receptors. *J Exp Med* 1991; **174**: 281–284.

63 Hofstetter M, Fasano M, Ottesen EA. Modulation of the host response in human schistosomiasis. IV. Parasite antigen induces release of histamine that inhibits lymphocyte responsiveness in vitro. *J Immunol* 1983; **130**: 1376–1380.

64 Gauchat JF, Henchoz S, Mazzei G *et al.* Induction of human IgE synthesis in B cells by mast cells and basophils. *Nature* 1993; **365**: 340–343.

65 Schroeder JT, MacGlashan DW, Lichtenstein LM. Mechanisms and pharmacologic control of basophil-derived IL-4 and IL-13. *Int Arch Allergy Immunol* 1999; **118**: 87–89.

66 Devouassoux G, Foster B, Scott LM, Metcalfe DD, Prussin C. Frequency and characterization of antigen-specific IL-4- and IL-13- producing basophils and T cells in peripheral blood of healthy and asthmatic subjects. *J Allergy Clin Immunol* 1999; **104**: 811–819.

67 Ottesen EA, Ismail MM, Horton J. The role of albendazole in programmes to eliminate lymphatic filariasis. *Parasitol Today* 1999; **15**: 382–386.