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**Vaccine and Methods for Detecting and
Preventing Filariasis**

Introduction

[0001] This application claims the benefit of priority from U.S. Application Serial Number 16/790,277, filed February 13, 2020, the contents of which are incorporated herein by reference in their entireties.

[0002] This invention was made with government support under contract numbers AI064745 and AI116441 awarded by the National Institutes of Health. The government has certain rights in the invention.

Background

[0003] Lymphatic filariasis caused by the filarial nematodes *Wuchereria bancrofti*, *Brugia malayi*, and *Brugia timori*, affects more than 120 million people worldwide (WHO (1992) *World Health Organ. Tech. Rep. Ser.* 821:1-71). Mass drug administration program by the World Health Organization, is significantly reducing the incidence rate of lymphatic filariasis in many parts of the world (Hotez (2009) *Clin. Pharmacol. Ther.* 85(6):659-64). Nevertheless, lack of effectiveness to the mass drug administration has been reported from several endemic regions mainly due to noncompliance (Babu & (2008) *Trans. R. Soc. Trop. Med. Hyg.* 102(12):1207-13; El-Setouhy, et al. (2007) *Am. J. Trop. Med. Hyg.* 77(6):1069-73). In addition, drug resistance has been reported to at least one of the drugs in the mass drug combination (Horton (2009) *Ann. Trop. Med. Parasitol.* 103(1):S33-40; Schwab, et al. (2007) *Parasitology* 134(Pt 7):1025-40). Since yearly administration of the mass drugs is required for effective control, there is an alarming concern for selecting drug resistant parasites. Therefore,

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there is an immediate need for a multipronged approach in controlling this mosquito borne infection.

[0004] As with lymphatic filariasis, treatment of dirofilariasis (heartworm disease) in canids and felids has included the use of macrolide agents such as ivermectin, milbemycin oxime, moxidectin and selamectin, which prevent larval development during the first 2 months after infection. However, these agents must be administered monthly for effectiveness and can be very expensive to a pet owner.

[0005] Vaccination is one strategy for controlling these infections and several subunit candidate vaccine antigens have been tested in laboratory animals with variable results (Bottazzi, et al. (2006) *Expert Rev. Vaccines* 5(2):189-98; Chenthamarakshan, et al. (1995) *Parasite Immunol.* 17(6):277-85; Dissanayake, et al. (1995) *Am. J. Trop. Med. Hyg.* 53(3):289-94; Li, et al. (1993) *J. Immunol.* 150(5):1881-5; Maizels, et al. (2001) *Int. J. Parasitol.* 31(9):889-98; Thirugnanam, et al. (2007) *Exp. Parasitol.* 116(4):483-91; Veerapathran, et al. (2009) *PLoS Negl. Trop. Dis.* 3(6):e457). Lymphatic filariasis is a multicellular organism with complex life cycle and produce large array of host modulatory molecules. Thus, fighting against this infection with a single antigen vaccine can be difficult. By screening a phage display cDNA expression library of the *B. malayi* parasite with sera from immune individuals, several potential vaccine candidates were identified (Gnanasekar, et al. (2004) *Infect. Immun.* 72(8):4707-15). However, a varying degree of protection was achieved with each of the candidate vaccine antigens when given as a DNA, protein or prime boost vaccine (Veerapathran, et al. (2009) *supra*).

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Summary of the Invention

[0006] The present invention is a multivalent immunogenic composition composed of two or more antigens from *Dirofilaria immitis*. In some embodiments, the antigens are protein-based, DNA-based, or a combination thereof. In other embodiments, the antigens include an Abundant Larval Transcript (ALT), Small heat shock protein (HSP) 12.6, Thioredoxin Peroxidase 2 (TXP2), or optionally Tetraspanin (TSP). In some aspects, the antigens include an ALT antigen having the amino acid sequence of SEQ ID NO:98 or SEQ ID NO:99; an HSP12.6 antigen having the amino acid sequence of SEQ ID NO:100 or SEQ ID NO:101; and/or a TXP2 antigen having the amino acid sequence of SEQ ID NO:83 or SEQ ID NO:101. In certain aspects, the ALT antigen has the amino acid sequence of SEQ ID NO:93; the HSP12.6 antigen has the amino acid sequence of SEQ ID NO:91; and the TXP2 antigen has the amino acid sequence of SEQ ID NO:95. In certain aspects, the ALT antigen has the amino acid sequence of SEQ ID NO:121 or SEQ ID NO:122; the HSP 12.6 antigen has the amino acid sequence of SEQ ID NO:81 or SEQ ID NO:123; the TSP antigen has the amino acid sequence of SEQ ID NO:82; and the TXP2 antigen has the amino acid sequence of SEQ ID NO:83 or SEQ ID NO:124. In certain aspects, the antigens are covalently attached. This invention also provides a recombinant vector harboring nucleic acids encoding the multivalent immunogenic composition, a recombinant host cell harboring the recombinant vector, and the inclusion of an adjuvant in the multivalent immunogenic composition. Methods for inducing a protective immune response in a subject and immunizing an animal against filariasis or dirofilariasis are also provided. In some embodiments of these methods, the multivalent immunogenic composition is administered with an adjuvant, e.g., in one or more

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additional doses by subcutaneous or intramuscular injection.

Brief Description of the Drawings

[0007] FIG. 1 shows the titer of anti-BmHSP and anti-BmALT2 IgG antibodies in the sera of vaccinated mice. 6-week-old balb/c mice were immunized using a prime boost approach with a monovalent immunogenic composition (*Bmhsp* prime and rBmHSP boost or *Bmalt2* prime and rBmALT2 boost) and multivalent immunogenic composition (*Bmhsp/Bmalt2* prime and rBmHSP and rBmALT2 boost). Titer of IgG antibodies were measured in the sera using an indirect ELISA. The data presented is the antibody titer 2 weeks after the last booster. Results show that both bivalent and multivalent immunogenic compositions induce significant IgG antibodies against each of the component antigens. The findings also show that the antigens in the monovalent and multivalent formulations act synergistically in boosting the immune responses. N=5. Statistically significant ** $p < 0.001$, * $p < 0.05$. Values represented are mean $\pm$ SD.

[0008] FIGS. 2A-2B show the number of IL-4 (FIG. 2A) and IFN- γ (FIG. 2B) secreting cells in the spleen of mice vaccinated with monovalent (BmHSP or BmALT2) or multivalent immunogenic composition. An ELISPOT assay was performed after stimulating the cells with rBmHSP or rBmALT (1 μ g/ml). Single cell preparations of spleen cells were stimulated with respective antigens for 48 hours and spot forming cells were counted. Results show that both monovalent and multivalent immunogenic compositions promoted IL-4 secreting cells. Multivalent vaccination induced the higher number of IL-4 producing cells than controls. IFN- γ producing cells were comparatively low.

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These findings further confirm that BmHSP and BmALT2 synergistically boost the immune responses in vaccinated animals following a multivalent vaccination. N=5. Results are expressed as mean number of spot forming units per 3×10^6 cells $\pm$ SD.

[0009] FIG. 3 shows the degree of protection conferred by a multivalent immunogenic composition in a mouse model. Balb/c strain of mice were immunized with HAT (HSP/ALT2/TSP) hybrid DNA, with recombinant HAT protein or a combination of both using a prime boost approach. HAT hybrid DNA was used for priming. Two weeks following the priming, mice were boosted with HAT hybrid protein. Another group of mice were immunized with HAT hybrid DNA or with HAT hybrid protein. Control groups of mice received only blank vector or alum adjuvant. Two weeks after the last immunization, mice were challenged with 20 infective larvae of *Brugia malayi* by placing them in a micropore chamber in the peritoneal cavity of the immunized mice. After 48 hours, larval death was measured to determine the success of vaccination.

[0010] FIG. 4 shows multivalent immunogenic composition-induced protection against *Brugia malayi* infection in macaques. All animals (vaccinated and control) were challenged with 130-180 L3s of *Brugia malayi* one month after the last immunization. In weeks 5, 10, 15 and 18 post-challenge, 10 ml of blood was collected from each macaque between 18:00 and 22:00 hours and screened for the presence of microfilariae using a modified Knott technique and analyzed by PCR for the *Hha*-1 repeats. Absence of infection in microfilaria (Mf)-negative animals was further confirmed by SXP-1 (*B. malayi* diagnostic antigen) ELISA. Results show that rBmHAXT+AL019 (alum plus glucopyranosyl lipid adjuvant-stable emulsion) is a better immunogenic

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composition formulation than the other formulations tested (n = 10 per group). Chi-square test and Fisher's exact test were used to compare the proportions across the groups.

[0011] FIG. 5 shows the results of an antibody-dependent cell-mediated cytotoxicity (ADCC) assay. Approximately 10 *Brugia malayi* larvae were incubated for 72 hours at 37°C with 2×10^5 peripheral blood mononuclear cells (PBMCs) and 50 µl of sera samples from each macaque. Larval death in each well was monitored under a light microscope. Each data point indicates the percent larval death using a serum sample from one animal. '+' indicates the average percent larvicidal activity for that group. n = 10 macaques per group. *P ≤ 0.005 compared with the AL019 (alum plus glucopyranosyl lipid adjuvant-stable emulsion) group. Statistical analysis was performed by a Kruskal-Wallis test followed by Bonferroni correction for multiple tests. rBmHAXT, recombinant *B. malayi* HSP/ALT-2/TPX-2/TSPLLEL.

[0012] FIG. 6 shows the results of an ADCC assay for killing of drug-sensitive and drug-resistant *Dirofilaria immitis* in dogs. Approximately 8-10 *D. immitis* larvae were incubated for 96 hours at 37°C with 0.5 million PBMCs and 100 µl of sera samples from each dog. Larval death in each well was monitored under a light microscope. Each data point indicates the percent larval death using a serum sample from one animal. rBmHAXT, recombinant *B. malayi* HSP/ALT-2/TPX-2/TSPLLEL.

Detailed Description of the Invention

[0013] A multivalent immunogenic composition for filariasis has now been developed. Combinations of antigens, such as Abundant Larval Transcript (ALT2), Tetraspanin (TSP), Small heat shock protein (HSP) 12.6, Vespil Venom Allergen homologue-Like protein (VAL-1), Glutathione S-Transferase

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(GST), and Thioredoxin Peroxidase 2 (TPX-2), and fragments thereof, were tested in experimental animals (*i.e.*, mouse, jirds, mastomys, macaque, and dogs) and shown to provide >80% protection against infection by filarial nematodes such as *Brugia malayi* and *Dirofilaria immitis*. Accordingly, the present invention features protein-based and DNA-based compositions composed of filarial nematode antigens or nucleic acids encoding the same and use of the immunogenic compositions to prevent or control filariasis in humans and animals, in particular canids and felids. In addition to vaccination, the present invention also provides assays and kits for detecting the presence of a filarial nematode.

[0014] For the purposes of the present invention, a multivalent or polyvalent immunogenic composition refers to an immunogenic composition or vaccine prepared from several antigens. According to some embodiments, the antigen is a nucleic acid molecule, which is referred to herein as a "DNA-based" antigen. According to other embodiments, the antigen is a protein or polypeptide, which is referred to herein as "protein-based" antigen. A multivalent immunogenic composition of the invention can be composed of two, three, four, five, six or up to ten antigens or their fragments in various permutation combinations. In particular embodiments, the multivalent immunogenic composition is composed of two, three or four antigens. In some embodiments, the multivalent immunogenic composition is composed of solely of protein antigens. In other embodiments, the multivalent immunogenic composition is composed solely of DNA-based antigens. In yet other embodiments, the multivalent immunogenic composition is composed of a mixture of protein- and DNA-based antigens.

[0015] Antigens of the instant invention can be provided or expressed from a single nucleic acid molecule containing,

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e.g., internal ribosome entry sites between the antigens. Moreover, the antigens of the multivalent immunogenic composition of this invention can be covalently attached to form a hybrid or chimeric molecule or fusion protein, wherein the antigens are immediately adjacent to one another (e.g., an in-frame fusion with or without a short spacer). Alternatively, antigens of the instant invention can be provided as a mixture of individual antigens. Moreover, it is contemplated that the instant immunogenic composition can be composed of a hybrid molecule containing, e.g., two antigens, in admixture with a third non-covalently attached antigen. By way of illustration, a multivalent immunogenic composition of the invention can be composed of a chimeric TSP-HSP protein in admixture with a nucleic acid molecule encoding ALT2.

[0016] In one embodiment, the antigens of the multivalent immunogenic composition are different proteins from one species of filarial nematode. As an example of this embodiment, the multivalent immunogenic composition is composed of ALT2, HSP, and TSP and/or TPX2 or GST antigens isolated from one or more strains of *B. malayi* or *D. immitis*. In another embodiment, the antigens are the same, but from different species of filarial nematodes. As an example of this embodiment, the multivalent immunogenic composition is composed of the ALT2 antigen isolated from *W. bancrofti*, *B. malayi*, *B. timori*, and *D. immitis*. In yet a further embodiment, the multivalent immunogenic composition is composed of a combination of different antigens from different species of filarial nematodes. By way of illustration, the multivalent immunogenic composition can be composed of the ALT2 antigen isolated from *W. bancrofti*, *O. volvulus* and *L. loa* and the HSP antigen isolated from *B. malayi* and *D. immitis*.

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[0017] For preparing multivalent DNA-based or multivalent recombinant DNA-based immunogenic composition, the DNA sequence of the gene of interest (also used interchangeably as DNA molecule) need not contain the full length of DNA encoding the corresponding protein. Likewise, when preparing fusion protein-based or multivalent recombinant protein immunogenic compositions, the protein sequence need not contain the full-length protein. In most cases, a fragment of the protein or gene which encodes an epitope region is sufficient for immunization. The DNA/protein sequence of an epitope region can be found by sequencing the corresponding part of the gene from various strains or species and comparing them. The major antigenic determinants are likely to be those showing the greatest heterology. Also, these regions are likely to lie accessibly in the conformational structure of the proteins. One or more such fragments of proteins or genes encoding the antigenic determinants can be prepared by chemical synthesis or by recombinant DNA technology. These fragments of proteins or genes, if desired, can be linked together or linked to other proteins or DNA molecules, respectively.

[0018] As described herein, the ALT2, TSP, VAL-1, GST and HSP antigens were identified as providing protection against infection by filaria larvae. Accordingly, in particular embodiments, the instant immunogenic composition includes the ALT2, TSP, VAL-1, TPX2, GST and/or HSP protein antigens and/or nucleic acid molecules encoding the ALT2, TSP, VAL-1, TPX2, GST and/or HSP protein, or fragments thereof. Protein and nucleic acid sequences for these antigens are available under the GENBANK accession numbers and/or sequences listed in Table 1.

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TABLE 1

Antigen	Source	Protein	SEQ ID NO:	Nucleic Acid	SEQ ID NO:
ALT2	<i>B. malayi</i>	P90708	37	BMU84723	38
		XP 001896203	39	XM 001896168	40
	<i>W. bancrofti</i>	AAC35355	41	AF084553	42
	<i>L. loa</i>	XP 003151340	43	XM 003151292	44
	<i>D. immitis</i>	AAC47031	93	-	92
TSP	<i>B. malayi</i>	ABN55911	45	EF397425	46
	<i>L. loa</i>	XP 003136177	47	XM 003136129	48
HSP	<i>B. malayi</i>	AAU04396	49	AY692227	50
	<i>O. volvulus</i>	CAA48633	51	X68669	52
	<i>L. loa</i>	XP 003139338	53	XM 003139290	54
	<i>D. immitis</i>	QHA79233	91	-	90
VAL-1	<i>B. malayi</i>	AAB97283	55	AF042088	56
	<i>W. bancrofti</i>	AAD16985	57	AF109794	58
	<i>O. volvulus</i>	AAB69625	59	AF020586	60
	<i>L. loa</i>	XP_003146897	61	XM_003146849	62
TPX2	<i>B. malayi</i>	Q17172	71	U47100	72
	<i>D. immitis</i>	AAC38831	95	-	94
GST	<i>W. bancrofti</i>	AAO45827	85	AY195867	86
	<i>D. immitis</i>	P46426	103	-	102
	<i>B. malayi</i>	XP 001898233	120	-	-

[0019] In addition, the nucleotide sequence encoding *O. volvulus* TSP can be found under GENBANK Accession No. JN861043. The protein antigens and nucleic acid molecules of the invention can be used as full length molecules or less than full length molecules. In this respect, the present invention further includes the use of fragments of the above-referenced protein antigens and nucleic acid molecules. Fragments are defined herein as 20, 30, 40, 50, 60, 70, 80, 90, 100, 150, or 200 amino acid residue portions of full-length protein antigens (e.g., those listed in Table 1) or 60, 90, 120, 150, 180, 210, 240, 270, 300, 350, or 600 nucleotide portion of full-length nucleic acid molecules (e.g., those listed in Table 1). Exemplary protein fragments include the large extracellular loop (LEL) domain of TSP (see, e.g., the LEL domain of *B. malayi* TSP of SEQ ID NO:63 or SEQ ID NO:77) and N-terminal

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deletion of HSP 12.6 (cHSP; see, e.g., the *B. malayi* HSP fragment of SEQ ID NO:64), as well as the nucleic acid molecules encoding the same (see, SEQ ID NO:65 and SEQ ID NO:66, respectively). An exemplary fusion protein containing ALT2, HSP and TSP protein sequences is set forth in SEQ ID NO:70. An exemplary fusion protein containing ALT2, HSP and TPX2 protein sequences is set forth in SEQ ID NO:73 and SEQ ID NO:97. An exemplary fusion protein containing ALT2, HSP, TSP and TPX2 protein sequences is set forth in SEQ ID NO:74.

[0020] In particular embodiments, the protein or protein fragments of this invention have one or more antigenic sequences for eliciting an immune response in an animal. In certain embodiments, the ALT2 protein of the invention is a *B. malayi* ALT2 protein or fragment comprising or consisting of the sequence VSESDEEFDDSAADDTTDDSEAGGGSEGGDEYVT (SEQ ID NO:78) and/or EFVETDGKKKECSSHEACYDQREPQ (SEQ ID NO:79) or *D. immitis* ALT2 protein or fragment comprising or consisting of the sequence ASESQEETVSFEESDEDYEDDSE (SEQ ID NO:98) and/or FVESDGKMKHCKTHEACYDQREPQ (SEQ ID NO:99), which, based upon the Bepipred Linear Epitope Prediction method (Larsen, et al. (2006) *Immunome Res.* 2:2), are predicted B-cell epitopes. In other embodiments, the HSP protein of the invention is a *B. malayi* HSP protein or fragment comprising or consisting of the sequence WSAEQWDWPLQH (SEQ ID NO:80) and/or KLPSDVDTKTL (SEQ ID NO:81) or *D. immitis* HSP protein or fragment comprising or consisting of the sequence NWSADQWDWPLQHNDVVKVTNTNDK (SEQ ID NO:100) and/or KLPSDVDTKTL (SEQ ID NO:81), which are predicted B-cell epitopes. In further embodiments, the TSP protein of the invention is a *B. malayi* TSP protein or fragment comprising or consisting of the sequence KTGSESEDMQ (SEQ ID NO:82), which is a predicted B-cell

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epitope. In yet a further embodiment, the TPX2 protein of the invention is a *B. malayi* TPX2 protein or fragment comprising or consisting of the sequence FIGQPAPNFKT (SEQ ID NO:83) and/or GEVCPANWHPGSETIKPGVKESKA (SEQ ID NO:84) or *D. immitis* TPX2 protein or fragment comprising or consisting of the sequence FIGQPAPNFKT (SEQ ID NO:83) and/or GEVCPANWQPGSEAIKPGVKESKA (SEQ ID NO:101), which are predicted B-cell epitopes.

[0021] In certain embodiments, ALT2 protein fragments of this invention comprise or consist of the amino acid sequences $X_1X_2ESDEX_3X_4X_5DX_6$ (SEQ ID NO:121), wherein independently X_1 is V or F, X_2 is S or E, X_3 is E or D, X_4 is F or Y, X_5 is D or E, and X_6 is S or D; or $FVEX_1DGKX_2KX_3CX_4X_5HEACYDQREPQ$ (SEQ ID NO:122), wherein independently X_1 is S or T; X_2 is M or K; X_3 is E or H, X_4 is S or K, and X_5 is S or T. In other embodiments, HSP protein fragments of this invention comprise or consist of the amino acid sequences $WSAX_1QWDWPLQH$ (SEQ ID NO:123), wherein independently X_1 is Glu or Asp; or $KLPSDVDTKTL$ (SEQ ID NO:81). In further embodiments, TPX2 protein fragments of this invention comprise or consist of the amino acid sequences FIGQPAPNFKT (SEQ ID NO:83); or $GEVCPANWX_1PGSEX_2IKPGVKESKA$ (SEQ ID NO:124), wherein independently X_1 is H or Q, and X_2 is T or A.

[0022] With respect to certain embodiments of the invention, the multivalent immunogenic composition of the invention includes other known antigens from filarial nematodes. Examples of other suitable antigens include, but are not limited to, glutathione peroxidase (see Cookson, et al. (1992) *Proc. Natl. Acad. Sci. USA* 89:5837-5841; Maizels, et al. (1983) *Parasitology* 87:249-263; Maizels, et al. (1983) *Clin. Exp. Immunol.* 51:269-277); recombinant antigen (*BmR1*; see Noordin, et al. (2004) *Filaria J.* 3:10);

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class II aminoacyl-tRNA synthetase (see Kron, et al. (1995) *FEBS Lett.* 374:122-4); heat shock cognate 70 (hsc70) protein (see Selkirk, et al. (1989) *J. Immunol.* 143:299-308); paramyosin (see Li, et al. (1991) *Mol. Biochem. Parasitol.* 49:315-23); tropomyosin (Hartmann, et al. (2006) *Vaccine* 24(17):3581-90); chitinase (Adam, et al. (1996) *J. Biol. Chem.* 271(3):1441-7); Abundant Larval Transcript (ALT)-1 (Gregory, et al. (2000) *Infect. Immun.* 68(7):4174-9); immunodominant hypodermal antigen SPX1 (Bradley, et al. (1993) *Exp. Parasitol.* 77(4):414-424). In some embodiments, the antigen is obtained from a filarial nematode selected from the group of *W. bancrofti*, *B. malayi*, *O. volvulus*, *L. loa*, *D. immitis* and *B. timori*. In certain embodiments, the antigen is *B. malayi* or *Dirofilaria* tropomyosin having an amino acid sequence as set forth in SEQ ID NO:104 and SEQ ID NO:105, respectively, or a fragment thereof; *B. malayi* or *Dirofilaria* chitinase having an amino acid sequence as set forth in SEQ ID NO:106 and SEQ ID NO:107, respectively, or a fragment thereof; *B. malayi* or *Dirofilaria* ALT-1 having an amino acid sequence as set forth in SEQ ID NO:108 and SEQ ID NO:109, respectively, or a fragment thereof; *B. malayi* or *Dirofilaria* SPX1 having an amino acid sequence as set forth in SEQ ID NO:110 and SEQ ID NO:111, respectively, or a fragment thereof; *B. malayi* or *D. immitis* venom allergen antigen 5-like protein having an amino acid sequence as set forth in SEQ ID NO:112 and SEQ ID NO:113, respectively, or a fragment thereof; *B. malayi* or *D. immitis* Macrophage migration Inhibitory Factor (MIF)-1 protein having an amino acid sequence as set forth in SEQ ID NO:114 and SEQ ID NO:115, respectively, or a fragment thereof; *B. malayi* or *Dirofilaria* MIF-2 protein having an amino acid sequence as set forth in SEQ ID NO:116 and SEQ ID NO:117, respectively, or a fragment thereof; or *B.*

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malayi or *Dirofilaria* cystatin protein having an amino acid sequence as set forth in SEQ ID NO:118 and SEQ ID NO:119, respectively, or a fragment thereof.

[0023] According to the present invention, the antigens of the fusion protein and immunogenic composition are isolated from a filarial nematode. In this respect, an isolated nucleic acid molecule or protein is a nucleic acid molecule or protein that has been removed from its natural milieu (*i.e.*, that has been subjected to human manipulation). As such, "isolated" does not reflect the extent to which the nucleic acid molecule or protein has been purified. In particular embodiments, the antigens are purified (*e.g.*, purified to greater than 95% homogeneity). An isolated and optionally purified nucleic acid molecule or protein of the present invention can be obtained from its natural source or produced using recombinant DNA technology (*e.g.*, polymerase chain reaction (PCR) amplification or cloning) or chemical synthesis. Isolated nucleic acid molecules and proteins can also include, for example, natural allelic variants or isomers that induce an immune response in the host.

[0024] One embodiment of the present invention includes a recombinant vector, which includes at least one isolated nucleic acid molecule of the present invention, inserted into a vector capable of delivering the nucleic acid molecule into a host cell. Such a vector contains heterologous nucleic acid sequences, that are nucleic acid sequences that are not naturally found adjacent to nucleic acid molecules of the present invention and that preferably are derived from a species other than the species from which the nucleic acid molecule(s) are derived. The vector can be either prokaryotic or eukaryotic, and typically is a virus or a plasmid. Recombinant vectors can be used in the

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cloning, sequencing, and/or otherwise manipulating the nucleic acid molecules of the present invention.

[0025] The present invention also includes an expression vector, which includes a nucleic acid molecule of the present invention in a recombinant vector that is capable of expressing the nucleic acid molecule when transformed into a host cell. Preferably, the expression vector is also capable of replicating within the host cell. Expression vectors can be either prokaryotic or eukaryotic, and are typically viruses or plasmids. Expression vectors of the present invention include any vectors that function (*i.e.*, direct gene expression) in recombinant cells of the present invention, including in bacterial, fungal, parasite, insect, other animal, and plant cells. Preferred expression vectors of the present invention can direct gene expression in bacterial, yeast, helminth or other parasite, insect and mammalian cells.

[0026] In particular, expression vectors of the present invention contain regulatory sequences such as transcription control sequences, translation control sequences, origins of replication, and other regulatory sequences that are compatible with the recombinant cell and that control the expression of nucleic acid molecules of the present invention. In particular, recombinant molecules of the present invention include transcription control sequences. Transcription control sequences are sequences which control the initiation, elongation, and termination of transcription. Particularly important transcription control sequences are those which control transcription initiation, such as promoter, enhancer, operator and repressor sequences. Suitable transcription control sequences include any transcription control sequence that can function in at least one of the recombinant cells of

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the present invention. A variety of such transcription control sequences are known to those skilled in the art. Preferred transcription control sequences include those which function in bacterial, yeast, helminth or other endoparasite, or insect and mammalian cells, such as, but not limited to, *tac*, *lac*, *trp*, *trc*, *oxy-pro*, *omp/lpp*, *rrnB*, bacteriophage lambda (such as lambda *p_L* and lambda *p_R* and fusions that include such promoters), bacteriophage T7, T7lac, bacteriophage T3, bacteriophage SP6, bacteriophage SP01, metallothionein, alpha-mating factor, *Pichia* alcohol oxidase, alphavirus subgenomic promoter, antibiotic resistance gene, baculovirus, Heliothis zea insect virus, vaccinia virus, herpesvirus, raccoon poxvirus, other poxvirus, adenovirus, cytomegalovirus (such as immediate early promoter), simian virus 40, retrovirus, actin, retroviral long terminal repeat, Rous sarcoma virus, heat shock, phosphate and nitrate transcription control sequences as well as other sequences capable of controlling gene expression in prokaryotic or eukaryotic cells. Additional suitable transcription control sequences include tissue-specific promoters and enhancers as well as lymphokine-inducible promoters (e.g., promoters inducible by interferons or interleukins). Transcription control sequences of the present invention can also include naturally occurring transcription control sequences naturally associated with parasitic helminths, such as *B. malayi* or *D. immitis* transcription control sequences.

[0027] Recombinant molecules of the present invention may also contain (a) secretory signals (*i.e.*, signal segment nucleic acid sequences) to enable an expressed protein of the present invention to be secreted from the cell that produces the protein and/or (b) fusion sequences which lead to the expression of nucleic acid molecules of the present

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invention as fusion proteins. Examples of suitable signal segments include any signal segment capable of directing the secretion of a protein of the present invention. Preferred signal segments include, but are not limited to, tissue plasminogen activator (t-PA), interferon, interleukin, growth hormone, histocompatibility and viral envelope glycoprotein signal segments. In addition, a nucleic acid molecule of the present invention can be joined to a fusion segment that directs the encoded protein to the proteosome, such as a ubiquitin fusion segment. Eukaryotic recombinant molecules may also include intervening and/or untranslated sequences surrounding and/or within the nucleic acid sequences of nucleic acid molecules of the present invention.

[0028] Another embodiment of the present invention includes a recombinant host cell harboring one or more recombinant molecules of the present invention. Transformation of a nucleic acid molecule into a cell can be accomplished by any method by which a nucleic acid molecule can be inserted into the cell. Transformation techniques include, but are not limited to, transfection, electroporation, microinjection, lipofection, adsorption, and protoplast fusion. A recombinant cell may remain unicellular or may grow into a tissue, organ or a multicellular organism. Transformed nucleic acid molecules of the present invention can remain extrachromosomal or can integrate into one or more sites within a chromosome of the transformed (*i.e.*, recombinant) cell in such a manner that their ability to be expressed is retained.

[0029] Suitable host cells to transform include any cell that can be transformed with a nucleic acid molecule of the present invention. Host cells can be either untransformed cells or cells that are already transformed with at least

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one nucleic acid molecule (e.g., nucleic acid molecules encoding one or more proteins of the present invention and/or other proteins useful in the production of multivalent immunogenic compositions). Host cells of the present invention either can be endogenously (i.e., naturally) capable of producing proteins of the present invention or can be capable of producing such proteins after being transformed with at least one nucleic acid molecule of the present invention. Host cells of the present invention can be any cell capable of producing at least one protein of the present invention, and include bacterial, fungal (including yeast), parasite (including helminth, protozoa and ectoparasite), other insect, other animal and plant cells. Preferred host cells include bacterial, mycobacterial, yeast, helminth, insect and mammalian cells. More preferred host cells include *Salmonella*, *Escherichia*, *Bacillus*, *Listeria*, *Saccharomyces*, *Spodoptera*, *Mycobacteria*, *Trichoplusia*, BHK (baby hamster kidney) cells, MDCK cells (Madin-Darby canine kidney cell line), CRFK cells (Crandell feline kidney cell line), CV-1 cells (African monkey kidney cell line used, for example, to culture raccoon poxvirus), COS (e.g., COS-7) cells, and Vero cells. Particularly preferred host cells are *Escherichia coli*, including *E. coli* K-12 derivatives; *Salmonella typhi*; *Salmonella typhimurium*; *Spodoptera frugiperda*; *Trichoplusia ni*; BHK cells; MDCK cells; CRFK cells; CV-1 cells; COS cells; Vero cells; and non-tumorigenic mouse myoblast G8 cells (e.g., ATCC CRL 1246). Additional appropriate mammalian cell hosts include other kidney cell lines, other fibroblast cell lines (e.g., human, murine or chicken embryo fibroblast cell lines), myeloma cell lines, Chinese hamster ovary cells, mouse NIH/3T3 cells, LMTK³¹ cells and/or HeLa cells. In one

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embodiment, the proteins may be expressed as heterologous proteins in myeloma cell lines employing immunoglobulin promoters.

[0030] A recombinant cell is preferably produced by transforming a host cell with one or more recombinant molecules, each comprising one or more nucleic acid molecules of the present invention and one or more transcription control sequences, examples of which are disclosed herein.

[0031] Recombinant DNA technologies can be used to improve expression of transformed nucleic acid molecules by manipulating, for example, the number of copies of the nucleic acid molecules within a host cell, the efficiency with which those nucleic acid molecules are transcribed, the efficiency with which the resultant transcripts are translated, and the efficiency of post-translational modifications. Recombinant techniques useful for increasing the expression of nucleic acid molecules of the present invention include, but are not limited to, operatively linking nucleic acid molecules to high-copy number plasmids, integration of the nucleic acid molecules into one or more host cell chromosomes, addition of vector stability sequences to plasmids, substitutions or modifications of transcription control signals (e.g., promoters, operators, enhancers), substitutions or modifications of translational control signals (e.g., ribosome binding sites, Shine-Dalgarno sequences), modification of nucleic acid molecules of the present invention to correspond to the codon usage of the host cell, deletion of sequences that destabilize transcripts, and use of control signals that temporally separate recombinant cell growth from recombinant enzyme production during fermentation. The activity of an expressed

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recombinant protein of the present invention may be improved by fragmenting, modifying, or derivatizing nucleic acid molecules encoding such a protein. Moreover, while non-codon-optimized sequences may be used to express fusion proteins in host cells such as *E. coli* (see Table 1), in embodiments pertaining to DNA vaccines, the nucleic acid molecule may be codon-optimized to facilitate expression in mammalian cells. In this respect, codon-optimized sequences for BmALT2, N-terminal deleted HSP 12.6 (CHSP) of *B. malayi*, and LEL domain of *B. malayi* Tetraspanin are set forth in SEQ ID NO:67, SEQ ID NO:68, and SEQ ID NO:69, respectively. Moreover, to facilitate expression of one or more of the recombinant proteins in a recombinant host cell, the protein sequence can be manipulated. By way of illustration, the insertion of a glycine residue after the N-terminal methionine residue of the *B. malayi* ALT2 protein was found to improve expression of this protein in *E. coli*.

[0032] Isolated protein-based antigens of the present invention can be produced in a variety of ways, including production and recovery of natural proteins, production and recovery of recombinant proteins, and chemical synthesis of the proteins. In one embodiment, an isolated protein of the present invention is produced by culturing a cell capable of expressing the protein under conditions effective to produce the protein, and recovering the protein. A preferred cell to culture is a recombinant cell of the present invention. Effective culture conditions include, but are not limited to, effective media, bioreactor, temperature, pH and oxygen conditions that permit protein production. An effective medium refers to any medium in which a cell is cultured to produce a protein of the present invention. Such medium typically includes an aqueous medium having assimilable carbon, nitrogen and

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phosphate sources, and appropriate salts, minerals, metals and other nutrients, such as vitamins. Cells of the present invention can be cultured in conventional fermentation bioreactors, shake flasks, test tubes, microtiter dishes, and petri plates. Culturing can be carried out at a temperature, pH and oxygen content appropriate for a recombinant cell. Such culturing conditions are within the expertise of one of ordinary skill in the art.

[0033] Depending on the vector and host system used for production, resultant proteins of the present invention may either remain within the recombinant cell; be secreted into the fermentation medium; be secreted into a space between two cellular membranes, such as the periplasmic space in *E. coli*; or be retained on the outer surface of a cell or viral membrane.

[0034] Recovery of proteins of invention can include collecting the whole fermentation medium containing the protein and need not imply additional steps of separation or purification. Proteins of the present invention can be purified using a variety of standard protein purification techniques, such as, but not limited to, affinity chromatography, ion exchange chromatography, filtration, electrophoresis, hydrophobic interaction chromatography, gel filtration chromatography, reverse phase chromatography, concanavalin A chromatography, chromatofocusing and differential solubilization. Proteins of the present invention are preferably retrieved in substantially pure form thereby allowing for the effective use of the protein as a therapeutic composition. A therapeutic composition for animals, for example, should exhibit no substantial toxicity and preferably should be capable of stimulating the production of antibodies in a treated animal.

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[0035] One embodiment of the present invention is an immunogenic composition or vaccine that, when administered to an animal in an effective manner, is capable of protecting that animal from filariasis or dirofilariasis caused by a filarial nematode such as a *Dirofilaria* nematode. In some embodiments, the invention provides a method for treating or protecting an animal from a disease caused by a filarial nematode. In other embodiments, the invention provides a method for treating or protecting an animal, e.g., a dog or cat, from dirofilariasis (heartworm disease). Immunogenic compositions include protective molecules such as an isolated antigenic protein of the present invention, an isolated nucleic acid molecule of the present invention, and hybrids and mixtures thereof. As used herein, the multivalent immunogenic composition of the invention induces a protective immune response when administered in an effective manner to an animal such as a human, cat or dog thereby treating, ameliorating, and/or preventing disease caused by a filarial or dirofilarial nematode including, but not limited to, *W. bancrofti*, *B. malayi*, *O. volvulus*, *L. loa*, *D. immitis*, *Mansonella streptocerca*, *Dracunculus medinensis*, *M. perstans*, *M. ozzardi*, and/or *B. timori*. Immunogenic composition of the present invention can be administered to any animal susceptible to such therapy, preferably to mammals, and more preferably to humans, pets such as dogs and cats, and economic food animals and/or zoo animals.

[0036] In one embodiment, a multivalent immunogenic composition of the present invention when administered to the host can develop antibodies that can kill the parasites in the vector in which the filarial nematode develops, such as in a mosquito when they feed the host.

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[0037] In order to protect an animal from disease caused by a filarial nematode, an immunogenic composition of the present invention is administered to the animal in an effective manner such that the composition is capable of protecting that animal from a disease caused by the filarial nematode. Compositions of the present invention can be administered to animals prior to infection in order to prevent infection (*i.e.*, as a preventative vaccine) and/or can be administered to animals after infection in order to treat disease caused by the filarial nematode (*i.e.*, as a therapeutic vaccine).

[0038] Compositions of the present invention can be formulated in an excipient that the animal to be treated can tolerate. Examples of such excipients include water, saline, Ringer's solution, dextrose solution, Hank's solution, and other aqueous physiologically balanced salt solutions. Nonaqueous vehicles, such as fixed oils, sesame oil, ethyl oleate, or triglycerides may also be used. Other useful formulations include suspensions containing viscosity enhancing agents, such as sodium carboxymethylcellulose, sorbitol, or dextran. Excipients can also contain minor amounts of additives, such as substances that enhance isotonicity and chemical stability. Examples of buffers include phosphate buffer, bicarbonate buffer and Tris buffer, while examples of preservatives include thimerosal, m- or o-cresol, formalin and benzyl alcohol. Standard formulations can either be liquid injectables or solids which can be taken up in a suitable liquid as a suspension or solution for injection. Thus, in a non-liquid formulation, the excipient can comprise dextrose, human serum albumin, preservatives, etc., to which sterile water or saline can be added prior to administration.

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[0039] In one embodiment of the present invention, the immunogenic composition can include an adjuvant. An "adjuvant," as defined herein, is a substance that serves to enhance the immunogenicity of an immunogenic composition of the invention. An immune adjuvant may enhance an immune response to an antigen that is weakly immunogenic when administered alone, e.g., inducing no or weak antibody titers or cell-mediated immune response, increase antibody titers to the antigen, and/or lowers the dose of the antigen effective to achieve an immune response in the individual. Thus, adjuvants are often given to boost the immune response and are well known to the skilled artisan.

[0040] Suitable adjuvants to enhance effectiveness of the immunogenic composition include, but are not limited to:

- (1) aluminum salts (alum), such as aluminum hydroxide, aluminum phosphate, aluminum sulfate, etc.;

- (2) calcium-based salts;

- (3) silica;

- (4) oil-in-water emulsion formulations (with or without other specific immunostimulating agents such as muramyl peptides (defined below) or bacterial cell wall components), such as, for example,

- (a) MF59 (WO 90/14837), containing 5% squalene, 0.5% polysorbate 80, and 0.5% sorbitan trioleate (optionally containing various amounts of muramyl tripeptide phosphatidylethanolamine) formulated into submicron particles using a microfluidizer such as Model 110Y microfluidizer (Microfluidics, Newton, MA),

- (b) SAF, containing 10% squalene, 0.4% polysorbate 80, 5% pluronic-blocked polymer L121, and thr-MDP either microfluidized into a submicron emulsion or vortexed to generate a larger particle size emulsion,

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(c) Ribi™ adjuvant system (RAS), (Corixa, Hamilton, MT) containing 2% squalene, 0.2% polysorbate 80, and one or more bacterial cell wall components from the group consisting of 3-O-deacylated monophosphorylipid A (MPL™) described in US 4,912,094, trehalose dimycolate (TDM), and cell wall skeleton (CWS), preferably MPL+CWS (Detox™); and

(d) a Montanide ISA;

(5) saponin adjuvants, such as those sold under the tradenames QUIL-A® or QS-21 STIMULON® (Antigenics, Framingham, MA) (see, e.g., US 5,057,540), may be used or particles generated therefrom such as ISCOM (immunostimulating complexes formed by the combination of cholesterol, saponin, phospholipid, and amphipathic proteins) and Iscomatrix™ (having essentially the same structure as an ISCOM but without the protein);

(6) bacterial components (e.g., endotoxins, in particular superantigens, exotoxins and cell wall components) and lipopolysaccharides, synthetic lipid A analogs such as aminoalkyl glucosamine phosphate compounds (AGP), or derivatives or analogs thereof, which are available from Corixa, and described in US 6,113,918; one such AGP is 2-[(R)-3-tetradecanoyloxytetradecanoylamino]ethyl 2-Deoxy-4-O-phosphono-3-O-[(R)-3-tetradecanoyloxytetradecanoyl]-2-[(R)-3-tetradecanoyloxytetradecanoylamino]-β-D-glucopyranoside, which is also known as 529 (formerly known as RC529), which is formulated as an aqueous form or as a stable emulsion;

(7) synthetic polynucleotides such as oligonucleotides containing CpG motif(s) (US 6,207,646);

(8) cytokines and chemokines (e.g., granulocyte macrophage colony stimulating factor (GM-CSF), granulocyte colony stimulating factor (G-CSF), macrophage colony stimulating factor (M-CSF), colony stimulating factor

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(CSF), erythropoietin (EPO), interleukin 2 (IL-2), IL-3, IL-4, IL-5, IL-6, IL-7, IL-8, IL-10, IL-12, IL-15, IL-18, interferon gamma, interferon gamma inducing factor I (IGIF), transforming growth factor beta, RANTES (regulated upon activation, normal T-cell expressed and presumably secreted), macrophage inflammatory proteins (e.g., MIP-1 alpha and MIP-1 beta), tumor necrosis factor (TNF), costimulatory molecules B7-1 and B7-2, and Leishmania elongation initiating factor (LEIF));

(9) complement, such as a trimer of complement component C3d;

(10) toll-like receptor agonists, e.g., TLR4 agonists such as glucopyranosyl lipid adjuvant (GLA);

(11) serum proteins, e.g., transferrin;

(12) viral coat proteins, e.g., rotavirus *capsid* VP6 protein; and

(13) block copolymer adjuvants, e.g., Hunter's TITERMAX® adjuvant (VAXCEL, Inc. Norcross, GA).

[0041] Muramyl peptides include, but are not limited to, N-acetyl-muramyl-L-threonyl-D-isoglutamine (thr-MDP), N-acetyl-normuramyl-L-alanine-2-(1'-2'dipalmitoyl-sn-glycero-3-hydroxyphosphoryloxy)-ethylamine (MTP-PE), etc.

[0042] Protein adjuvants of the present invention can be delivered in the form of the protein themselves or of nucleic acid molecules encoding such proteins using the techniques described herein.

[0043] In certain embodiments, the adjuvant includes an aluminum salt. The aluminum salt adjuvant may be an alum-precipitated vaccine or an alum-adsorbed vaccine. Aluminum-salt adjuvants are well-known in the art and are described, for example, in Harlow & Lane ((1988) *Antibodies: A Laboratory Manual*, Cold Spring Harbor Laboratory) and Nicklas ((1992) *Res. Immunol.* 143:489-493). The aluminum

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salt includes, but is not limited to, hydrated alumina, alumina hydrate, alumina trihydrate (ATH), aluminum hydrate, aluminum trihydrate, aluminum (III) hydroxide, aluminum hydroxyphosphate sulfate, Aluminum Phosphate Adjuvant (APA), amorphous alumina, trihydrated alumina, or trihydroxyaluminum.

[0044] APA is an aqueous suspension of aluminum hydroxyphosphate. APA is manufactured by blending aluminum chloride and sodium phosphate in a 1:1 volumetric ratio to precipitate aluminum hydroxyphosphate. After the blending process, the material is size-reduced with a high-shear mixer to achieve a monodisperse particle size distribution. The product is then diafiltered against physiological saline and steam sterilized.

[0045] In certain embodiments, a commercially available $\text{Al}(\text{OH})_3$ (e.g., aluminum hydroxide gel sold under the tradename Alhydrogel®) is used to adsorb proteins in a ratio of 50-200 μg protein/mg aluminum hydroxide. Adsorption of protein is dependent, in another embodiment, on the pI (Isoelectric pH) of the protein and the pH of the medium. A protein with a lower pI adsorbs to the positively charged aluminum ion more strongly than a protein with a higher pI. Aluminum salts may establish a depot of antigen that is released slowly over a period of 2-3 weeks, be involved in nonspecific activation of macrophages and complement activation, and/or stimulate innate immune mechanism (possibly through stimulation of uric acid). See, e.g., Lambrecht, et al. (2009) *Curr. Opin. Immunol.* 21:23.

[0046] In some embodiments, the adjuvant is a mixture of 2, 3, or more of the above adjuvants, e.g., SBAS2 (an oil-in-water emulsion also containing 3-deacylated monophosphoryl lipid A and QS-21); or alum in combination with GLA (AL019).

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[0047] The multivalent immunogenic composition of the invention can be formulated as single dose vials, multi-dose vials or as pre-filled glass or plastic syringes.

[0048] In one embodiment, multivalent immunogenic compositions of the present invention are administered orally, and are thus formulated in a form suitable for oral administration, *i.e.*, as a solid or a liquid preparation. Solid oral formulations include tablets, capsules, pills, granules, pellets and the like. Liquid oral formulations include solutions, suspensions, dispersions, emulsions, oils and the like.

[0049] Pharmaceutically acceptable carriers for liquid formulations are aqueous or non-aqueous solutions, suspensions, emulsions or oils. Examples of nonaqueous solvents are propylene glycol, polyethylene glycol, and injectable organic esters such as ethyl oleate. Aqueous carriers include water, alcoholic/aqueous solutions, emulsions or suspensions, including saline and buffered media. Examples of oils are those of animal, vegetable, or synthetic origin, for example, peanut oil, soybean oil, olive oil, sunflower oil, fish-liver oil, another marine oil, or a lipid from milk or eggs.

[0050] The pharmaceutical composition may be isotonic, hypotonic or hypertonic. However, it is often preferred that a composition for infusion or injection is essentially isotonic, when it is administered. Hence, storage of the composition may preferably be isotonic or hypertonic. If the composition is hypertonic for storage, it may be diluted to become an isotonic solution prior to administration.

[0051] The isotonic agent may be an ionic isotonic agent such as a salt or a non-ionic isotonic agent such as a carbohydrate. Examples of ionic isotonic agents include but

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are not limited to NaCl, CaCl₂, KCl and MgCl₂. Examples of non-ionic isotonic agents include but are not limited to mannitol, sorbitol and glycerol.

[0052] It is also preferred that at least one pharmaceutically acceptable additive is a buffer. For some purposes, for example, when the composition is meant for infusion or injection, it is often desirable that the composition includes a buffer, which is capable of buffering a solution to a pH in the range of 4 to 10, such as 5 to 9, for example 6 to 8.

[0053] The buffer may, for example, be selected from Tris, acetate, glutamate, lactate, maleate, tartrate, phosphate, citrate, carbonate, glycinate, histidine, glycine, succinate and triethanolamine buffer. The buffer may be selected from USP compatible buffers for parenteral use, in particular, when the formulation is for parenteral use. For example the buffer may be selected from the group of monobasic acids such as acetic, benzoic, gluconic, glyceric and lactic; dibasic acids such as aconitic, adipic, ascorbic, carbonic, glutamic, malic, succinic and tartaric, polybasic acids such as citric and phosphoric; and bases such as ammonia, diethanolamine, glycine, triethanolamine, and Tris.

[0054] Parenteral vehicles (for subcutaneous, intravenous, intraarterial, or intramuscular injection) include sodium chloride solution, Ringer's dextrose, dextrose and sodium chloride, lactated Ringer's and fixed oils. Intravenous vehicles include fluid and nutrient replenishers, electrolyte replenishers such as those based on Ringer's dextrose, and the like. Examples are sterile liquids such as water and oils, with or without the addition of a surfactant and other pharmaceutically acceptable adjuvants. In general, water, saline, aqueous dextrose and related

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sugar solutions, glycols such as propylene glycols or polyethylene glycol, Polysorbate 80 (PS-80), Polysorbate 20 (PS-20), and Poloxamer 188 (P188) are preferred liquid carriers, particularly for injectable solutions. Examples of oils are those of animal, vegetable, or synthetic origin, for example, peanut oil, soybean oil, olive oil, sunflower oil, fish-liver oil, another marine oil, or a lipid from milk or eggs.

[0055] The formulations of the invention may also contain a surfactant. Preferred surfactants include, but are not limited to, the polyoxyethylene sorbitan esters surfactants, especially PS-20 and PS-80; copolymers of ethylene oxide (EO), propylene oxide (PO), and/or butylene oxide (BO), sold under the tradename DOWFAX™, such as linear EO/PO block copolymers; octoxynols, which can vary in the number of repeating ethoxy (oxy-1,2-ethanediyl) groups, with octoxynol-9 (Triton X-100, or t-octylphenoxy polyethoxyethanol) being of particular interest; (octylphenoxy) polyethoxyethanol (IGEPAL CA-630/NP-40); phospholipids such as phosphatidylcholine (lecithin); nonylphenol ethoxylates, such as the Tergitol™ NP series; polyoxyethylene fatty ethers derived from lauryl, cetyl, stearyl and oleyl alcohols (known as Brij surfactants), such as triethyleneglycol monolauryl ether (Brij 30); and sorbitan esters, such as sorbitan trioleate and sorbitan monolaurate. A preferred surfactant for including in the emulsion is PS-80.

[0056] Mixtures of surfactants can be used. A combination of a polyoxyethylene sorbitan ester such as polyoxyethylene sorbitan monooleate (PS-80) and an octoxynol such as t-octylphenoxy polyethoxyethanol is also suitable. Another useful combination comprises laureth 9 plus a polyoxyethylene sorbitan ester and/or an octoxynol.

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[0057] Poloxamer may also be used in the compositions of the invention. A poloxamer is a nonionic triblock copolymer composed of a central hydrophobic chain of polyoxypropylene (poly(propylene oxide)) flanked by two hydrophilic chains of polyoxyethylene (poly(ethylene oxide)). Poloxamers are also known by the tradename Pluronic®. Because the lengths of the polymer blocks can be customized, many different poloxamers exist that have slightly different properties. For the generic term "poloxamer", these copolymers are commonly named with the letter "P" (for poloxamer) followed by three digits, the first two digits x 100 give the approximate molecular mass of the polyoxypropylene core, and the last digit x10 gives the percentage polyoxyethylene content (e.g., P407=Poloxamer with a polyoxypropylene molecular mass of 4,000 g/mol and a 70% polyoxyethylene content). For the Pluronic® tradename, coding of these copolymers starts with a letter to define its physical form at room temperature (L=liquid, P=paste, F=flake (solid)) followed by two or three digits. The first digit (two digits in a three-digit number) in the numerical designation, multiplied by 300, indicates the approximate molecular weight of the hydrophobe; and the last digit x10 gives the percentage polyoxyethylene content (e.g., L61is a Pluronic® with a polyoxypropylene molecular mass of 1,800 g/mol and a 10% polyoxyethylene content). See US 3,740,421.

[0058] Preferably, the poloxamer generally has a molecular weight in the range from 1100 to 17,400 Da, from 7,500 to 15,000 Da, or from 7,500 to 10,000 Da. The poloxamer can be selected from poloxamer 188 or poloxamer 407. The final concentration of the poloxamer in the formulations is from 0.001% to 5% weight/volume, or 0.025% to 1% weight/volume. In certain aspects, the polyol is propylene glycol and is at final concentration from 1% to 20% weight/volume. In

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certain aspects, the polyol is polyethylene glycol 400 and is at final concentration from 1% to 20% weight/volume.

[0059] Suitable polyols for the formulations of the invention are polymeric polyols, particularly polyether diols including, but are not limited to, propylene glycol and polyethylene glycol, Polyethylene glycol monomethyl ethers. Propylene glycol is available in a range of molecular weights of the monomer from about 425 to about 2700. Polyethylene glycol and Polyethylene glycol monomethyl ether is also available in a range of molecular weights ranging from about 200 to about 35000 including but not limited to PEG200, PEG300, PEG400, PEG1000, PEG MME 550, PEG MME 600, PEG MME 2000, PEG MME 3350 and PEG MME 4000. A preferred polyethylene glycol is polyethylene glycol 400. The final concentration of the polyol in the formulations of the invention may be 1% to 20% weight/volume or 6% to 20% weight/volume.

[0060] The formulation may also contain a pH-buffered saline solution. The buffer may, for example, be selected from the group consisting of Tris, acetate, glutamate, lactate, maleate, tartrate, phosphate, citrate, carbonate, glycinate, histidine, glycine, succinate, HEPES (4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid), MOPS (3-(N-morpholino)propanesulfonic acid), MES (2-(N-morpholino)ethanesulfonic acid) and triethanolamine buffer. The buffer is capable of buffering a solution to a pH in the range of 4 to 10, 5.2 to 7.5, or 5.8 to 7.0. In certain aspects of the invention, the buffer is selected from the group of phosphate, succinate, histidine, MES, MOPS, HEPES, acetate or citrate. The buffer may furthermore, for example, be selected from USP compatible buffers for parenteral use, in particular, when the pharmaceutical formulation is for parenteral use. The concentrations of

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buffer will range from 1 mM to 100 mM. The concentrations of buffer will range from 10 mM to 80 mM. The concentrations of buffer will range from 1 mM to 50 mM or 5 mM to 50 mM.

[0061] While the saline solution (*i.e.*, a solution containing NaCl) is preferred, other salts suitable for formulation include but are not limited to, CaCl₂, KCl and MgCl₂ and combinations thereof. Non-ionic isotonic agents including but not limited to sucrose, trehalose, mannitol, sorbitol and glycerol may be used in lieu of a salt. Suitable salt ranges include, but are not limited to 25 mM to 500 mM or 40 mM to 170 mM. In one aspect, the saline is NaCl, optionally present at a concentration from 20 mM to 170 mM.

[0062] In some aspects, the composition of the invention is administered to a subject by one or more methods known to a person skilled in the art, such as parenterally, transmucosally, transdermally, intramuscularly, intravenously, intra-dermally, intra-nasally, subcutaneously, intra-peritoneally, and formulated accordingly. In one embodiment, a composition of the present invention is administered via epidermal injection, intramuscular injection, intravenous, intra-arterial, subcutaneous injection, or intra-respiratory mucosal injection of a liquid preparation. Liquid formulations for injection include solutions and the like.

[0063] One embodiment of the present invention is a controlled release formulation that is capable of slowly releasing a composition of the present invention into an animal. As used herein, a controlled release formulation includes a composition of the present invention in a controlled release vehicle. Suitable controlled release vehicles include, but are not limited to, biocompatible

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polymers, other polymeric matrices, capsules, microcapsules, microparticles, bolus preparations, osmotic pumps, diffusion devices, liposomes, lipospheres, and transdermal delivery systems. Other controlled release formulations of the present invention include liquids that, upon administration to an animal, form a solid or a gel *in situ*. Preferred controlled release formulations are biodegradable (*i.e.*, bioerodible).

[0064] A preferred controlled release formulation is capable of releasing an immunogenic composition of the present invention into the blood of the treated animal at a constant rate sufficient to attain therapeutic dose levels of the composition to protect an animal from disease caused by a filarial nematode. For example, the immunogenic composition can be administered using intravenous infusion, a transdermal patch, liposomes, or other modes of administration. In another embodiment, polymeric materials are used, *e.g.*, in microspheres in or an implant. The immunogenic composition is preferably released over a period of time ranging from about 1 to about 12 months. A controlled release formulation of the present invention is capable of effecting a treatment preferably for at least about 1 month, more preferably for at least about 3 months, even more preferably for at least about 6 months, even more preferably for at least about 9 months, and even more preferably for at least about 12 months.

[0065] Immunogenic compositions or vaccines of the present invention can be administered to animals prior to infection in order to prevent infection and/or can be administered to animals after infection in order to treat disease caused by a filarial nematode. For example, proteins, nucleic acids and mixtures thereof can be used as immunotherapeutic agents. Acceptable protocols to administer compositions in

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an effective manner include individual dose size, number of doses, frequency of dose administration, and mode of administration. Determination of such protocols can be accomplished by those skilled in the art. A suitable single dose is a dose that is capable of protecting an animal from disease when administered one or more times over a suitable time period. For example, a preferred single dose of a protein-based vaccine is from about 1 microgram (pg) to about 10 milligrams (mg) of protein-based vaccine per kilogram body weight of the animal. Booster vaccinations can be administered from about 2 weeks to several years after the original administration. Booster administrations preferably are administered when the immune response of the animal becomes insufficient to protect the animal from disease. A preferred administration schedule is one in which from about 10 µg to about 1 mg of the vaccine per kg body weight of the animal is administered from about one to about two times over a time period of from about 2 weeks to about 12 months. Modes of administration can include, but are not limited to, subcutaneous, intradermal, intravenous, intranasal, oral, transdermal and intramuscular routes.

[0066] Wherein the immunogenic composition includes a nucleic acid molecule, the immunogenic composition can be administered to an animal in a fashion to enable expression of that nucleic acid molecule into a protective protein in the animal. Nucleic acid molecules can be delivered to an animal in a variety of methods including, but not limited to, administering a naked (*i.e.*, not packaged in a viral coat or cellular membrane) nucleic acid as a genetic vaccine (*e.g.*, as naked DNA molecules, such as is taught, for example in Wolff, et al. (1990) *Science* 247:1465-1468); or administering a nucleic acid molecule packaged as a recombinant virus vaccine or as a recombinant cell vaccine

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(*i.e.*, the nucleic acid molecule is delivered by a viral or cellular vehicle).

[0067] A genetic (*i.e.*, naked nucleic acid) vaccine of the present invention includes a nucleic acid molecule of the present invention and preferably includes a recombinant molecule of the present invention that preferably is replication, or otherwise amplification, competent. A genetic vaccine of the present invention can include one or more nucleic acid molecules of the present invention in the form of, for example, a dicistronic recombinant molecule. Preferred genetic vaccines include at least a portion of a viral genome (*i.e.*, a viral vector). Preferred viral vectors include those based on alphaviruses, poxviruses, adenoviruses, herpesviruses, picornaviruses, and retroviruses, with those based on alphaviruses (such as sindbis or Semliki forest virus), species-specific herpesviruses and poxviruses being particularly preferred. Any suitable transcription control sequence can be used, including those disclosed as suitable for protein production. Particularly preferred transcription control sequences include cytomegalovirus immediate early (preferably in conjunction with Intron-A), Rous sarcoma virus long terminal repeat, and tissue-specific transcription control sequences, as well as transcription control sequences endogenous to viral vectors if viral vectors are used. The incorporation of a "strong" polyadenylation signal is also preferred.

[0068] Genetic vaccines of the present invention can be administered in a variety of ways, including intramuscular, subcutaneous, intradermal, transdermal, intranasal and oral routes of administration. Moreover, it is contemplated that the vaccine can be delivered by gene gun, skin patch, electroporation, or nano-based delivery. In this respect,

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DNA-based and protein-based vaccines can be administered at the same time. A preferred single dose of a genetic vaccine ranges from about 1 nanogram (ng) to about 600 µg, depending on the route of administration and/or method of delivery, as can be determined by those skilled in the art. Suitable delivery methods include, for example, by injection, as drops, aerosolized and/or topically. Genetic vaccines of the present invention can be contained in an aqueous excipient (e.g., phosphate-buffered saline) alone or in a carrier (e.g., lipid-based vehicles).

[0069] A recombinant virus vaccine of the present invention includes a recombinant molecule of the present invention that is packaged in a viral coat and that can be expressed in an animal after administration. Preferably, the recombinant molecule is packaging- or replication-deficient and/or encodes an attenuated virus. A number of recombinant viruses can be used, including, but not limited to, those based on alphaviruses, poxviruses, adenoviruses, herpesviruses, picornaviruses, and retroviruses. Preferred recombinant virus vaccines are those based on alphaviruses (such as Sindbis virus), raccoon poxviruses, species-specific herpesviruses and species-specific poxviruses. Examples of methods to produce and use alphavirus recombinant virus vaccines are disclosed in PCT Publication No. WO 94/17813.

[0070] When administered to an animal, a recombinant virus vaccine of the present invention infects cells within the immunized animal and directs the production of a protective protein that is capable of protecting the animal from filariasis caused by filarial nematodes. By way of illustration, a single dose of a recombinant virus vaccine of the present invention can be from about 1×10^4 to about 1×10^8 virus plaque forming units (pfu) per kilogram body

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weight of the animal. Administration protocols are similar to those described herein for protein-based vaccines, with subcutaneous, intramuscular, intranasal and oral as routes of administration.

[0071] A recombinant cell vaccine of the present invention includes recombinant cells of the present invention that express a protein of the present invention. Preferred recombinant cells for this embodiment include *Salmonella*, *E. coli*, *Listeria*, *Mycobacterium*, *S. frugiperda*, yeast, (including *Saccharomyces cerevisiae* and *Pichia pastoris*), BHK, CV-1, myoblast G8, COS (e.g., COS-7), Vero, MDCK and CRFK recombinant cells. Recombinant cell vaccines of the present invention can be administered in a variety of ways but have the advantage that they can be administered orally, preferably at doses ranging from about 10^8 to about 10^{12} cells per kilogram body weight. Administration protocols are similar to those described herein for protein-based vaccines. Recombinant cell vaccines can include whole cells, cells stripped of cell walls or cell lysates.

[0072] In some embodiments of the composition of the invention, all of the antigens are present in the composition in the same amount. In further embodiments, the antigens are present in the composition in different amounts (i.e., at least one antigen is present in an amount that is different than one or more of the other antigens of the composition).

[0073] Optimal amounts of components for a particular immunogenic composition can be ascertained by standard studies involving observation of appropriate immune responses in subjects. For example, in another embodiment, the dosage for human vaccination is determined by

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extrapolation from animal studies to human data. In another embodiment, the dosage is determined empirically.

[0074] As is known in the art, there are three groups of filarial nematodes, classified according to the niche within the body that they occupy: lymphatic filariasis, subcutaneous filariasis, and serous cavity filariasis. Lymphatic filariasis is caused by the worms *W. bancrofti*, *B. malayi* and *B. timori*. These worms occupy the lymphatic system, including the lymph nodes, and cause fever, lymphadenitis (swelling of the lymph nodes), lymphangitis (inflammation of the lymphatic vessels in response to infection), and lymphedema (elephantiasis). Subcutaneous filariasis may be caused by *Loa loa* (the African eye worm), *Mansonella streptocerca*, *O. volvulus*, *Dracunculus medinensis*, or *Dirofilaria immitis*. Many of these worms occupy the subcutaneous layer of the skin, in the fat layer, and present with skin rashes, urticarial papules, and arthritis, as well as hyper- and hypopigmentation macules. *Onchocerca volvulus* manifests itself in the eyes, causing "river blindness." Adult *Dirofilaria immitis* reside in pulmonary arteries and are the causal agent of heartworm disease. Serous cavity filariasis is caused by the worms *M. perstans* and *M. ozzardi*, which occupy the serous cavity of the abdomen. Serous cavity filariasis presents with symptoms similar to subcutaneous filariasis, in addition to abdominal pain, because these worms are also deep tissue dwellers.

[0075] Dogs infected with *Brugia malayi* develop clinical lymphedema, scrotal enlargement, conjunctivitis and lymphagitis similar to the human lymphatic filariasis; however, the pathology is not as severe as in the human. Since dogs carry the infection in the nature, humans can get the *Brugia malayi* infections from dogs. Thus, zoonotic

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infections are common in the endemic areas, where dogs and cats carry the infection in the nature and they transmit the infection to the humans. Dogs and cats can also be infected with *Brugia malayi* under laboratory conditions. Thus, an immunogenic composition developed against lymphatic filariasis in dogs are also important in blocking transmission of the disease in the human.

[0076] The efficacy of a multivalent immunogenic composition of the present invention to protect an animal from filariasis or dirofilariasis caused by filarial nematodes can be tested in a variety of ways including, but not limited to, detection of protective antibodies (using, for example, proteins of the present invention), detection of cellular immunity within the treated animal, and/or challenge of the treated animal with the a filarial nematode to determine whether the treated animal is resistant to disease and fails to exhibit one or more signs of disease. Challenge studies can include implantation of chambers including filarial nematode larvae into the treated animal and/or direct administration of larvae to the treated animal. In one embodiment, therapeutic compositions can be tested in animal models such as mice, jirds (*Meriones unguiculatus*), mastomys (e.g., *Mastomys natalensis*) and/or dogs. Such techniques are known to those skilled in the art.

[0077] To detect the presence/amount of anti-filarial nematode antibodies, e.g., protective or neutralizing antibodies resulting from the vaccination of an animal, this invention also provides a method and kit for efficacy evaluation, as well as for detecting prior exposure to filarial proteins and/or infection with a filarial nematode. In accordance with such a method, one or more antigenic proteins/epitopes is contacted with a biological

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sample from an animal and binding between the antigenic proteins/epitopes and antibodies in the biological sample is quantitatively or qualitatively determined as described herein, wherein the presence and/or amount of antibodies to the antigenic proteins/epitopes is indicative of vaccine efficacy, as well as prior exposure to filarial proteins or an existing infection with a filarial nematode. In certain embodiments, the method and kit use an array-based format in which serial dilutions of one or more antigens or epitopes are printed. In some embodiments, the one or more of the filarial nematode proteins are present on one or more solid surfaces or particles. In other embodiments, the one or more of the filarial nematode proteins are in an array so that the presence of multiple antibodies can be assessed in a single assay due to the multiplexing capability of an array-based approach. In this respect, the array can contain one or more of ALT2, TSP, VAL-1, TPX2, GST or HSP protein or an epitope thereof. In other embodiments, the array at least contains each of the proteins used in the multivalent immunogenic composition. For example, to assay for protective or neutralizing antibodies against a multivalent immunogenic composition containing HSP, ALT2 and TSP, the array would contain HSP, ALT2 and TSP, or a fusion protein thereof.

[0078] For testing for the presence of a filarial nematode, this invention also provides a method and kit for detecting a filarial nematode. The assay method generally includes the steps of contacting, *in vitro*, a biological sample with one or more binding agents against filarial nematode proteins selected from the group of ALT2, TSP, VAL-1, TPX2, GST and HSP or fragments thereof. The bound binding agents are then detected. The bound binding agents can be detected using automated detection of binding such as an image

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reader of an ELISA assay, and if a bound binding agent is detected, the data indicating that a bound binding agent has been detected can be transferred, e.g., to a computer display or on a paper print out. Detection of a filarial nematode protein indicates that the sample or subject from which the sample was obtained has filariasis. Therefore, detection allows selection of treatment options for the subject. Thus, in one embodiment, if one or more of ALT2, TSP, VAL-1, TPX2, GST and HSP is detected, the patient will be given a treatment suitable for filariasis, including but not limited to treatment with diethylcarbamazine, mebendazole, flubendazole, albendazole, ivermectin or a combination thereof.

[0079] A biological sample is any material to be tested for the presence or amount of a protein of interest (e.g., an antibody or antigen/epitope). The sample can be a fluid sample, preferably a liquid sample. Examples of liquid samples that may be tested in accordance with this invention include bodily fluids including blood, serum, plasma, saliva, urine, ocular fluid, semen, and spinal fluid. Viscous liquid, semi-solid, or solid specimens (e.g., human tissue, or mosquito or fly tissue) may be used to create liquid solutions, eluates, suspensions, or extracts that can be samples. In some embodiments, the biological sample is undiluted. In other embodiments, the sample is diluted or concentrated depending on the detection application.

[0080] In certain embodiments, one can concentrate the proteins in the sample by using a solid surface coated with a monoclonal antibody to capture the protein. The recovered captured proteins can then be analyzed using any suitable method described herein. The solid surface can be, e.g., beads, such as magnetic beads, polystyrene beads, or gold

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beads, or in an array or a microarray format using a glass, a plastic or a silicon chip. Such protein capture can be also a part of a channel in a microfluidic device.

[0081] Binding agents of use in this invention include an antibody, an antibody fragment, or an antibody derivative (e.g., an aptamer) which specifically binds to a cognate filarial nematode protein. Specific binding between two entities generally refers to an affinity of at least 10^6 , 10^7 , 10^8 , 10^9 , or 10^{10} M^{-1} . Affinities greater than 10^8 M^{-1} are desired to achieve specific binding.

[0082] When the binding agent is an antibody, the antibody can be produced by natural (i.e., immunization) or partial or wholly synthetic means. Antibodies can be monoclonal or polyclonal and include commercially available antibodies. An antibody can be a member of any immunoglobulin class, including any of the human classes: IgG, IgM, IgA, IgD, and IgE. Bispecific and chimeric antibodies are also encompassed within the scope of the present invention. Derivatives of the IgG class, however, are desirable. Further, an antibody can be of human, mouse, rat, goat, sheep, rabbit, chicken, camel, or donkey origin or other species which may be used to produce native or human antibodies (i.e., recombinant bacteria, baculovirus or plants).

[0083] For example, naturally-produced monoclonal antibodies can be generated using classical cloning and cell fusion techniques or techniques wherein B-cells are captured and nucleic acids encoding a specific antibody are amplified (see, e.g., US 20060051348). In such methods, a collection of proteins or an individual protein (e.g., a peptide or polypeptide) can be used for the initial immunization and in the context of antibody production is referred to herein as the antigen. The antigen of interest

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is typically administered (e.g., intraperitoneal injection) to wild-type or inbred mice (e.g., BALB/c) or rats, rabbits, chickens, sheep, goats, or other animal species which can produce native or human antibodies. The antigen can be administered alone, or mixed with an adjuvant. After the animal is boosted, for example, two or more times, the spleen or large lymph node, such as the popliteal in rat, is removed and splenocytes or lymphocytes are isolated and fused with myeloma cells using well-known processes, for example, see Kohler & Milstein ((1975) *Nature* 256:495-497) or Harlow & Lane (*Antibodies: A Laboratory Manual* (Cold Spring Harbor Laboratory, New York (1988))). The resulting hybrid cells are then cloned in the conventional manner, e.g., using limiting dilution, and the resulting clones, which produce the desired monoclonal antibodies, are cultured (see Stewart (2001) *Monoclonal Antibody Production*. In: *Basic Methods in Antibody Production and Characterization*, Howard and Bethell (eds.), CRC Press, Boca Raton, FL, pp.51-67).

[0084] Alternatively, antibodies can be derived by a phage display method. Methods of producing phage display antibodies are known in the art, e.g., see Huse, et al. ((1989) *Science* 246(4935):1275-81). Selection of antibodies is based on binding affinity to a protein or proteins of interest.

[0085] An antibody fragment encompasses at least a significant portion of the full-length antibody's specific binding ability. Examples of antibody fragments include, but are not limited to, Fab, Fab', F(ab')₂, scFv, Fv, dsFv, diabody, Fd fragments or microbodies. An antibody fragment can contain multiple chains which are linked together, for instance, by disulfide linkages. A fragment can also optionally be a multi-molecular complex. A functional

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antibody fragment will typically include at least about 50 amino acid residues and more typically will include at least about 200 amino acid residues. The antibody fragment can be produced by any means. For instance, the antibody fragment can be enzymatically or chemically produced by fragmentation of an intact antibody or it can be recombinantly-produced from a gene encoding the partial antibody sequence. Alternatively, the antibody fragment can be wholly or partially synthetically-produced.

[0086] Peptide aptamers which specifically bind to a protein are, in general, rationally designed or screened for in a library of aptamers (e.g., provided by Aptanomics SA, Lyon, France). In general, peptide aptamers are synthetic recognition molecules whose design is based on the structure of antibodies. Peptide aptamers are composed of a variable peptide loop attached at both ends to a protein scaffold. This double structural constraint greatly increases the binding affinity of the peptide aptamer to levels comparable to that of an antibody (nanomolar range).

[0087] Recombinant production of binding agents of this invention can be achieved using conventional molecular biology techniques and commercially available expression systems. Furthermore, binding agents can be produced using solid-phase techniques (see, e.g., Merrifield (1963) *J. Am. Chem. Soc.* 85:2149-2154; Seeberger (2003) *Chem. Commun. (Camb)* (10):1115-21). Protein synthesis can be performed using manual techniques or by automation. Automated synthesis can be achieved, for example, using Applied Biosystems 431A Peptide Synthesizer (Perkin Elmer, Boston, MA). Various fragments of a binding agent can be chemically-synthesized separately and combined using chemical methods to produce a full-length molecule.

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[0088] Moreover, combinatorial chemistry approaches can be used to produce binding agents (see, e.g., Lenssen, et al. (2002) *Chembiochem.* 3(9):852-8; Khersonsky, et al. (2003) *Curr. Top. Med. Chem.* 3(6):617-43; Anthony-Cahill & Magliery (2002) *Curr. Pharm. Biotechnol.* 3(4):299-315).

[0089] The binding agents described herein can be labeled. In some embodiments, the binding agent is an antibody labeled by covalently linking the antibody to a direct or indirect label. A direct label can be defined as an entity, which in its natural state, is visible either to the naked eye or with the aid of an optical filter and/or applied stimulation, e.g., ultraviolet light, to promote fluorescence. Examples of colored labels which can be used include metallic sol particles, gold sol particles, dye sol particles, dyed latex particles or dyes encapsulated in liposomes. Other direct labels include radionuclides and fluorescent or luminescent moieties.

[0090] Indirect labels such as enzymes can also be used according to the invention. Various enzymes are known for use as labels such as, for example, alkaline phosphatase, horseradish peroxidase, lysozyme, glucose-6-phosphate dehydrogenase, lactate dehydrogenase and urease. For a detailed discussion of enzymes in immunoassays see Engvall (1980) *Methods of Enzymology* 70:419-439.

[0091] The proteins described herein (i.e., antibodies or antigens/epitopes) can be attached to a surface. Examples of useful surfaces on which the protein can be attached for diagnostic purposes include nitrocellulose, PVDF, polystyrene, nylon or other suitable plastic. The surface or support may also be a porous support (see, e.g., US 7,939,342).

[0092] Further, the proteins of the invention can be attached to a particle or bead. For example, antibodies to

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the filarial nematode proteins or the filarial nematode proteins themselves can be conjugated to superparamagnetic microparticles, e.g., as used in LUMINEX-based multiplex assays.

[0093] The filarial nematode proteins of this invention may be isolated and/or purified or produced synthetically or using recombinant nucleic acid technology. The purification may be partial or substantial. With reference to filarial nematode protein fragments, the term "fragment" refers to a protein having an amino acid sequence shorter than that of the proteins described herein. Preferably, such fragments are at least 5 consecutive amino acids long or up to 35 amino acids long. In certain embodiments, the protein fragment includes at least one epitope. An "epitope" is a feature of a molecule, such as primary, secondary and/or tertiary peptide structure, and/or charge, that forms a site recognized by an immunoglobulin, T cell receptor or HLA molecule. Alternatively, an epitope can be defined as a set of amino acid residues which is involved in recognition by a particular immunoglobulin, or in the context of T cells, those residues necessary for recognition by T cell receptor proteins and/or Major Histocompatibility Complex (MHC) receptors.

[0094] In some embodiments, the protein fragment of the invention is a fragment of ALT2 comprising or consisting of the epitope of SEQ ID NO:121, in particular epitopes of SEQ ID NO:78 or SEQ ID NO:98. In other embodiments, the protein fragment of the invention is a fragment of ALT2 comprising or consisting of the epitope of SEQ ID NO:122, in particular SEQ ID NO:79 or SEQ ID NO:99. In further embodiments, the protein fragment of the invention is a fragment of HSP comprising or consisting of the epitope of SEQ ID NO:81 or SEQ ID NO:123, in particular SEQ ID NO:80

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or SEQ ID NO:100. In certain embodiments, the protein fragment of the invention is a fragment of TSP comprising or consisting of the epitope of SEQ ID NO:82. In other embodiments, the protein fragment of the invention is a fragment of TPX2 comprising or consisting of the epitope of SEQ ID NO:83 or SEQ ID NO:124, in particular SEQ ID NO:84 or SEQ ID NO:101.

[0095] The fragments of the invention can be isolated, purified or otherwise prepared/derived by human or non-human means. For example, epitopes can be prepared by isolating the filarial nematode protein fragment from a bacterial culture, or they can be synthesized in accordance with standard protocols in the art. Synthetic epitopes can also be prepared from amino acid mimetics, such as D isomers of natural occurring L amino acids or non-natural amino acids such as cyclohexylalanine.

[0096] In some embodiments, the filarial nematode protein or protein fragment is conjugated or fused to a high molecular weight protein carrier to facilitate antibody production. In some embodiments, the high molecular weight protein is bovine serum albumin, thyroglobulin, ovalbumin, fibrinogen, or keyhole limpet hemocyanin. A particularly preferred carrier is keyhole limpet hemocyanin.

[0097] Any suitable immunoassay method may be used, including those which are commercially available, to determine the level of at least one of the specific filarial nematode proteins, protein fragments or protective/neutralizing antibodies according to the invention. Extensive discussion of the known immunoassay techniques is not required here since these are known to those of skill in the art. Typical suitable immunoassay techniques include sandwich enzyme-linked immunoassays (ELISA), radioimmunoassays (RIA), competitive binding

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assays, homogeneous assays, heterogeneous assays, etc. Various of the known immunoassay methods are reviewed, e.g., in *Methods in Enzymology* (1980) 70:30-70 and 166-198.

[0098] In some embodiments, the immunoassay method or assay includes a double antibody technique for measuring the level of the filarial nematode proteins or protein fragments in the biological sample. According to this method one of the antibodies is a "capture" antibody and the other is a "detector" antibody. The capture antibody is immobilized on a solid support which may be any of various types which are known in the art such as, for example, microtiter plate wells, beads, tubes and porous materials such as nylon, glass fibers and other polymeric materials. In this method, a solid support, e.g., microtiter plate wells, coated with a capture antibody, preferably monoclonal, raised against the particular protein of interest, constitutes the solid phase. The biological sample, which may be diluted or not, typically at least 1, 2, 3, 4, 5, 10, or more standards and controls are added to separate solid supports and incubated. When the protein of interest is present in the sample it is captured by the immobilized antibody which is specific for the protein in question. After incubation and washing, a detector antibody, e.g., a polyclonal rabbit anti-marker protein antibody, is added to the solid support. The detector antibody binds to the protein bound to the capture antibody to form a sandwich structure. After incubation and washing an anti-IgG antibody, e.g., a polyclonal goat anti-rabbit IgG antibody, labeled with an enzyme such as horseradish peroxidase (HRP) is added to the solid support. After incubation and washing a substrate for the enzyme is added to the solid support followed by incubation and the

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addition of an acid solution to stop the enzymatic reaction.

[0099] The degree of enzymatic activity of immobilized enzyme is determined by measuring the optical density of the oxidized enzymatic product on the solid support at the appropriate wavelength, e.g., 450 nm for HRP. The absorbance at the wavelength is proportional to the amount of protein of interest in the sample. A set of marker protein standards is used to prepare a standard curve of absorbance vs. filarial nematode protein concentration. This method is useful because test results can be provided in 45 to 50 minutes and the method is both sensitive over the concentration range of interest for each filarial nematode protein and is highly specific.

[00100] The standards may be positive samples containing various concentrations of the protein to be detected to ensure that the reagents and conditions work properly for each assay. The standards also typically include a negative control, e.g., for detection of contaminants. In some aspects of the embodiments of the invention, the positive controls may be titrated to different concentrations, including non-detectable amounts and clearly detectable amounts, and in some aspects, also including a sample that shows a signal at the threshold level of detection in the biological sample.

[00101] The method of the invention can be carried out in various assay device formats including those described in US 6,426,050, US 5,910,287, US 6,229,603, and US 6,232,114 to Aurora Biosciences Corporation. The assay devices used according to the invention can be arranged to provide a quantitative or a qualitative (present/not present) result. In some embodiments, the method includes the use of a microtiter plate or a microfluidic device format. The

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assays may also be carried out in automated immunoassay analyzers which are known in the art and which can carry out assays on a number of different samples. These automated analyzers include continuous/random access types. Examples of such systems are described in US 5,207,987, US 5,518,688, US 6,448,089, and US 6,814,933. Various automated analyzers that are commercially available include the OPUS® and OPUS MAGNUM® analyzers.

[00102] Another assay format which can be used according to the invention is a rapid manual test which can be administered at the point-of-care at any location. Typically, such point-of-care assay devices will provide a result which is either "positive," i.e., showing the protein is present, or "negative" showing that the protein is absent. Typically, a control showing that the reagents worked in general is included with such point-of-care system. Point-of-care systems, assays and devices have been well described for other purposes, such as pregnancy detection (see, e.g., US 7,569,397 and US 7,959,875). Accordingly, the invention also provides devices, such as point-of-care test strips and microfluidic devices to perform the *in vitro* assays of the present invention.

[00103] It should be recognized also that the assay devices used according to the invention can be provided to carry out one single assay for a particular protein or to carry out a plurality of assays, from a single volume of body fluid, for a corresponding number of different filarial nematode proteins or antibodies thereto. In some embodiments, an assay device of the latter type is one which can provide a semi-quantitative result for the filarial nematode protein or antibodies measured according to the invention, i.e., one or more of ALT2, TSP, VAL-1, TPX2, GST and HSP, or antibodies thereto. These devices

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typically are adapted to provide a distinct visually detectable colored band at the location where the particular protein of interest is located when the concentration of the protein is above the threshold level. For additional detailed discussion of assay types which can be utilized according to the invention as well as various assay formats and automated analyzer apparatus see, e.g., US 5,747,274. Filarial nematode protein detection can further be performed using multiplex technologies.

[00104] In other embodiments, the assays or immunoassays of the invention include beads coated with a binding agent against a filarial nematode protein or a fragment thereof, or antibody. Commonly used are polystyrene beads that can be labeled to establish a unique identity. Detection is performed by flow cytometry. Other types of bead-based immunoassays are known in the art, e.g., laser bead immunoassays and related magnetic bead assays (see, e.g., Fritzler, et al. (2009) *Expert Opinion on Medical Diagnostics* 3:81-89).

[00105] The methods of the invention can be automated using robotics and computer directed systems. The biological sample can be injected into a system, such as a microfluidic device entirely run by a robotic station from sample input to output of the result. The step of displaying the result can also be automated and connected to the same system or in a remote system. Thus, the sample analysis can be performed in one location and the result analysis in another location, the only connection being, e.g., an internet connection, wherein the analysis is subsequently displayed in a format suitable for either reading by a health professional or by a patient.

[00106] In certain embodiments, the presence of any one or any combination of protective/neutralizing antibodies

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described herein identifies a subject as having been immunized with a multivalent immunogenic composition against a filarial nematode. Thus, depending on antibody titer, the subject may or may not receive additional booster vaccinations.

[00107] In some embodiments, the presence of any one or any combination of the filarial nematode proteins described herein identifies a subject as having a filarial nematode infection. Thus, the subject is diagnosed as having filariasis and, in certain embodiments of this invention, treated with diethylcarbamazine, mebendazole, flubendazole, albendazole, ivermectin or a combination thereof. In one embodiment, the diagnosis can be made if the presence of any one of the filarial nematode proteins is detected in the subject's sample. In another embodiment, treatment is prescribed or administered if at least two of the filarial nematode proteins are identified positively in the biological sample.

[00108] Kits provided according to this invention include one or more binding agents, e.g., antibodies or antibody fragments, or filarial nematode proteins, and optionally a device with a solid surface. In some embodiments, the solid surface is a bead, slide, assay plate (e.g., a multiwell plate) or a lateral flow device, to which the binding agents/proteins are bound. In some embodiments, the kit further includes one or more standards or controls.

[00109] In some embodiments, the invention provides a microplate-based array for multiplex immunoassays. In accordance with some embodiments, each well can contain a single antibody against at least one of the listed filarial nematode proteins. In other embodiments, each well contains an array of antibodies against at least two or more of the listed filarial nematode proteins. In certain embodiments,

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each well of the plate includes an antibody to two, three, four, or five of the following proteins: ALT2, TSP, VAL-1, TPX2, GST and HSP. In particular embodiments, each well of the plate includes an antibody to each of ALT2, TSP, VAL-1, TPX2, GST and HSP.

[00110] In other embodiments, each well contains an array of at least two or more of the filarial nematode proteins of this invention. In certain embodiments, each well of the plate includes two, three, four, or five of the following proteins: ALT2, TSP, VAL-1, TPX2, GST and HSP. In particular embodiments, each well of the plate includes each of ALT2, TSP, VAL-1, TPX2, GST and HSP.

[00111] In other embodiments, the invention provides simple to use point-of-care diagnostic test strips akin to pregnancy detection strips, wherein the strip includes at least one antibody against at least one of the listed filarial nematode proteins. In alternative embodiments, the invention provides simple to use point-of-care diagnostic test strips, wherein the strip includes at least one of the instant filarial nematode proteins.

[00112] The test strip may include a positive and negative control to show the user that the reagents work properly and/or that the sample has been added to the strip properly. The strips may be provided with or without a casing and with or without additional reagents. Diagnostic test strips for lateral flow assays, such as the test strip assay described herein, may be constructed as described in the art, see, e.g., US 2010/0196200; US 2010/0129935; US 2009/0253119; and US 2009/0111171. Suitable materials for test strips include, but are not limited to, materials derived from cellulose, such as filter paper, chromatographic paper, nitrocellulose, and cellulose acetate, as well as materials made of glass fibers, nylon,

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dacron, PVC, polyacrylamide, cross-linked dextran, agarose, polyacrylate, ceramic materials, and the like. The material or materials of the test strip may optionally be treated to modify their capillary flow characteristics or the characteristics of the applied sample. For example, the sample application region of the test strip may be treated with buffers to correct the pH or specific gravity of an applied sample, to ensure optimal test conditions.

[00113] The invention is described in greater detail by the following non-limiting examples.

Example 1: Small Heat Shock Protein Vaccine

[00114] *Parasites. B. malayi* L3s were obtained from the NIAID/NIH Filariasis Research Reagent Resource Center (FR3) at the University of Georgia, Athens, GA.

[00115] *Human Sera Samples.* About 10 ml of blood samples were collected from the following clinical groups of subjects (1) Endemic normal (EN) subjects, these were individuals who were asymptomatic and non-microfilaraemic; (2) asymptomatic microfilaraemic subjects (Mf) who had circulating microfilaria in their blood and were identified by microscopic examination of their night blood smears; (3) Chronic Pathology (CP) patients include those subjects who exhibited lymph edema and other chronic clinical symptoms of filariasis and (4) Non-endemic normal subjects (NEN) who lived in non-endemic areas and had no circulating parasites or antibodies and showed no evidence of any filarial disease. Sera were separated from these blood samples and were stored at -80°C until use.

[00116] *Expression and Purification of Recombinant B. malayi Heat Shock Protein.* To produce recombinant *B. malayi* small heat shock protein 12.6 (rBmHSP), the full-length gene sequence was cloned into pRSET-A (with an N-terminal

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hexahistidine tag) and was transformed into BL21(DE3) containing pLysS (Invitrogen, Carlsbad, CA) to minimize toxicity due to the protein. When absorbance of the cultures reached 0.6 OD value, 1 mM of IPTG (isopropyl thio-d-galactopyranoside) was added to the cultures and incubated for an additional 3 hours to induce gene expression. After lysing the cells, total proteins were separated in a 15% SDS-PAGE to confirm the expression of his-tagged protein. Subsequently, the histidine-tagged recombinant protein was purified using an immobilized cobalt metal affinity column chromatography (Clontech, Mountain View, CA) as per the manufacturer's recommendations. Recombinant protein was then separated in a 15% SDS-PAGE and stained with COOMASSIE brilliant blue R250. A single band was obtained after column purification.

[00117] *Three-Dimensional Model of BmHSP.* A three-dimensional model of BmHSP protein was constructed by homology modeling. BLAST sequence homology searches were performed to identify template proteins in the PDB database. Human alpha-crystallin A, a recently crystallized protein, showed significant sequence identity and was therefore chosen as the template for modeling BmHSP. Model building was performed using MODELLER 9v6 (Sali & Blundell (1993) *J. Mol. Biol.* 234:779-815). The 3-D structure obtained was subsequently validated using PROCHECK program (Laskowski, et al. (1993) *J. Appl. Cryst.* 26:283-29). The best model predicted by PROCHECK had a score of -0.46 and was chosen for further modeling and for generating the 3-D structure using Rasmol program.

[00118] *Analysis of the Structure of BmHSP.* The secondary structure and protein-protein interaction site of BmHSP was predicted at PDBsum and the Predict Protein E-mail server at the European Molecular Biology Laboratory, Heidelberg

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(Roos, et al. (1995) *Parasitol. Today* 11:148-150). Motif scanning was carried out via PROSITE pattern analysis to identify the functional motifs in BmHSP. B-cell, T-cell and CTL epitopes in BmHSP sequences were predicted using Immune Epitope Database and Analysis Resource (IEDB).

[00119] *Phylogenetic Analysis of BmHSP*. Amino acid sequences of BmHSP were compared with members of other small heat shock family of proteins from different organisms. The following sequences were analyzed. Accession numbers are given in parenthesis. *Aconthocheilonema vitae* (CAA48631); *Archaeoglobus fulgidus* (O28308); *Artibeus jamaicensis* (P02482); *Aspergillus fumigatus* (Q4WV00); *Arabidopsis thaliana* (O81822); *Artemia persimilis* (DQ310578); *Azotobacter vinelandii* (P96193); *Brugia pahangi* (CAA61152); *Brugia malayi* (AAU04396); *Buchnera aphidicola* (P57640); *Bombyx mori* (AF315318_1); *Bradyrhizobium japonicum* (P70918); *Caenorhabditis elegans* (Q7JP52); *Coccidioides immitis* (Q1E6R4); *Carica papaya* (Q69BI7); *Caenorhabditis remanei* (AAZ42349); *Dictyostelium discoideum* (Q54I91); *Escherichia coli* (ibpA; P0C054); *Escherichia coli* (ibpB; P0C058); *Homo sapiens* (P02489); *Haemonchus contortus* (AAN05752); *Lygodactylus picturatus* (Q6EWI0); *Onchocercara volvulus* (CAA48633); *Ostertagia ostergi* (CAG25499); *Macaca mulatta* (P02488); *Mycobacterium tuberculosis* (P0A5B7); *Mus musculus* (AAA37861); *Nippostrongylus brasiliensis* (BAI81970); *Plasmodium falciparum* (Q8IB02); *Rattus* (CAA42910); *Saccharomyces cerevisiae* (P15992); *Solanum lycopersicum* (O82545); *Streptococcus thermophilus* (P80485); *Trichinella spiralis* (ABJ55914); *Trypanosoma brucei* (Q57V53); *Toxoplasma gondii* (Q6DUA8). The alpha-crystallin domain from all sHSP sequences were aligned using ClustalW algorithm and the data set were used to build a phylogenetic tree with the PHYLIP software. The trees were

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made using the neighbor joining method, with Poisson-corrected amino acid distances.

[00120] *Chaperone Assay.* One of the typical characteristics of chaperone is that they can bind to and protect cellular proteins from heat damage. When proteins are exposed to heat damage, they aggregate (thermal aggregation). Chaperones prevent this aggregation. To determine whether BmHSP could prevent thermal aggregation, a citruline synthase (CS) (Sigma, St. Louis, MO) thermal aggregation assay was used. CS was selected because this protein is highly sensitive to heat denaturation. An established method was used (Gnanasekar, et al. (2009) *Biochem. Biophys. Res. Commun.* 386:333-337). Briefly, 1 μ M of CS was exposed to 45°C in the presence or absence of BmHSP (2 μ M) suspended in 50 mM of sodium phosphate pH 7.4 buffer containing 100 mM NaCl. BSA was used as a control. CS was incubated with BmHSP at a molar ratio of (1:2) for various time intervals from 0 to 40 minutes. Thermal denaturation (aggregation) was monitored spectrophotometrically at 360 nm.

[00121] *In Vitro Peptide Binding Assay for Chaperone Activity.* Another characteristic of heat shock proteins is that they can bind to a variety of proteins. To determine whether BmHSP also possesses this function, CS and another protein, luciferase, were chemically denatured with 6M guanidine hydrochloride according to known methods (Gnanasekar, et al. (2009) *supra*). Native and chemically denatured proteins were then coated onto 96-well plates overnight at 4°C. After washing with PBS, wells were blocked with 3% BSA at room temperature. Following further washing, wells were incubated with his-tagged rBmHSP for 1 hour at 37°C. After washing again with PBS, optimally diluted anti-his-tagged HRP conjugate was added and

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incubated at 37°C for 1 hour. After final washing, color was developed with ABTS [2,2'-azinobis(3-ethylbenzothiazoline-6-sulfonic acid)] and OD was measured at 405 nm.

[00122] *Anti-BmHSP Antibody Levels in Human Sera.* A total of 20 sera samples belonging to different clinical groups such as Mf, CP, EN and NEN were analyzed for the presence and titer of anti-BmHSP IgG antibodies using an indirect ELISA (Cheirmaraj, et al. (1992) *J. Trop. Med. Hyg.* 95:47-51). Briefly, wells of a 96-well microtiter plate were coated with rBmHSP (1 µg/ml) in carbonate buffer, pH 9.6, overnight at 4°C and blocked with 3% BSA for 1 hour at 37°C. Sera samples were added to the wells and the plates were incubated overnight at 4°C. After washing the wells, HRP-labeled mouse anti-human IgG was added (1:5000) and incubated further for 1 hour at 37°C. Color was developed using ABTS substrate. Absorbance was measured at 405 nm in a microplate reader (BIO-RAD, Hercules, CA). The isotype of anti-BmHSP IgG antibodies in the sera of subjects was also determined using an isotype-specific ELISA. Biotinylated mouse monoclonal antihuman IgG1, IgG2, IgG3 and IgG4 were used as the secondary antibodies and color was developed with avidin-HRP conjugate (Sigma, St. Louis, MO) as the secondary antibodies.

[00123] *Cloning of Codon-Optimized BmHSP into pVAX Vector for DNA Vaccine.* Codon-optimized *Bmhsp* genes were cloned into eukaryotic expression vector pVAX (Invitrogen) using insert-specific primers (forward primer, 5'-CGC GGA TCC ATG GAA GAG AAG GTG GTG-3' (SEQ ID NO:1) containing *Bam*HI site and reverse primer, 5'-CCG GAA TTC TCA CTT GTC GTT GGT G-3' (SEQ ID NO:2) containing *Eco*RI site). PCR parameters were as follows: 94°C of denaturation for 30 seconds, 50°C of primer annealing for 30 seconds, 72°C of primer extension

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for 30 seconds for 30 cycles; and a final extension of 5 minutes was performed at 72°C. Insert DNA was sequenced to ensure authenticity of the cloned nucleotide sequence on both strands. Plasmids were maintained and propagated in *E. coli* TOP10F' cells. Subsequently, plasmids were purified using endotoxin-free plasmid extraction kit (Qiagen, Hilden, Germany). DNA was analyzed by agarose gel electrophoresis and quantified by spectrophotometry (OD 260/280, ratio > 1.8).

[00124] *Immunization of Mice.* Six-week-old male Balb/c mice purchased from Charles River Laboratories were used in these experiments. Humane use of animals in this study and the protocol was approved by the IACUC committee at the College of Medicine, University of Illinois Rockford. Each group was composed of five (5) mice and all mice were immunized intraperitoneally using three different immunization regimens. Group A mice were immunized using a prime-boost regimen. Mice were primed twice at two-week intervals with 100 µg of endotoxin-free, codon-optimized pVAX *Bmhsp* DNA suspended in 50 µl volume. Following priming, all mice received two booster doses of 15 µg of rBmHSP protein (50 µl each) suspended in alum at two weeks interval. Group B mice were immunized with rBmHSP protein alone. These mice received four doses of 15 µg of rBmHSP protein suspended in alum given at two-week intervals. Group C mice were immunized with DNA alone. These mice received four doses of 100 µg of pVAX *Bmhsp* DNA given at two-week intervals. Group D animals received 100 µg of pVAX vector control and adjuvant at the same interval and remained as negative controls. Blood samples were collected from each mouse before immunization and one month after the last booster dose. After separating the sera, titer of circulating anti-BmHSP IgG antibodies and the respective

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isotypes were determined. Sera that showed high titer of antibodies against BmHSP were used in the Antibody Dependent Cellular Cytotoxicity (ADCC) assay described herein.

[00125] *Anti-BmHSP Antibody Levels in the Sera of Mice.* Anti-BmHSP IgG antibody levels in the sera of immunized and control groups of mice were determined using an indirect ELISA (Veerapathran, et al. (2009) *PLoS Negl. Trop. Dis.* 3:e457). IgG1, IgG2a, IgG2b and IgG3 anti-BmHSP antibody levels were also determined using a mouse antibody isotyping ELISA kit (ThermoFisher Scientific, Rockford, IL). Color was developed with ABTS (2,2'-azinobis (3-ethyl benzothiazoline-6-sulfonic acid) chromogen substrate and the absorbance was measured at 405 nm in an ELISA reader (BIO-RAD).

[00126] *Depletion of Anti-BmHSP Antibodies from Human and Mice Sera.* Anti-BmHSP antibodies were depleted from pooled sera of EN subjects and immunized mice by incubating the pooled sera with cobalt IMAC resin coupled with his-tagged rBmHSP according to established methods (Veerapathran, et al. (2009) *supra*). Briefly, 1 mg of his-tagged rBmHSP was coupled to 2 ml bed volume of IMAC resin for 2 hours at 37°C. After washing the resin once with 10 ml of PBS (pH.8), 200 µl of pooled sera was added and incubated overnight at 4°C. After incubation, the resin mixture was centrifuged for 2 minutes at 750 rpm and the supernatant was collected. Depletion of anti-BmHSP antibodies in the supernatant was confirmed by ELISA as described herein.

[00127] Anti-BmHSP IgG1, anti-BmHSP IgG2a, anti-BmHSP IgG2b, anti-BmHSP IgG3 and anti-BmHSP IgG4 antibodies from pooled sera of EN subjects and pooled sera of immunized mice were depleted using NHS (N-hydroxysuccinimidyl) resin (Thermo fisher scientific). Briefly, 1 µg of respective monoclonal

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antibodies were coupled to NHS resin column. After washing the resin twice with PBS (pH.8), 100 µl of sera were passed through the column. The flow through was collected as the antibody depleted sera. Depletion of the specific isotype of antibody was confirmed by an isotype-specific ELISA as described herein. After washing the column three times with PBS (pH 7.4), bound antibodies were eluted using Glycine-HCl buffer (pH 2.7) from the resin and the pH was adjusted to 7.4 with 1 M Tris buffer (pH 8). The recovered elute contained the specific antibody as confirmed again by an ELISA. The antibody depleted sera was also reconstituted with the eluted antibodies. An aliquot of depleted sera was reconstituted with the eluted antibodies to its original concentration using values determined by an earlier ELISA on the neat serum samples. Antibody depleted sera, eluted antibodies and reconstituted sera samples were then used in an ADCC assay.

[00128] *Antibody-Dependent Cellular Cytotoxicity (ADCC) Assay.* *In vitro* ADCC assay was performed according to known methods (Chandrasekhar, et al. (1985) *Parasite Immunol.* 7:633-641). Briefly, ten (10) L3 of *B. malayi* were incubated with 2×10^5 peritoneal cells (PEC) collected from normal mice, 50 µl of pooled mouse sera samples and 50 µl of RPMI 1640 media in a 96-well culture plate (Thermo Fisher Scientific). After 48 hours of incubation at 37°C and 5% CO₂, larval viability was determined at 400X using a light microscope. Larvae that were limp and damaged were counted as dead. In addition, dead larvae also had clumps of cells adhered to it and were more transparent than live. Larvae that were active, coiled and translucent were counted as live. ADCC was estimated as the percent larval death calculated using the formula:

$$\text{Number of Dead larvae} \div \text{Total Number of Larvae} \times 100.$$

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[00129] ADCC assay was also performed with pooled human sera samples as described herein except that the human sera samples were incubated with 2×10^5 PBMCs collected from normal health subjects and 6-12 *B. malayi* L3 for 48 hours at 37°C and 5% CO₂. Larval viability and death were determined as described above.

[00130] *Protection Studies in Mice.* Vaccine potential of BmHSP was evaluated in a mouse model of challenge infection. Mice were immunized as described above using prime-boost, DNA alone or protein alone approach. Vector and alum group served as negative controls. Immunized and control animals were challenged using a micropore chamber method as known in the art (Abraham, et al. (1986) *Immunology* 57:165-169). Briefly, micropore chambers were assembled using 14 x 2 mm PLEXIGLASS (acrylic) rings (Millipore Corporations, Bedford, MA) and 5.0 µm NUCLEOPORE polycarbonate membranes (Millipore Corporations). The membranes were attached to the PLEXIGLASS rings with cyanoacrylic adhesive and dental cement. The chambers were immersed overnight at 37°C in sterile RPMI medium containing gentamycin and antimycotic solution. Before challenge experiments, 20 live, infective L3s suspended in RPMI 1640 medium supplemented with 15% heat-inactivated fetal calf serum (FCS) were introduced into the micropore chambers and the opening was sealed with dental cement. Micropore chamber containing the L3s were then surgically implanted into the peritoneal cavity of each mice under anesthesia. Aseptic conditions were followed for the surgical procedures. After 48 hours of implantation, animals were sacrificed and the chambers were recovered from peritoneal cavity. Contents of each chamber were emptied and larvae were examined microscopically for adherence of cells and for larval death. Dead and live

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larvae were identified as described above under ADCC. The percentage of protection was expressed as the number of dead parasites ÷ number of total parasites recovered x 100.

[00131] *Splenocyte Proliferation Assay.* Spleens were collected from all mice from the above experiment and single-cell suspension of spleen cells was prepared. Approximately 2×10^5 cells/well suspended in complete RPMI 1640 medium supplemented with 10% heat-inactivated FCS were incubated at 37°C and 5% CO₂ for 72 hours with rBmHSP (1 µg/ml), ConA (1 µg/ml) or with medium alone. After incubation, cell proliferation was determined using cell counting kit (CCK-8) purchased from Dojindo Molecular Technologies, Inc. (Gaithersburg, MD). Stimulation index of spleen cell proliferation was calculated using the formula: Absorbance of stimulated cells ÷ Absorbance of unstimulated cells.

[00132] *Cytokine Analysis.* Spleen cells from immunized and control mice were cultured at 37°C and 5% CO₂ for 72 hours with rBmHSP (1 µg/ml), ConA (1 µg/ml) or with medium alone as described above. After 72 hours, culture supernatants and cell pellets were collected separately for cytokines analysis. For measuring cytokine mRNA, cell pellets were suspended in TRIZOL (phenol, guanidinium and thiocyanate) reagent (GIBCO-BRL, Life technologies, Carlsbad, CA) and total RNA was extracted as per the manufacturer's instructions. After ethanol washes, RNA pellets were dissolved in RNase-free water (Sigma) and treated with DNase I before determining total RNA concentration using a Beckman spectrophotometer at 260 nm. Reverse transcription of total RNA was performed using first strand cDNA synthesis kit (SABiosciences, Frederick, MD) as per manufacturer's recommendations. Relative quantification of the expression of genes of interest was measured in an

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Applied BioSystems 7300 real-time PCR machine (Applied BioSystems, Foster City, CA). PCR amplifications were performed with the LIGHTCYCLER-DNA SYBR Green (cyanine dye) mix (SABiosciences). The reaction was performed using the following PCR conditions: 15 minutes activation step at 95°C for one cycle, 15 seconds denaturation step at 95°C, annealing of primers for 20 seconds at 50°C and elongation step for 15 seconds at 72°C. DNA was amplified for 50 cycles. The fluorescent DNA binding dye SYBR Green (cyanine dye) was monitored. RT-PCR data array set was generated and analyzed using SABiosciences web-based data analysis system.

[00133] Culture supernatants were then collected from splenocyte cultures 72 hours after incubation with rBmHSP (1 µg/ml), ConA (1 µg/ml) or with medium alone. Secreted levels of IL-2, IL-4, IFN-γ and IL-10 protein in the culture supernatants were determined using a sandwich ELISA kit purchased from ThermoFisher Scientific. Concentration of each cytokine was determined from a standard curve plotted using recombinant mouse IL-2, IL-4, IFN-γ or IL-10.

[00134] *Statistical Analysis.* Statistical analysis was performed using XL STAT software v.7.5.2 (Kovach Computing Services, Anglesey, UK). Statistical significance between comparable groups was estimated using appropriate non-parametric tests, with the level of significance set at $p < 0.05$.

[00135] *Expression of Recombinant BmHSP12.6 (BmHSP).* BmHSP was cloned in pRSET A vector and was expressed as a histidine-tagged (his-tagged) fusion protein in *E. coli* BL21 (DE3)PLYsS. Recombinant BmHSP protein was subsequently purified using IMAC column. The molecular mass of the purified recombinant his-tag fusion protein was found to be

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approximately 18 kDa. The column-purified recombinant protein appeared as a single band in SDS-PAGE.

[00136] *Predicted Three-Dimensional Structure of BmHSP.* Amino acid sequences of the human alpha crystalline A chain share 42% similarity with BmHSP. Since crystal structure of the human alpha crystalline A chain is already available, this was used that as a template to model the putative structure of BmHSP using the Modeller 9v6 program. PROCHECK analysis was used to select the best model that showed a score of -0.41 compared to the template (Laskowski, et al. (1993) *J. Appl. Cryst.* 26:283-29). A Ramachandran plot analysis was also performed on the BmHSP sequence. These analyses showed that 92% of residues were in the most favorable region with no steric hindrance. About 6.7% residues were found in the additional allowed region. Models that showed over 90% residues in the most favored regions were predicted as the most ideal three-dimensional model as predicted by the Ramachandran plot (Balazs, et al. (2001) *Protein Eng. Des. Sci.* 14:875-880). Secondary structure prediction analysis was also performed on BmHSP protein using PDBsum server at EMBL. This analysis showed that each alpha-crystalline domain of BmHSP monomer had an immunoglobulin core composed of seven β -strands arranged in two anti-parallel sheets. The secondary structure prediction of BmHSP showed two sheets, four beta hairpins, one beta bulge, seven strands, two helices, seven beta turns and one gamma turn in the structure of BmHSP.

[00137] Previous studies showed that BmHSP binds to human IL-10 receptor I α chain (Gnanasekar, et al. (2008) *Mol. Biochem. Parasit.* 159:98-103). To identify the IL-10 receptor binding site on BmHSP, a predictive protein-protein interaction analysis was performed (Ofraan & Rost (2007) *Bioinformatics* 23:e13-e16). Results from the

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prediction analysis showed that the N-terminal fragment of BmHSP (amino acids from Met1 to Asn26) had a strong protein-protein interaction region. Further sequence analysis of this region showed that the amino acid sequences from Val5 to Glu42 had significant sequence identity to human IL-10R binding region of human IL-10. These findings confirm that the N-terminal region of BmHSP may be involved in the binding of BmHSP to human IL-10 receptor I α chain.

[00138] *Motif and Phylogenetic Analysis on BmHSP.* Motif analysis performed at PROSITE showed several putative post-translation modification sites such as N-glycosylation sites (residues 11 to 14 and 98 to 101), protein kinase-c phosphorylation sites (residues 83 to 85 and 100 to 102), casein kinase II phosphorylation sites (residues 68 to 71 and 88 to 91) and N-myristylation sites (residues 40 to 45) on BmHSP. Similar motifs were also observed in human IL-10 further indicating that BmHSP may mimic human IL-10 function (Gnansekar, et al. (2008) *supra*). Epitope mapping on BmHSP revealed the presence of B-cell, T-cell and CTL epitope regions, indicating that BmHSP is potentially a highly immunogenic protein (Table 2).

TABLE 2

Epitope Predicted	Position of Epitope in the Amino Acid Sequence	Peptide Sequence	SEQ ID NO:
B-Cell Epitopes	12-23	WSAEQWDWPLQH	3
	26-35	EVIKTNTNDK	4
	67-74	SRAEHYGE	5
	84-94	KLPSDVDTKTL	6
T-Cell Epitopes	45-53	FTPKEIEVK	7
	50-57	IEVKVAGD	8
	38-45	VGLDASFF	9
	39-47	GLDASFFTP	10
	52-60	VKVAGDNLV	11
	84-92	KLPSDVDTK	12
	92-100	KTLTSLNLTK	13

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	27-35	VIKTNTNDK	14
	90-98	DTKTLTSLN	15
	44-52	FFTPKEIEV	16
	38-46	VGLDASFFT	17
	100-108	KRGHLVIAA	18
	73-81	GEIKREISR	19
	43-51	SFFTPKEIE	20
CTL Epitopes	78-86	REISRTYKL	21
	74-82	GEIKREISR	22
	70-78	AEHYGEIKR	23

[00139] A phylogenetic analysis performed using representative sHSP sequences from different groups of organisms showed that BmHSP, *C. elegans* HSP and *C. remani* HSP form a monophyletic group, separated from the other groups of organisms.

[00140] *BmHSP is a Chaperone.* Most of the heat shock proteins reported to date have chaperone function. To determine whether BmHSP also has similar chaperone function, a thermal aggregation reaction was performed using a model substrate, Citrulline synthase (CS). Incubation of CS at 42°C resulted in unfolding of the protein and subsequent aggregation within 10 minutes. Addition of BmHSP to CS protein (at a molar ratio of 1:2), before the heat treatment, significantly ($P < 0.01$) inhibited the thermal aggregation of CS protein. A non-chaperone control protein, BSA, had no effect on the heat-induced aggregation of CS protein.

[00141] Another function of chaperone proteins is that they can specifically bind to denatured proteins. To determine whether BmHSP can specifically bind to denatured proteins, rBmHSP was incubated with native and denatured CS or native and denatured luciferase substrates. These studies showed that rBmHSP preferentially bound to denatured protein substrates compared to native or control protein. These findings thus confirmed that BmHSP can act as a molecular

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chaperone potentially protecting the parasite cellular proteins from the damaging effects of the host.

[00142] *Antibody Responses in Human.* The results presented herein indicate that BmHSP has several T-cell and B-cell epitopes. Therefore, it was evaluated whether filariasis-infected individuals carry antibodies to BmHSP. Accordingly, the titer of anti-BmHSP IgG antibodies in the sera of EN, CP, Mf and NEN subjects was measured. The results showed that the EN subjects had the highest levels of anti-BmHSP antibodies ($p < 0.001$). Subsequent isotype analysis of the IgG antibodies showed that compared to the infected groups (Mf and CP) of individuals, sera from EN subjects had high titers of IgG1 and IgG3 anti-BmHSP antibodies. Mf carriers had only significant levels of anti-BmHSP IgG2 antibodies in their sera. Similarly, CP individuals had only significant levels of anti-BmHSP IgG4 antibodies in their sera. Anti-BmHSP IgG1 and IgG3 levels were very low in the sera of these Mf and CP individuals. Anti-BmHSP antibodies were not detectable in the sera of NEN subjects.

[00143] *Results of ADCC Assay.* Since antibodies to BmHSP were present in all infected groups of individuals (Mf and CP) and EN subjects, it was determined whether these antibodies were functional. Using an antibody-dependent cell cytotoxicity assay, it was tested if anti-BmHSP12.6 IgG antibodies had any protective function against *B. malayi*. These studies showed that pooled EN sera promoted adherence of PBMC's to L3 and induced significant (77.37%) death of *B. malayi* L3s *in vitro* (Table 3), whereas, pooled sera from Mf and CP failed to participate in the ADCC function. These findings indicated that EN sera have anti-parasitic activities. To determine if this function is associated with antibodies, antibody depletion studies were

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performed. Depletion of anti-BmHSP antibodies from EN sera resulted in significant reduction (21.42%) in larval death (Table 3) confirming that anti-BmHSP antibodies in the sera of EN subjects, but not Mf or CP subjects, participate in larval killing.

TABLE 3

Groups	Dead L3	Live L3	Total L3	% Larval Death (Mean $\pm$ SD*)
Endemic Normal (EN) sera	5	1	6	77.37 $\pm$ 8.41
	5	2	7	
EN sera depleted of anti-rBmHSP antibodies	2	5	7	21.42 $\pm$ 10.12
	1	6	7	
Non-Endemic Normal (NEN) sera	1	5	6	19.44 $\pm$ 3.92
	2	7	9	

*Values represent mean $\pm$ SD of three wells.

[00144] Further depletion studies showed that the anti-parasitic effect of anti-BmHSP antibodies was associated with IgG1 isotype of antibodies. Depletion of IgG1 antibodies from EN sera significantly (40%) inhibited the ADCC function (Table 4). Reconstitution of anti-BmHSP antibody depleted EN sera with eluted anti-BmHSP IgG1 antibodies regained the ADCC function (Table 3). These findings thus indicated that anti-BmHSP IgG1 antibodies are critical for ADCC function.

TABLE 4

EN Sera		% Larval Death
Neat Sera		72
Depleted of:	IgG1	40
	IgG2	71.43
	IgG3	60
	IgG4	62.5
Reconstituted with:	IgG1	70
	IgG2	69.23
	IgG3	66.67
	IgG4	54.55

Values represent mean of three wells.

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[00145] *Antibody Responses in Mice.* Mice immunized with rBmHSP developed significant levels of anti-BmHSP IgG antibodies. More specifically, prime-boost vaccine regimen induced significantly higher titer of IgG antibodies compared to DNA vaccine alone group ($p < 0.05$). However, rBmHSP protein vaccine induced the highest IgG antibody titer. Analysis of the isotype of anti-BmHSP IgG antibodies showed that predominantly IgG1, IgG2a and IgG2b anti-BmHSP antibodies were present in the sera of vaccinated animals. The ADCC assay was also performed with mouse sera. These studies showed that sera from BmHSP-vaccinated mice promoted adherence of peritoneal exudate cells to L3 and participated in ADCC function (83.02% larval killing) compared to control sera (13%) ($p < 0.002$) (Table 5).

TABLE 5

Immunization Regimen	% Larval Death
<i>Bmbsp</i> DNA prime and rBmHSP protein boost	83.02±3.62
<i>Bmbsp</i> DNA	43.7±8.12
rBmHSP protein	55.08±1.15
pVAX & alum control	13±2.35

Values represent mean $\pm$ SD of three wells.

[00146] Similar to human sera, individual isotypes of IgG antibodies were depleted from the sera of vaccinated mice to determine the isotype of anti-BmHSP antibodies that participate in the ADCC function. Results from these studies showed that, similar to that observed with EN sera, anti-BmHSP IgG1 antibodies were involved in ADCC-mediated killing of L3 in mice as well (Table 6).

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TABLE 6

Immunized Mice Sera		% Larval Death
Neat Sera of BmHSP prime-boost		80.16
Depleted of:	IgG1	37
	IgG2a	72
	IgG2b	71
	IgG3	80
Reconstituted with:	IgG1	80
	IgG2a	63
	IgG2b	87
	IgG3	71

Values represent mean of three wells.

[00147] *Vaccine Potential of BmHSP in Mice.* Vaccine potential of BmHSP was assessed in Balb/c mice using a micropore chamber method. Results showed that mice immunized using the prime-boost vaccination regimen and protein vaccine of BmHSP exhibited nearly 72% and 58% mortality, respectively, of L3s implanted into the peritoneal cavity of the immunized mice (Table 7). While chambers implanted in the control groups of animals showed only 7% mortality of the parasite, the difference between the protection of control group of mice and vaccinated mice was significant ($P < 0.001$). On the other hand, mice immunized by DNA vaccine alone induced only 31% protection. Thus, the prime-boost vaccination regimen appeared to be highly efficient in conferring vaccine-induced protection against a challenge infection compared to DNA alone or protein alone immunization protocols.

TABLE 7

Immunization Regimen	% Larval Death
<i>Bmhsp</i> DNA prime and rBmHSP protein boost	72±10.22
<i>Bmhsp</i> DNA	31±5.23
rBmHSP12.6 protein	58±7.76
pVAX & alum control	7±5.2

Values represent mean ± SD. N=5. Data is from one of two similar experiments showing comparable results.

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[00148] *Immune Responses in BmHSP Vaccinated Mice.* To determine cellular immune responses to BmHSP in the vaccinated mice, spleen cells collected from vaccinated and control mice were cultured in the presence of rBmHSP protein and their proliferative responses and cytokine profiles were evaluated. Proliferative response of spleen cells from animals immunized with the prime-boost vaccine regimen was significantly ($P > 0.05$) higher (stimulation index of 3.35 ± 0.176) compared to rBmHSP protein alone vaccination group (stimulation index of 2.22 ± 0.018) or *Bmhs*p DNA vaccination alone group (stimulation index of 3.53 ± 0.102). Spleen cells from the control group of animals failed to proliferate in response to rBmHSP (stimulation index of 0.98 ± 0.013) and was similar to media alone controls. Since the spleen cells from vaccinated animals were proliferating significantly to recall response to rBmHSP, levels of cytokines in the culture supernatants were measured. These results showed that IFN- γ was the predominant cytokine secreted by spleen cells from vaccinated animals at 72 hours after stimulation with rBmHSP. A real time-PCR cytokine gene array was performed on mRNA collected from the spleen cells stimulated with rBmHSP. These results showed that both Th1 (IFN- γ , CD-28, IL-12, IL-2) and Th2 (IL-4, IL-5, IL-1R) cytokine genes were significantly increased in vaccinated animals.

Example 2: rBmALT2+rBmHSP Multivalent immunogenic composition

[00149] *Parasite.* *Brugia malayi* L3s were obtained from the NIAID/NIH Filariasis Research Reagent Resource Center (FR3) at the University of Georgia, Athens, GA.

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[00150] *Construction of Monovalent and Multivalent DNA Vaccines.* Monovalent DNA vaccine was composed of Bmhsp or Bmalt2 in pVAX1 vector. To prepare the monovalent vaccine, codon optimized Bmhsp or BmALT2 genes were cloned into the eukaryotic expression vector pVAX1 (Invitrogen, Carlsbad, CA) using insert-specific primers (Gnanasekar, et al. (2004) *supra*). The multivalent immunogenic composition was composed of Bmhsp and Bmalt2 genes in the same pVAX1 vector. Codon optimized Bmhsp gene was first cloned into pVAX1 vector with no stop codon in the reverse primer (5'-CCG GAA TTC TCA CTT GTC GTT GGT G-3'; SEQ ID NO:24) but contained a *Pst*I site. Codon optimized Bmalt2 gene was then inserted into this clone using gene specific primers (Gnanasekar, et al. (2004) *supra*). PCR parameters for all the three constructs were: 94°C denaturation for 30 seconds, 50°C primer annealing for 30 seconds, 72°C primer extension for 30 seconds for 30 cycles; a final extension of 5 minutes was performed at 72°C. Insert DNA was finally sequenced to ensure authenticity of the cloned nucleotide sequence on both strands. Plasmids were maintained and propagated in *E. coli* TOP10F' cells. Plasmids were purified using endotoxin-free plasmid extraction kit (Qiagen, Valencia, CA). DNA was analyzed by agarose gel electrophoresis and quantified in a spectrophotometer (OD 260/280, ratio >1.8).

[00151] *Expression and Purification of Recombinant Proteins.* All the genes were cloned in pRSET-A vector (with an N-terminal hexahistidine tag) to produce recombinant proteins. Bmhsp and Bmalt2 constructs were transformed into BL21(DE3) containing pLysS *E. coli* host (Invitrogen) to minimize toxicity due to the protein. When absorbance of the cultures reached 0.6 OD value, 1 mM of IPTG (isopropyl thio-d-galacto pyranoside) was added to the cultures and

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incubated for an additional 3 hours to induce the gene expression. After lysing the cells, total proteins were separated in 15% and 12% SDS-PAGE to confirm the expression of his-tag recombinant BmHSP (rBmHSP) and rBmALT2 proteins. The recombinant proteins were then purified using an immobilized cobalt metal affinity column chromatography (Clontech, Mountain View, CA) as per the manufacturer's recommendations. Recombinant proteins were then separated in SDS-PAGE and stained with COOMASSIE brilliant blue R250 and silver stain. These studies showed that a single band was obtained after column purification. Endotoxins if any in the recombinant preparations were removed by passing the recombinant proteins through polymyxin B affinity columns (Thermo Fisher Scientific, Rockford, IL) and the levels of endotoxin in the final preparations were determined using an E-TOXATE kit (Sigma, St Louis, MO) as per manufacturer's instructions. Endotoxin levels were below detection limits in these recombinant protein preparations.

[00152] *Immunization of Mice.* Six-weeks old male Balb/c mice purchased from Charles River Laboratories were used in these experiments. Humane use of animals in this study and the protocol was approved by the IACUC committee at the College of Medicine, University of Illinois Rockford. Mice were divided into four (4) groups of five (5) animals each. All mice were immunized subcutaneously using a DNA prime - protein boost vaccine regimen. All experimental groups of mice were primed with two injections of endotoxin-free codon optimized DNA given in 50 µl volume and boosted with two doses of recombinant proteins suspended in alum (50 µl each) given at two weeks interval.

[00153] Group A mice were primed with 100 µg of pVAXBmhsp and boosted with 15 µg of rBmHSP; Group B mice were primed

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with 100 µg of pVAX Bmalt2 and boosted with 15 µg of rBmALT2; Group C mice were primed with 100 µg of pVAXBmhspl/Bmalt2 DNA and boosted with 15 µg of rBmHSP and 15 µg of rBmALT2. Group D mice received 100 µg of pVAX1 vector plus 50 µl of alum and served as controls. Blood samples were collected from each mouse before immunization and one month after the last booster dose. Sera were separated and stored at -80°C.

[00154] *Evaluation of Antibody Responses in Mice.* Levels of anti-BmHSP and anti-BmALT2 antibodies were measured in the sera of immunized and control groups of mice using an indirect ELISA according to established methods (Veerapathran, et al. (2009) *supra*; Gnanasekar, et al. (2004) *supra*). Briefly, wells of 96-well microtiter plates were coated with rBmHSP, rBmALT2 or rBmHSP (1 µg/ml) in carbonate buffer (pH 9.6) overnight at 4°C. After washing the wells, unbound sites were blocked with 3% BSA for 1 hour at 37°C. Diluted sera samples were then added to the wells and incubated further overnight at 4°C. After washing the wells, HRP-labelled rabbit anti-mouse IgG was added (1:5000) and incubated further for 1 hour at 37°C. Color was developed using ABTS (2, 2'-azinobis (3-ethylbenzothiazoline-6-sulfonic acid)) substrate. Absorbance was measured at 405 nm in a microplate reader (BIO-RAD, Hercules, CA).

[00155] *Protection Studies in Mice.* Vaccine potential of the monovalent and multivalent immunogenic composition formulations were then evaluated in a mice model. Mice were immunized as described above using the prime boost approach. Vector plus alum group served as negative controls. Immunized and control animals were challenged using a micropore chamber method known in the art (Abraham, et al. (1989) *Am. J. Trop. Med. Hyg.* 40(6):598-604).

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Briefly, micropore chambers were assembled using 14 x 2 mm PLEXIGLASS (acrylic) rings (Millipore Corporations, Bedford, MA) and 5.0 μ m NUCLEOPORE polycarbonate membranes (Millipore Corporations) that were attached to the PLEXIGLASS (acrylic) rings with cyanoacrylic adhesive and dental cement. The chambers were immersed overnight at 37°C in sterile RPMI medium containing gentamycin and antimycotic solution. Before challenge experiments, 20 live infective L3s suspended in RPMI1640 medium supplemented with 15% heat inactivated fetal calf serum (FCS), were introduced into the micropore chambers and the opening was sealed with dental cement. Micropore chamber containing the L3s were then surgically implanted into the peritoneal cavity of each mice under anaesthesia. Aseptic conditions were followed for the surgical procedures. After 48 hours of implantation, animals were sacrificed and the chambers were recovered from peritoneal cavity. Contents of each chamber were emptied and larvae were examined microscopically for adherence of cells and for larval death. Larval viability was determined microscopically at 100 x. The percentage of protection was expressed as the number of dead parasites ÷ number of total parasites recovered x 100.

[00156] *Cytokine Analysis in Mice.* The percent of rBmHSP and rBmALT2 specific interferon- γ (IFN- γ) and interleukin-4 (IL-4) secreting cells were determined in the spleen of control and vaccinated mice using an ELISPOT assay. Briefly, MILLIPORE MULTISCREEN HTS Filter plates were coated with monoclonal rat anti mouse IFN- γ or monoclonal rat anti-mouse IL-4 antibodies (BD Pharmigen, San Diego, CA) at a concentration of 10 μ g/ml in PBS buffer. After washing the plates, non-specific sites were blocked by

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incubating the wells in complete RPMI with 10% fetal calf serum for one hour at room temperature. Approximately 3×10^6 spleen cells suspended in complete RPMI1640 medium supplemented with 10% heat inactivated FBS were then added to each well. Cells were stimulated with rBmHSP or rBmALT2 (1 μ g/ml). Unstimulated cells served as controls. Forty-eight hours after incubation at 37°C in humidified 5% CO₂, plates were washed and further incubated for 1 hour at room temperature with 2 μ g of biotinylated rat anti-mouse IFN- γ or biotinylated rat anti-mouse IL-4 antibody (BD Pharmingen). After washing the plates, streptavidin-conjugated horseradish peroxidase (Thermo Fisher Scientific) was added (1:800) to each well and incubated at room temperature for one hour. Plates were washed and color developed using DAB substrate (Thermo Fisher Scientific). Total numbers of spots were counted under a dissection microscope.

[00157] Statistical Analysis. Statistical analysis was performed using XL STAT software v.7.5.2 (Kovach Computing Services, Anglesey, UK). Statistical significance between comparable groups was estimated using appropriate non-parametric tests, with the level of significance set at $p < 0.05$.

[00158] Antibody Responses in Mice. It was first determined whether the multivalent immunogenic composition could elicit significant antibodies against each of the antigenic components. Previous studies have shown that mice similarly vaccinated with *B. malayi* antigens elicited significant host protective IgG antibodies (Veerapathran, et al. (2009) *supra*). Therefore, IgG antibody titers were analyzed. The results of this analysis indicated that the monovalent immunization with Bmhsp + rBmHSP and Bmalt2 + rBmALT2 elicited significant ($p < 0.005$) titers of anti-BmHSP and

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anti-BmALT2 IgG antibodies (FIG. 1). The multivalent immunogenic composition also elicited significant IgG antibody titers. Following multivalent immunogenic composition, the mice produced IgG antibodies against both BmHSP and BmALT2 equally, suggesting that the antigens do not interfere or compete for dominance. An interesting finding was that the multivalent immunogenic composition elicited 1.5- to 1.75-fold higher ($p < 0.005$) titers of IgG antibodies compared to the monovalent vaccine (FIG. 1). These finding indicated that the two antigens in the multivalent formulation can act synergistically by increasing the vaccine-induced antibody responses against each antigen in the vaccinated mice. The findings also indicated that combining these two antigens in the vaccine formulation has a great advantage. Given the robust IgG antibody responses induced following vaccination, it is also possible that the concentration of the component antigens in the multivalent preparation can be reduced.

[00159] *Multivalent immunogenic composition Induces Significant Protection in Mice.* The results herein showed that significant IgG antibodies were elicited following vaccination with monovalent and multivalent immunogenic composition preparations. To test if the immune responses elicited following vaccination were protective, vaccinated animals were challenged with live third stage infective larvae (L3) of *B. malayi*. Since the parasites do not reach maturity in these animals, a better recovery of worms is obtained if the parasites are surgically implanted into the animals. A standard micropore chamber challenge method (Abraham, et al. (1989) *supra*). These studies showed that close to 61% protection could be achieved in mice immunized with a monovalent vaccine (Table 8). This was highly significant ($p < 0.001$) compared to negative controls. This

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finding also showed that rBmHSP and rBmALT2 are of use in vaccines for lymphatic filariasis. Challenge experiments in mice immunized with multivalent immunogenic composition showed that significantly ($p < 0.005$) higher protection could be achieved compared to monovalent vaccination (Table 8). These findings also clearly correlated with the higher IgG antibody titer in these animals and support the above finding that rBmALT2 and rBmHSP can synergistically enhance the protective immune responses in vaccinated animals when given as a prime boost regimen (Table 8).

TABLE 8

Vaccination regimen	Percent Larval Death ^a	Groups
<i>Bmhsp</i> DNA prime and rBmHSP protein boost	61 ± 4.24	Monovalent
<i>Bmalt2</i> DNA prime and rBmALT2 protein boost	76 ± 8.21	Monovalent
<i>Bmhsp+Bmalt2</i> prime and rBmHSP and rBmALT2 protein boost	90 ± 7.53	Multivalent
pVAX plus alum control	22 ± 10.41	Control

^aValues are mean + SD. N=5. Data is from one of two similar experiments showing comparable results.

[00160] To further demonstrate efficacy, mice were immunized with various prime-boost combinations. As shown in FIG. 3, 100% protection can be achieved in mice following immunization with HAT hybrid protein or after prime boost immunization with HAT hybrid DNA and HAT hybrid protein.

[00161] *Cytokine Responses.* The immunological characteristics of the protective responses in vaccinated mice were determined by evaluating the secreted cytokine responses of spleen cells in response to the vaccine antigens. When spleen cells were stimulated with rBmHSP or rBmALT there was significant antigen-specific proliferation of spleen cells suggesting a strong recall cellular response to the antigens. To identify the cytokine profile of these antigen-responding cells, the IFN- γ and IL-4

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secreting cells were counted using an ELISPOT assay. Results from these studies showed that spleen cells from mice vaccinated with multivalent immunogenic composition were predominantly secreting IL-4 (FIG. 2A). The numbers of IFN- γ secreting cells were very low (FIG. 2B). Overall, these findings indicated that vaccine-induced protection was largely mediated by Th2 type responses.

Example 3: BmVal-1+BmALT2 Multivalent immunogenic composition

[00162] *Sera*. Sera samples used in this study were from archived samples stored at the Mahatma Gandhi Institute of Medical Sciences, Sevagram, India. These samples were collected as part of epidemiological surveys in and around Wardha, an area endemic for lymphatic filariasis.

[00163] No demographic data was available to this study except that the sera samples were classified into microfilaremic (MF), chronic pathology (CP) or Endemic normals (EN) based on the detection of circulating parasites, parasite antigens or by evaluating clinical symptoms of lymphatic filariasis. Circulating microfilariae were detected in the blood of subjects according to known methods (Haslbeck, et al. (2005) *Nat. Struct. Mol. Biol.* 12:842-846; Yoo, et al. (2005) *Biotechnol. Lett.* 27:443-448). The presence of circulating antigen was detected using an Og4C3 kit and a WbSXP-based enzyme-linked immunosorbent assay (ELISA). Subjects with no circulating antigen or microfilariae were classified as EN, whereas subjects with circulating microfilariae and/or circulating antigen, as detected by ELISA, were considered as MF. Subjects showing lymphedema and other visible clinical symptoms of filariasis were grouped into CP. Control non-

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endemic normal (NEN) sera were collected at the University of Illinois Clinic at Rockford, IL.

[00164] *Parasites. Brugia malayi* L3s were obtained from the NIAID/NIH Filariasis Research Reagent Resource Center (FR3) at the University of Georgia, Athens, GA.

[00165] *Construction of Monovalent and Multivalent DNA Vaccines.* To prepare monovalent vaccine, codon optimized *Bmval-1* or *Bmalt-2* genes were cloned into the eukaryotic expression vector pVAX1 (Invitrogen, Carlsbad, CA) using insert-specific primers (Yoo, et al. (2005) *supra*; Huang, et al. (2005) *Immunol. Lett.* 101:71-80). To prepare multivalent immunogenic composition, codon-optimized *Bmval-1* gene was first cloned into pVAX1 vector with no stop codon using already published primer sequences with a *Pst*I site. Codon-optimized *Bmalt-2* gene was then inserted into this clone using gene-specific primers. PCR parameters for all the constructs were: 94°C denaturation for 30 seconds, 50°C primer annealing for 30 seconds, 72°C primer extension for 30 seconds for 30 cycles; and a final extension of 5 minutes was performed at 72°C. Insert DNA was sequenced to ensure authenticity of the cloned nucleotide sequence on both strands. Plasmids were maintained and propagated in *E. coli* TOP10F' cells. Plasmids were purified using endotoxin-free plasmid extraction kit (Qiagen, Valencia, CA). DNA was analyzed by agarose gel electrophoresis and quantified in a spectrophotometer (OD 260/280, ratio > 1.8).

[00166] *Expression and Purification of Recombinant Proteins.* Recombinant BmVAL-1 and rBmALT2 were expressed in pRSET-A vector and purified using an immobilized cobalt metal affinity column chromatography according to published methods (Norimine, et al. (2004) *Infect. Immun.* 72:1096-1106; Shinnick, et al. (1988) *Infect. Immun.* 56:446-451). Endotoxin in the recombinant preparations were removed by

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passing the recombinant proteins through polymyxin B affinity columns (Thermo Fisher Scientific, Rockford, IL) and the levels of endotoxin in the final preparations were determined using an E-TOXATE kit (Sigma, St Louis, MO) as per manufacturer's instructions. Endotoxin levels in the final preparations (0.005 EU/ml) were below detection limits in these recombinant protein preparations.

[00167] *Immunoreactivity of Human Sera.* To determine if the human sera samples carried antibodies against BmVAL-1 or BmALT2, an ELISA was performed (Haslbeck, et al. (2005) *supra*; Yoo, et al. (2005) *supra*). For isotype-specific ELISA, alkaline phosphatase-conjugated goat anti-human IgG1, anti-human IgG2, anti-human IgG3, and anti-human IgG4 antibodies (Sigma) were used as the secondary antibodies.

[00168] *Immunization Protocol for Mice and Jirds.* Six-week old male Balb/c mice and 35-40 gm outbred male mongolian gerbils (jirds) purchased from Charles River Laboratories (Wilmington, MA) were used in these experiments. Animals were treated as per the guidelines in the Guide for the Care and Use of Laboratory Animals. Two different animal models were used because *B. malayi* parasite does not mature into adults in mouse, so vaccine-induced protection against the L3 stages can be evaluated in the mouse model. In addition, significant immunological parameters can be measured in mice. Conversely, *B. malayi* parasite develops into mature adult worms in jirds. Therefore, vaccine-induced protection can be evaluated against adult worm establishment in jirds.

[00169] Three sets of experiments were performed: (1) monovalent BmVAL-1 vaccination, (2) monovalent BmALT2 vaccination and (3) multivalent mVAL-1/BmALT2 vaccination. Each experimental set had four groups (a) DNA prime plus DNA boost (homologous), (b) protein prime plus protein

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boost (homologous), (c) DNA prime plus protein boost (heterologous) and pVAX plus alum controls. Each group included ten (10) animals each. All animals were immunized subcutaneously with codon-optimized DNA (100 µg) in 50 µl volume or with recombinant protein (150 µg) plus alum in 50 µl volume. Control group received 100 µg of pVAX1 blank vector or 50 µl of alum. Blood samples were collected at frequent intervals, sera separated and stored at -80°C. The protocol used for immunizing mice and jirds was as follows. Animals were prebled and given a first dose on day 0. A second dose was administered on day 14 and subsequently bled. Third and fourth doses were administered on days 28 and 42, respectively, and the animals were subsequently bled. Mice were challenged on day 56 and protection was determined on day 58. Jirds were challenged on day 60 and protection was determined on day 155.

[00170] *Protection Studies in Mice.* Challenge studies were conducted in mice by surgically implanting twenty live, infective *B. malayi* L3s into the peritoneal cavity in a micropore chamber (Veerapathran, et al. (2009) *supra*; Abraham, et al. (1988) *supra*). Aseptic conditions were followed for the surgical procedures. Forty-eight hours after implantation, chambers were recovered from the peritoneal cavity and viability of the larvae was determined under a light microscope. The percentage of protection was expressed as the number of dead parasites + number of total parasites recovered x 100.

[00171] *Splenocyte Proliferation and Cytokine Assays.* Single-cell suspension of spleen cells (0.5×10^6 cells per well suspended in 200 µl media) were prepared from each mouse and cultured in triplicate wells with either (1) 1 µg/ml rBmVAL-1, (2) 1 µg/ml rBmALT2, (3) 1 µg/ml rBmVAL-1+BmALT2, (4) a nonspecific recombinant protein (1 µg/ml of

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Schistosoma mansoni G-binding protein) or (5) were left unstimulated in the media. All cells were incubated for 3 days at 37°C with 5% CO₂. After 3 days, ³H-Thymidine (0.5 µCi per well, Amersham Biosciences) was added to each well and further incubated. Cells were harvested 16 hours later and ³H-thymidine uptake was measured in a liquid scintillation counter and expressed as stimulation index (SI) = (counts per minute of stimulated cultures counts per minute of unstimulated cultures). Cell culture supernatants collected from the spleen cultures were assayed for IFN-γ, IL-4, IL-5 and IL-10 using an ELISA kit purchased from eBioscience Inc. (San Diego, CA).

[00172] *BmVAL-1 and BmALT2 Specific IgG Antibodies in the Sera of Immunized Mice.* Titer of anti-BmVAL-1- and anti-BmALT2-specific antibodies was determined in the sera of immunized mice using an ELISA (Veerapathran, et al. (2009) *supra*; Gnanasekar, et al. (2004) *Infect. Immun.* 72:4707-15). Pre-immune sera served as controls. HRP-conjugated goat anti-mouse IgG was used as the secondary antibody (Thermo Fisher Scientific) for mouse assays. OPD (Sigma) was used as the substrate and optical density (OD) was measured at 405 nm.

[00173] Anti-BmVAL-1- and anti-BmALT2-specific IgG1, IgG2a, IgG2b, IgG3 and IgG4 antibodies were determined in the sera of mouse using a mouse antibody isotyping kit purchased from Thermo Fisher Scientific. All ELISAs were performed as per the manufacturer's recommendation and absorbance was read at 405 nm. Respective HRP-labeled goat anti-IgG isotype antibody was used as the secondary antibodies and color was developed using OPD substrate.

[00174] *Challenge Studies in Jirds.* Jirds were challenged with 100 *B. malayi* L3s and worm establishment was determined on day 95 after challenge according to

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established methods (Weil, et al. (1992) *supra*). Jirds are permissive hosts for *B. malayi* and the worms mature into adult males and females in about 75 days. Presence of mature worms in the control group of jirds was confirmed by demonstrating microfilariae in their blood on day 80 after challenge. Percent reduction in the worm establishment was calculated using the formula: average number of worms recovered from control worms - average number of worms recovered from vaccinated animals / average number of worms recovered from control animals x 100.

[00175] *Statistical Analysis.* Statistical analysis was performed using SIGMASTAT program (Jandel Scientific, San Rafael, California) and STATVIEW (SAS Institute, Cary, NC) software. Wilcoxon signed rank test was used to compare paired data; comparison between the groups was performed using the Mann-Whitney U test. p value of $p < 0.05$ was considered statistically significant.

[00176] *EN individuals Carry High Titer of Antibodies Against BmVAL-1 and BmALT2.* Significant anti-BmVAL-1 and anti-BmALT2 IgG antibodies were present in the sera of EN subjects compared to MF subjects ($p < 0.01$) and CP subjects ($p < 0.005$). NEN subjects did not carry IgG antibodies against either of the antigens. Subsequent analysis of the IgG isotype of antibodies in the sera of EN subjects showed that anti-BmVAL-1 and anti-BmALT2 antibodies were predominantly of IgG1 and IgG3 isotypes.

[00177] *High Titer of Antibody Responses in the Sera of Immunized Mice.* It has been shown that mice vaccinated with *B. malayi* antigens elicit significant host protective IgG antibodies. Therefore, IgG antibody titers in the sera of immunized mice were determined. Monovalent immunization with *BmVal-1* and monovalent immunization with *BmAlt2* both elicited significant ($p < 0.005$) titers of anti-BmVAL-1 and

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anti-BmALT2 IgG antibodies in the sera of mice. Compared to controls, the prime boost immunized group gave the maximum titer of antibodies followed by protein immunized and DNA immunized groups. Immunization with the multivalent immunogenic formulation (*BmVAL-1* + *BmALT2*) also elicited significant IgG antibody titers against both rBmVAL-1 and rBmALT2 and the titers were comparable, indicating that the antigens do not interfere with each other or compete for dominance. An interesting finding was that the multivalent immunogenic elicited significantly higher ($p < 0.001$) titer of IgG antibodies in mice compared to any of the monovalent vaccines. These finding indicated that the two antigens in the multivalent formulation synergistically increased the vaccine-induced antibody responses.

[00178] Overall, protein vaccination elicited higher titer of IgG antibodies compared to DNA vaccines, indicating that protein vaccinations were highly immunogenic. Another observation was that a heterologous prime boost approach gave a higher seroconversion than homologous prime boost approach. Thus, overall heterologous prime boost approach appeared to stimulate the highest titer of antibodies.

[00179] IgG antibody subset analysis showed that BmVAL-1 vaccination elicited primarily IgG1 and IgG2a isotype of antibodies, whereas, BmALT2 vaccination induced IgG1, IgG2a and IgG3 isotype of antigen-specific antibody responses. Antigen-specific IgG4 antibody responses were not evident. The prime boost approach significantly amplified the IgG isotype responses. Following multivalent vaccination regimen IgG1, IgG2a and IgG3 subset of antigen specific antibodies were present in the sera of mouse.

[00180] *Antigen-Specific Responses in the Spleen of Mice.* Spleen cells from immunized mice stimulated with either rBmVAL-1 or rBmALT2 proliferated significantly ($SI\ 10.8 \pm$

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1.1 and SI 14.6 ± 1.2 , respectively) compared to the media control (SI 2.1 ± 0.9). Spleen cells from mice immunized with the multivalent construct responded to both rBmVAL-1 (SI 18.9 ± 2.6) and rBmALT2 (SI 23.5 ± 3.1), indicating that a strong recall cellular response was generated to both BmVAL-1 and BmALT2 following vaccination with the multivalent construct.

[00181] *Cytokine Analysis from Proliferated Culture Supernatants.* To identify the cytokine profile of the antigen-responding cells, the culture supernatant of mouse spleen cells stimulated with respective antigen (rBmVAL-1 or rBmALT2) was collected and the level of IFN- γ , IL-4, IL-5 and IL-10 was measured. These results showed that significant levels of IL-5 and IFN- γ were secreted by the spleen cells in response to rBmVAL-1. Spleen cells stimulated with rBmALT2 predominantly secreted IL-4 and IL-5.

[00182] *Multivalent immunogenic composition Induces Significant Protection in Mice and Jirds.* The results herein indicated that significant IgG antibodies were elicited following vaccination with monovalent and multivalent immunogenic preparations. To test if the immune responses elicited following vaccination were protective, vaccinated animals were challenged with live, third stage infective larvae (L3) of *B. malayi*. Since the parasites do not reach to maturity in mice, a standard micropore chamber challenge method was used (Gnanasekar, et al. (2004) *supra*). These studies showed that 39% to 74% protection was achieved in mice following immunization with monovalent vaccine (Table 9).

TABLE 9

Vaccination Group	Mean $\pm$ SD Live L3s	Percent Protection
pVAXBmVAL-1 DNA monovalent homologous	12.2 $\pm$ 4.5	39.0 $\pm$ 1.7%**
rBmVAL-1 protein monovalent homologous	10.4 $\pm$ 3.1	48.0 $\pm$ 2.1%*
pVAXBmVAL-1 DNA plus rBmVAL-1 monovalent heterologous	9.2 $\pm$ 2.2	54.0 $\pm$ 3.1%*
pVAXBmALT2 DNA monovalent homologous	9.8 $\pm$ 2.1	51.0 $\pm$ 2.5%*
rBmALT2 protein monovalent homologous	7.0 $\pm$ 1.1	65.0 $\pm$ 4.2%*
pVAXBmALT2 DNA plus rBmALT2 monovalent heterologous	5.1 $\pm$ 0.5	74.5 $\pm$ 3.1%*
pVAXBmVAL-1/ALT2 DNA multivalent homologous	8.6 $\pm$ 0.1	57.0 $\pm$ 2.2%*
rBmVAL-1/rBmALT2 protein multivalent homologous	5.2 $\pm$ 1.1	74.0 $\pm$ 3.3%*
pVAXBmVAL-1/BmALT2 DNA plus rBmVAL-1/rBmALT2 multivalent heterologous	4.4 $\pm$ 0.4	82.0 $\pm$ 2.2%*
pVAX + Alum control	20 $\pm$ 0	0%

Significance, * $p < 0.01$, ** $p < 0.05$ compared to control.

[00183] Protein vaccination gave better results than DNA vaccination. The prime boost regimen gave the best results overall. Vaccination with BmALT2 gave higher percent of protection compared to BmVAL-1. Similarly, multivalent vaccination regimen gave the 57% to 82% protection compared to the monovalent vaccination regimen. These finding indicated that BmVAL-1 and BmALT2 synergistically enhance the protective immune responses in vaccinated animals when given as a multivalent immunogenic composition .

[00184] Analysis of the thick blood smear prepared from the control group of jirds on day 80 after challenge showed that all five jirds were positive for microfilaria, whereas, microfilaria were not detected in the peripheral blood of vaccinated jirds. Fifteen (15) days later the animals were sacrificed and the male and female worms in

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the peritoneal, pelvic and pleural cavities were counted and the results between controls and vaccinated groups were compared (Table 10). Findings from vaccination of jirds also confirmed that the multivalent prime boost regimen gave the highest rate of protection. No female worms were recovered from the multivalent vaccinated animals.

TABLE 10

Vaccination Group	Percent Production
pVAXBmVAL-1 DNA monovalent homologous	50±3.7%
rBmVAL-1 protein monovalent homologous	40.0±3.1%
pVAXBmVAL-1 DNA plus rBmVAL-1 monovalent heterologous	52.4±2.5%
pVAXBmALT2 DNA monovalent homologous	58.3±2.1%
rBmALT2 protein monovalent homologous	72.0±5.5%
pVAXBmALT2 DNA plus rBmALT2 monovalent heterologous	78.5±3.2%
pVAXBmVAL-1/ALT2 DNA multivalent homologous	77.1±2.0%
rBmVAL-1/rBmALT2 protein multivalent homologous	79.9±3.5%
pVAXBmVAL-1/BmALT2 DNA plus rBmVAL-1/rBmALT2 multivalent heterologous	85.0±1.4%
pVAX + Alum control	0

Significance, $p < 0.01$ compared to control.

Example 4: BmHSP+BmALT2+BmTSP Multivalent Immunogenic Composition

[00185] *Parasites*. *Brugia malayi* L3s were obtained from the NIAID/NIH Filariasis Research Reagent Resource Center (FR3) at the University of Georgia, Athens, GA.

[00186] *Construction of pVAX Bmhsp+Bmalt2+Bmtsp DNA vaccine*. The codon-optimized DNA sequence coding for *Bmhsp* was amplified with the forward primer 5'-CGC GGA TCC ACC GTG ATC CAT TGT CG-3' (SEQ ID NO:25) containing *Bam*HI

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restriction site and the reverse primer 5'-AAC TGC AGC TGT TTT CCA TTT CCA TTC-3' (SEQ ID NO:26) containing *Pst*I restriction site without the stop codon and cloned into pVAX vector. The resulting plasmid was designated as pVAX Bmhsp*. Codon-optimized Bmalt2 gene was amplified with the forward primer 5'-AAC TGC AGA TGG GTA ACA AGC TCC TCA TCG-3' (SEQ ID NO:27) and the reverse primer without the stop codon 5'-CGC GAA TTC GGC GCA CTG CCA ACC TGC-3' (SEQ ID NO:28). Underlined sequences indicate *Pst*I and *Eco*RI restriction sites in the forward and reverse primers, respectively. The amplified Bmalt2 DNA insert was then subcloned into pVAX Bmhsp* plasmid at the *Pst*I and *Eco*RI restriction sites, resulting in pVAX Bmhsp+Bmalt2* plasmid. To clone the final product of pVAXBmhsp+Bmalt2+Bmtsp plasmid, the gene sequence encoding Bmtsp ECL domain alone was amplified with the forward primer 5'-CGC GAA TTC ACC ATG GTC CTG GAG-3' (SEQ ID NO:29) containing *Eco*RI restriction site and the reverse primer with stop codon 5'-GCT CTA GAT CAG TCC TTC TGG CTA G-3' (SEQ ID NO:30) containing *Xba*I restriction site and cloned into pVAX Bmhsp+Bmalt2* plasmid. Bivalent constructs of HSP+TSP, TSP+ALT and HSP+ALT were also constructed with their respective primers.

[00187] Construction of *prSETA Bmhsp+Bmalt2+Bmtsp*, a Multivalent Fusion Protein. The Bmhsp+Bmalt2+Bmtsp fusion protein was constructed in the same manner as above. The primer sequences of HSP, ALT2 and TSP were as follows. Bmhsp, forward primer, 5'-CGG GAT CCA TGG AAG AAA AGG TAG TG-3' (SEQ ID NO:31) containing *Bam*HI and reverse primer, 5'-CCC TCG AGT GCT TTC TTT TTG GCA GC-3' (SEQ ID NO:32) containing *Xho*I. Bmalt2, forward primer, 5'-CCC TCG AG A TGA ATA AAC TTT TAA TAG CAT-3' (SEQ ID NO:33) containing *Xho*I or

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5'-AAC TGC AGA TGG GTA ACA AGC TCC TCA TCG-3' (SEQ ID NO:27) and reverse primer, 5'-GGG TAC CCG CGC ATT GCC AAC CC-3' (SEQ ID NO:34) containing *KpnI*. Bmtsp, forward primer, 5'-GGG GTA CCC CGG CAA GGA TCA ATT TAA AA-3' (SEQ ID NO:35) containing *KpnI* and reverse primer, 5'-CGG AAT TCT CAA TCT TTT TGA GAT GAA T-3' (SEQ ID NO:36) containing *EcoRI* were used to amplify the Bmtsp fragment of SEQ ID NO:77. Primers were also designed to amplify a Tetraspanin Large Extracellular Loop (LEL) fragment of SEQ ID NO:63. Bivalent constructs (HA, HT and TA) were also cloned individually into a pRSETA vector.

[00188] *Immunization of Animals.* Six-week-old Balb/C mice were immunized with 100 µg of DNA intradermally (i.d.) as DNA vaccine or with 15 µg of recombinant protein subcutaneously (s.c.) as protein vaccine or with two doses of DNA and two doses of protein as prime-boost vaccine. Mice were randomly divided into 15 groups with 5 mice per group. Animals from groups 1-3 were immunized with HSP+ALT2 (HA). Groups 4-6 were immunized with HSP+TSP (HT), and 7-9 were immunized with TSP+ALT2 (TA). Mice from groups 10-12 were immunized with the multivalent immunogenic composition HSP+ALT2+TSP (HAT). Control group of animals received pVAX vector and/or alum (Infectious Disease Research Institute (IDRI)). This experiment was repeated twice with all the groups.

[00189] *Analysis of Antibody Response in Immunized Animals.* IgG antibody levels in the sera of immunized and control groups of animals against all the three proteins were determined using an indirect ELISA (Anandharaman, et al. (2009) *supra*). Briefly, wells of a 96-well microtiter plate were coated with recombinant proteins (rHSP, rALT2 or rTSP; 1 µg/ml) in carbonate buffer, pH 9.6, overnight at 4°C and

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blocked with 3% BSA for 1 hour at 37°C. Sera samples were added to the wells and the plates were incubated overnight at 4°C. After washing, HRP-labeled mouse anti-human IgG was added (1:5000) and incubated further for 1 hour at 37°C. The color was developed with OPD (o-phenylene diamine) substrate (Sigma Aldrich, USA). Absorbance was measured at 450 nm in a microplate reader (BIO-RAD, Hercules, CA).

[00190] Immunoblot analysis was also performed with the immunized mice sera. Sera samples from the mice immunized with the recombinant proteins (rHAT, rALT2, rTSP or rBmHAT) were used for the immunoblot study. The color of the blot was developed with the diaminobenzidine (DAB) substrate.

[00191] ADCC Assay. To evaluate the protection efficacy of the antigen combinations, *in vitro* ADCC was performed with the sera from the mice immunized with bivalent and trivalent vaccine constructs. The *in vitro* ADCC assay was performed according to known methods (Chandrasekhar, et al. (1990) *supra*). Briefly, Peritoneal Exudates Cells (PEC) were collected from normal Balb/c mice by washing the peritoneal cavity with sterile RPMI 1640 media. The cells were washed and suspended in RPMI 1640 medium supplemented with 10% Fetal Calf Serum (FCS). Ten L₃ of *B. malayi* were added to 2 x 10⁵ peritoneal exudates cells (PEC)/well in 96-well culture plates (Thermo Fisher Scientifics, USA.), 50 µl of immunized mice sera and 50 µl of RPMI 1640 media were added to the wells in triplicates and incubated for 48 hours in 5% CO₂ at 37°C. Larval viability was determined microscopically after 48 hours of incubation. Larvae that were limpid, damaged and with the clumps of cells adhered to it were counted as dead. ADCC was estimated as the percent larval death calculated using the formula: Number of Dead larvae ÷ Total number of larvae x 100.

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[00192] *Depletion of IgG Antibodies from the Sera Samples.* Sera from mice immunized with multivalent immunogenic composition was depleted of recombinant antigen specific IgG antibodies using cobalt IMAC resin coupled with his-tagged recombinant antigens (Anandharaman, et al (2009) *supra*). Briefly, 1 mg of his-tagged recombinant protein (rHSP) was coupled to 2 ml bed volume of IMAC resin for 2 hours at 37°C. The cobalt column was washed with ten bed volumes of PBS (pH.8) and incubated overnight at 4°C with 200 µl of pooled sera from the mice immunized with multivalent immunogenic composition. Supernatant containing the depleted sera was collected by centrifugation. Anti-HSP-depleted serum was incubated overnight at 4°C in rALT2-coupled column. The supernatant containing anti-HSP- and anti-ALT2-depleted serum was collected and incubated in rTSP-coupled column. Anti-HSP-, anti-ALT2-, and anti-TSP-depleted serum was collected and used. Depletion of IgG antibodies against specific antigens was confirmed by ELISA as described above. Antibody-depleted sera were then used in an ADCC assay.

[00193] *Analysis of in situ Cytotoxicity Against L3 Larvae in Immunized Mice (Micropore Chamber Technique).* The protective efficacy of vaccination was analyzed by challenging the immunized animals with infective L3 using micropore chamber method (Abraham, et al. (1989) *supra*). Micropore chambers were assembled using 14 x 2 mm PLEXIGLASS (acrylic) rings and 5.0 µm NUCLEOPORE polycarbonate membranes (Millipore Corporations, Bedford, MA). After 48 hours of implantation, animals were sacrificed and the chambers were recovered from peritoneal cavity. Contents of each chamber were examined microscopically for cell adherence and death of infective L3. The parasite was considered dead if it was not motile

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and limpid, and had several adherent cells on the surface. The percentage protection was calculated using the formula: number of dead parasites ÷ number of recovered parasites x 100. This experiment was repeated twice with five animals in each group.

[00194] *Splenocyte Proliferation*. Vaccinated and control mice were sacrificed on day 60 and the spleens were removed aseptically. Single-cell suspensions were prepared in RPMI 1640 medium supplemented with 10% heat-inactivated FCS, passed through a NYLON (aliphatic polyamide) mesh (BD Biosciences, Bedford, USA). After determining the viability of cells using trypan blue dye exclusion, approximately 2×10^6 cells per well in triplicates were plated in 96-well culture plates (ThermoFisher, USA). The splenocytes were stimulated with 1µg/100µl/well of recombinant proteins (rHSP, rALT2 or rTSP) or ConA or with medium alone (Unstimulated) for 72 hours at 37°C in the atmosphere of 5% CO₂. Cell proliferation was determined using cell counting kit (CCK-8) purchased from Dojindo Molecular Technologies, Inc. (Gaithersburg, MD). Stimulation index of spleen cell proliferation was calculated using the formula: Absorbance of stimulated cells ÷ Absorbance of unstimulated cells. All cultures were taken in triplicates and the results expressed as mean S.I.±SEM.

[00195] *Real Time-PCR (RT-PCR)*. Cytokine levels in the mRNA of the spleen cell pellets were analyzed by real time-PCR. The spleen cells of vaccinated and control group mice were cultured as above at a concentration of 2×10^6 cells/100µl/well in 96-well plates and stimulated with recombinant antigens (1 µg/ml). After 72 hours, cells were centrifuged (1000 rpm for 5 minutes) and total RNA was extracted from the cell pellets using TRIZOL (phenol, guanidinium and thiocyanate) reagent (Invitrogen) as per

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description of the manufacturer. Followed by RNA extraction, first-strand cDNA was synthesized by RT² First Strand Kit (SuperArray Bioscience Corporation, Frederick, MD). PCR array analysis was performed according to the manufacturer protocol with the RT² Real-Time TM SYBR Green (cyanine dye) PCR Master Mix. Aliquots from this mix were added to a 96-well plate, where each well contained predispensed gene-specific primer sets. Relative quantification of the genes of interest that expressed was measured in an Applied BioSystem 7300 real-time PCR machine (Applied BioSystems, Foster City, CA). Cycling parameters were as follows: 95°C for 10 minutes for activation of HOTSTART DNA polymerase, followed by 40 cycles of denaturation at 95°C for 15 seconds and primer extension at 60°C for 1 minute. RT-PCR data array set was generated and analyzed using SABiosciences web-based data analysis system. Results were expressed in terms of fold change of immunized mice compared to control mice by normalizing the expression of housekeeping genes.

[00196] *Cytokine Assay.* Splenocyte cell culture supernatants were collected after 72 hours incubation stimulated with recombinant antigens (1 µg/ml) or with medium alone. Secreted levels of IL-4 and IFN-γ cytokines in the culture supernatants were determined using a sandwich ELISA kit purchased from Thermo Scientifics, USA. All concentrations were derived from standard curves and data expressed in pg/ml.

[00197] *Construction of CHAT Plasmid and Expression of Fusion Proteins.* Since the N-terminal region of HSP is involved in IL-10 binding, this region was deleted and CHAT recombinant protein was prepared as 37 KDa His-tagged protein.

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[00198] Construction of Recombinant Plasmids and Expression of Fusion Proteins. The full-length *hsp*, *alt2* and *tsp* genes of *B. malayi* L3 stage were constructed with the expected size (850 bp). These fragments were further directionally cloned into the expression vectors pVAX1 and pRSETA with the specified restriction enzyme cutting sites. Results of the DNA sequence analysis confirmed gene insertion direction. rBmHAT was expressed as a 45 KDa His-tagged fusion protein, which was purified and analyzed in SDS-PAGE. The results indicated that the fusion protein was pure without any contaminating proteins. The presence of antibodies against all the three antigens was confirmed by immunoblot analysis.

[00199] *Antibody Titer in the Immunized Mice Sera.* The mean peak antibody titer of the sera samples from the mice immunized with prime-boost or protein vaccine was significantly higher ($p < 0.001$) compared to the DNA group. Sera collected from rBmHAT-immunized animals showed the maximum titer of 30,000 against rALT2 antigen, while the antibody titer against rHSP or rTSP antigen was in the range of 18,000-20,000. Similarly, the mice immunized with the bivalent vaccine showed the maximum titer of 30,000 against ALT2 antigen while anti-HSP and anti-TSP antibodies were in the range of 8,000-15,000.

[00200] *Antibody-Dependent Cell-Mediated Cytotoxicity.* Antibody-mediated adherence and cytotoxicity of immune cells to *B. malayi* L3 larvae was observed after 48 hours of incubation of parasites, with the sera and normal immune cells. ADCC showed maximum cytotoxicity of approximately 90% ($p < 0.001$) in the sera of mice immunized with rBmHAT or rWbHA vaccine constructs (Table 11). Bivalent vaccine constructs of rWbHT and rWbTA also gave better protection of 82% and 87%, respectively, which was significant

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compared to monovalent-vaccinated and control animals ($p < 0.001$). To evaluate the protection mediated by the antibodies generated against HSP, ALT and TSP antigens, IgG antibodies were depleted from the immunized sera and used in ADCC. Depleted antibodies showed only 6% protection against L3.

TABLE 11

Groups	% Cytotoxicity
H+A	90±2.4*
H+T	82.30±12.9*
T+A	87.06±9.8*
H+A+T	88.69±7.5*
anti-HSP + anti-ALT + anti-TSP antibodies depleted from HAT immunized sera	5.55±1.5

Values represent mean±SD of three wells. *Significant larval death ($P < 0.001$) compared to other mice groups.

[00201] *In situ Protection Study*. Two weeks after the final immunization, the ability of the vaccine candidates, to kill the filarial parasites in the immunized animals was evaluated by *in situ* micropore chamber studies. The data was combined from the two similar experiments and represented as mean count ± SEM. The analysis of percentage reduction in worm burden compared with control showed that multivalent immunogenic composition (HAT) conferred the maximum protection of 100% and 94% for protein and prime-boost vaccine, which was very significant protection (Table 12) ($P < 0.0001$) compared to control groups (5%). Interestingly, the percentage worm reduction of bivalent vaccines HA, TA and HT were 90%, 80% and 82%, respectively, which was also significantly high compared to the control. In the entire bivalent vaccine group, prime-boost vaccination was more protective compared to DNA and protein vaccination.

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TABLE 12

Trial 1 DNA Vaccine		Trial 2 Protein Vaccine		Trial 3 Prime-Boost Vaccine	
Group	% Cytotoxicity	Group	% Cytotoxicity	Group	% Cytotoxicity
pVAX	5 ± 4.23	Alum	3 ± 4.23	pVAX+Alum	5.9 ± 4.23
H+A	81 ± 11.23*	H+A	78 ± 11.23*	H+A	90 ± 11.23*
H+T	72 ± 12.03*	H+T	69 ± 12.03*	H+T	80 ± 12.03*
T+A	74 ± 11.21*	T+A	66 ± 11.21*	T+A	82 ± 11.21*
H+A+T	91 ± 11.92*	H+A+T	100 ± 0*	H+A+T	94 ± 11.92*

Values are mean ± SD. N=5. Data is from one of two similar experiments showing comparable results. *Significant larval death ($P < 0.001$) compared to other mice groups.

[00202] *Splenocyte Proliferation.* Spleen cells isolated from vaccinated and control animals were stimulated *in vitro* individually with rHSP, rALT2 or rTSP to analyze the protein-specific T-cell proliferation in vaccinated animals. Mice immunized with the prime-boost regimen in all the vaccine combinations and HAT as protein vaccine gave the highest protection. Hence the splenocytes were collected only from these animals analyzed for the immune response. Splenocytes from bivalent- and trivalent-vaccinated animals stimulated with respective recombinant proteins showed significantly high ($P < 0.001$) proliferation (mean S.I. = 4.25-5.8) when compared to monovalent and unstimulated controls. The proliferation index of spleen cells immunized with the monovalent construct showed significant proliferation. The stimulation of cells was comparable to the positive controls.

[00203] *RT-PCR Array.* To determine the cellular immune responses to multivalent constructs in the vaccinated mice, spleen cells collected from vaccinated and control mice were cultured in the presence of respective recombinant proteins and their proliferative responses and cytokine profiles were evaluated. Since the spleen cells from vaccinated animals were proliferating significantly to

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recall response, levels of cytokine mRNA were measured. An RT-PCR cytokine gene array was performed on mRNA collected from the spleen cells stimulated with recombinant proteins. These results showed that both Th1 (IFN- γ , IL-2) and Th2 (IL-4) cytokine genes were significantly increased in vaccinated animals.

[00204] *Cytokine Levels.* After identifying the presence of IFN- γ and IL-4 cytokine expression in the mRNA isolated from the vaccinated spleen cells, the secretion of same cytokines in the supernatant was investigated. The data were normalized with the unstimulated controls. Interestingly, the cytokine profiles observed in the supernatant exhibited significantly higher levels of IFN- γ showing a Th1-biased immune response. These results demonstrated that recombinant proteins stimulated the production of IFN- γ and induced a Th1-mediated protective response.

Example 5: Analysis of cHAT Vaccine in Various Adjuvant Formulations

[00205] *Preparation of cHAT.* Previous studies showed that the N-terminal sequence of BmHSP12.6 can bind to human IL-10 receptor and trigger IL-10-mediated responses (Gnanasekar, et al. (2008) *Mol. Biochem. Parasitol.* 159(2):98-103). Since IL-10 is an immunosuppressive agent, the IL-10 receptor binding sequences were deleted from HSP. The truncated sequence was referred to as cHSP. The cHSP was then used to replace the HSP gene and HSP protein in the multivalent HAT hybrid vaccine. Thus, the resulting new vaccine was called cHAT.

[00206] *Protection Studies Using cHAT-Fusion Protein Vaccine in Mice.* Mice were immunized with four doses of cHAT fusion protein at two-week intervals. One month after the final immunization, the ability of the vaccine candidates to kill

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the filarial parasites was evaluated by *in situ* micropore chamber studies. Results showed that when mice were immunized with cCHAT fusion protein with alum as the adjuvant, the vaccine conferred 81% protection (Table 13) ($P < 0.0001$) compared to control groups (2%) that received only phosphate-buffered saline (PBS) and alum. Different adjuvants were then tested to see if changing the adjuvant would improve the protection ability of cCHAT. Two additional adjuvants were tested: alum containing a TLR4 agonist (purchased from Infectious Disease Research Institute, Seattle, Washington) and ALHYDROGEL (purchased from Sigma, St. Louis, MO). cCHAT with no adjuvants remained as a control. Results from these studies (Table 13) showed that 78% protection was achieved with alum plus TLR4 agonist and cCHAT given in ALHYDROGEL adjuvant gave 70% protection. An interesting finding in these studies was that cCHAT without any adjuvant also gave 72% protection indicating that the cCHAT fusion protein vaccine could be administered without any adjuvant and still obtain significant protection.

TABLE 13

Group	% Larval Death (Mean $\pm$ SD)
cCHAT + Alum	81 $\pm$ 7.8
PBS + Alum Control	1.7 $\pm$ 1.3
cCHAT + Alum with TLR4 agonist	78 $\pm$ 8.4
cCHAT + ALHYDROGEL	70 $\pm$ 13
cCHAT With No adjuvant	72 $\pm$ 12

Values are mean $\pm$ SD. N=5. Data is from one of two similar experiments showing comparable results. *Significant larval death ($P < 0.001$) compared to other mice groups.

Example 6: Homologues of HSP, ALT2 and TSP

[00207] Homologues of the vaccine antigens, HSP, ALT2 and Tetraspanin are present in *O. volvulus* and *L. loa*. Comparison of the nucleotide sequence of HSP, ALT2 and Tetraspanin from *O. volvulus* and *L. loa* show that there is

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significant sequence homology (>90%) between the proteins from all filarial parasites. These findings indicate that the cCHAT fusion protein vaccine developed in Example 5 can be used as a vaccine against *O. volvulus* and *L. loa*.

[00208] As an example, *O. volvulus* tetraspanin was cloned from *O. volvulus* L3 cDNA library and recombinant proteins were prepared. Sera sample from mice vaccinated with cCHAT vaccine that gave the 81% protection in Table 13 was used to probe the recombinant *O. volvulus* tetraspanin after separating the protein in a 12% SDS-PAGE gel. *B. malayi* tetraspanin was used as a positive control. Results showed that the sera sample significantly reacted with *O. volvulus* tetraspanin thereby indicating that the cCHAT vaccine developed in Example 5 is of use as a vaccine against *O. volvulus*.

Example 7: Multivalent Immunogenic Composition Against Lymphatic Filariasis in Rhesus macaque Model

[00209] *Parasites.* *B. malayi* infective third stage larvae (L3) were obtained from the NIAID/NIH Filariasis Research Reagent Resource Center (University of Georgia, Athens, GA).

[00210] *Multivalent Fusion Protein rBmHAT.* The multivalent fusion protein rBmHAT expressed in *Escherichia coli* BL21 (pLysS), was purified and endotoxin removed by Pierce High Capacity Endotoxin removal resin column (Thermo Fisher Scientific, Rockford, IL) as described herein.

[00211] *Immunizations of rBmHAT.* Five macaques each received 200 µg of rBmHAT vaccine mixed with 100 µg of AL007 alum (IDRI, Seattle, WA) under ABSL-2 conditions. Five (5) macaques that received alum (AL007) only remained as controls. Each animal was anesthetized with ketamine/xylazine and the vaccine was administered

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intramuscularly in each thigh (one injection site per thigh per vaccination). Animals were immunized at 4-week intervals on days 0, 28 and 56. Intramuscular route is commonly used for clinical vaccine trials and hence the same procedure was followed for macaques. The injection sites were monitored daily for signs of fever, any adverse reactions (redness, swelling, etc.) for up to 7 days post immunization.

[00212] *B. malayi* L3 Challenge. On day 84, one month after the final dose of vaccine, macaques were anesthetized with ketamine HCl and challenged subcutaneously with 400–500 *B. malayi* L3. To facilitate the production of the relatively large number of L3 (500 L3/animal) required for challenging 10 immunized macaques, the animals were divided into 2 subgroups within each group. The subgroups were challenged one week apart. Before challenge, *B. malayi* L3 were counted and examined for viability under a microscope. Only viable parasites were used for challenge.

[00213] *Monitoring of Each Animal After Challenge.* All animals were monitored daily for clinical signs after the challenge. Behavioral observations were similarly conducted during the entire post-challenge period. Clinical monitoring included serum chemistry, hematology, complete blood count (CBC) analysis (IDEXX) and CD4+/CD8+ T cell flow cytometry analysis. Body weights, body condition, lymphoedema and lymph node measurements were also recorded each time the animal was sedated for procedures (like immunizations, challenge, and blood collections).

[00214] *Sample Collection.* Blood samples and peripheral blood mononuclear cells (PBMC) were collected. Whole blood was collected into BD VACUTAINER SST tubes according to manufacturer's instructions. Heparinized blood (1 ml) was collected from the femoral vein of each animal during the

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immunization period and from the saphenous vein during the challenge period. The shift in blood collection site was to eliminate any potential interference with the inguinal lymph node measurements or assessments of edema. Blood samples were obtained at multiple time points during the entire follow-up period.

[00215] *Isolation of PBMC.* The blood pellets after plasma separation was diluted in phosphate-buffered saline (PBS; 1:2) and subjected to gradient density centrifugation for 30 minutes at 2200 rpm using a 90% HISTOPAQUE separation solution (Sigma, St. Louis, MO). The opaque interface containing mononuclear cells was collected, washed three times in PBS by centrifugation at 800 rpm. PBMC were enumerated using Trypan blue dye exclusion method and resuspended in RPMI 1640 medium containing 10% FBS (100 U/ml Penicillin/Streptomycin, and 2 mM L-glutamine). PBMC collected before the challenge was analyzed for T cell proliferation and IFN- γ secretions. PBMC collected after the challenge experiments were tested for T cell proliferation and ELISPOT assays. Proliferation assay was performed with PBMC isolated on the same day of blood collection. PBMC suspended in RPMI media with 10% FBS were used for ADCC assay and for cytokines analysis.

[00216] *T Cell Proliferation and Flow Cytometry.* Carboxyfluorescein diacetate succinimidyl ester (CFSE)-based assay was used for assessment of antigen-specific proliferation within the T cell population (Parish, et al. (2009) *Curr. Protoc. Immunol.* Chapter 4: Unit 49). A 5 mM CFSE stock solution (Invitrogen, Grand Island, NY) was prepared according to manufacturer's instructions. PBMC collected four weeks after the final immunization were gently resuspended at 10^7 cells/ml in 5 μ M CFSE and incubated in the dark at 37°C for 15 minutes. Cells were

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centrifuged and washed with RPMI containing 10% FBS (100 U/ml Penicillin/Streptomycin, and 2 mM L-glutamine) and incubated for an additional 30 minutes at 37°C. Cells were then washed, resuspended in RPMI containing FBS, plated in a 24-well plate at 2×10^6 cells/ml per well and incubated overnight at 37°C. The medium (~500 μ l) was removed the following day and cells were stimulated with 1 μ g/mL of rBmHAT. Samples incubated only with RPMI medium served as negative controls. As a positive control for each animal, cells were stimulated with phytohemagglutinin (PHA). Cells were cultured and harvested after 5 days of stimulation. Following a washing step with PBS/0.2% FBS, cells were surface stained with an antibody cocktail of CD3-APC-Cy, CD4-PE and CD8-PerCP and incubated for 20 minutes at room temperature. After an additional washing step with PBS/0.2% FBS the cells were acquired on BD FACS CANTO II flow cytometer (BD, San Jose, CA) and analyzed on a BD FACS DIVA Software v6.1.2. At least 50,000 events within the live lymphocyte gate were acquired.

[00217] *Cell Counts, Serum Chemistry and Complete Blood Count (CBC) Analysis.* CBC, serum chemistries and eosinophil counts were analyzed using commercial automated hematology and serum chemistry analyzers by IDEXX. Samples collected prior to the initiation of the study served as a normal reference baseline for each animal.

[00218] *Measurement of Secreted Levels of IFN- γ .* PBMC (1×10^6 cells) were stimulated *in vitro* with 1 μ g/ml of rBmHAT for 5 days at 37°C. Following stimulation, the supernatants were harvested and assayed for secreted levels of IFN- γ using an ELISA kit (Mabtech AB, Ashburn, VA) according to manufacturer's instructions.

[00219] *ELISPOT Assay.* An ELISPOT assay was performed to determine the antigen-specific IFN- γ and IL-10 secreting

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cells in the PBMC of vaccinated and control macaques. A monkey ELISPOT kit purchased from U-Cytech biosciences (Yalelaan, The Netherlands) was used to determine the spot forming units as per the manufacturer's instruction. PBMC collected 20 weeks post challenge were plated in 96-well plates at 1×10^6 cells/ml and were stimulated with 100 ng/well of *B. malayi* adult soluble antigen (BmA) for 24 hours at 37°C and 5% CO₂. Wells of ELISPOT plates were coated with 100 µl/well of capture antibodies (anti-IL-10 or anti-IFN-γ) diluted in sterile coating buffer and incubated overnight at 4°C. Plates were washed 2 times with sterile coating buffer. After blocking the plates with 200 µl/well of blocking buffer for 1 hour at room temperature, PBMC that were already stimulated with BmA antigens or only media (negative control) were added to the wells of the ELISPOT plates at 100 µl/well and incubated for 24 hours at 37°C and 5% CO₂. All the cells were removed from the plates and the membrane was washed 3 times with sterile PBS. Following wash, 100 µl of detection antibodies were added to each well and incubated at room temperature for 2 hours. After washing the plate 4 times with wash buffer, avidin-HRP reagent was added (100 µl/well) and incubated for 45 minutes at room temperature. After a final wash with PBS, freshly prepared 3-amino-9-ethylcarbazole (AEC) substrate solution was added (100 µl/well) and monitored for the development of spots at room temperature for 10-60 minutes. The substrate reaction was stopped by washing wells 3 times with 200 µl/well ultrapure water. The plates were air dried. Spots were counted using a dissecting microscope. The plates were stored in the dark prior to reading. Antigen-specific responses were determined by subtracting the number of spots in the negative control wells from the

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wells containing antigens. Results are shown as the mean value of spots obtained from triplicate wells.

[00220] *Analysis of Serum Antibody Titers in Macaques.* Levels of IgG, IgG1, IgG2, IgG3, IgA and IgE antibodies against rBmHSP, rBmALT2, rBmTSP or rBmHAT were determined in the sera (collected one month after the final dose of vaccine) of each rhesus macaque using an indirect ELISA as described herein. Briefly, wells of a 96-well microtiter ELISA plates were coated with 100 ng/well of antigens (rBmHSP, rBmALT2, rBmTSP or rBmHAT) in 0.05 M carbonate-bicarbonate buffer, pH 9.6. The wells were blocked with 3% BSA in 0.05% PBS-TWEEN 20 (PBS-T), and 100 μ l of sera samples (diluted in the range of 1:100-1:50,000 in PBS-T) from each macaque were added to each well. Goat anti-monkey IgG antibodies conjugated to peroxidase (Rockland Immunochemicals, Gilbertsville, PA) was used as secondary antibodies to determine IgG titer antibodies. The color was developed using OPD substrate and absorbance was read at 492 nm in the ELISA reader (BioRad, Hercules, CA). To determine the levels of isotype antibodies, biotinylated anti-monkey IgG1 (1:2000), IgG2 (1:200), IgG3 (1:2000), IgA (1:2000) and IgE (1:1000) antibodies (NHP Reagent Resources, Boston, MA) were used as secondary antibodies. After washing the plates, optimally diluted streptavidin conjugated horse radish peroxidase (HRP) was added and further incubated for 60 minutes at room temperature and the color was developed.

[00221] *ADCC Assay.* PBMC were prepared from heparinized whole blood from a naive healthy animal as described above. Briefly, ten *B. malayi* L3 (suspended in 50 μ l RPMI 1640 medium containing 10% FBS) were incubated with 2×10^5 PBMC (in 50 μ l RPMI 1640) and 50 μ l of serum from each animal (collected one month after the final dose of vaccine) in a

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96-well round bottom tissue culture plate. Five replicates were performed for each serum sample. Control wells contained *B. malayi* L3 incubated in media, with sera alone or cells alone. The plates were incubated at 37°C with 5% CO₂ for 48 hours. Following incubation, *B. malayi* L3 were examined under a microscope at 24 and 48 hours to determine larval viability. Dead L3 were defined as those having a limp or straight appearance with no movements for an additional observation period of 8 hours at 37°C. Live larvae were active, coiled and motile. The percentage larval death was expressed as the ratio of the number of dead L3 to that of the total number recovered within the experimental period multiplied by 100. Average larval death in 5 wells were calculated and expressed as percent protection in each animal.

[00222] *Knott Test to Determine Microfilaremia (Mf) in Macaques.* The presence of Mf in the blood of macaques was detected using the Knott technique as described previously (Liu, et al. (1989) *J. Trop. Med. Hyg.* 92:93-96). Peripheral blood of macaques was screened weekly for Mf starting from 5 weeks to 20 weeks post challenge. Briefly, whole blood was mixed with 9 ml of a 2% formalin solution (prepared in PBS) in a 15 ml conical centrifuge tube. The tubes were gently rocked for 2 minutes at room temperature and centrifuged at 1,500 rpm for 5 minutes. The supernatant was then thoroughly decanted by turning the tube completely upside down to remove all the liquid. Following this 5 ml of ACK lysis buffer (Quality Biologicals, Gaithersburg, MD) was added to the pellet and the tube was vortexed. Two to three drops of methylene blue solution (Fisher Scientific, Hannover Park, IL) was then added to the tubes, gently mixed, and smeared onto five glass slides. The samples were allowed to dry and read under a microscope using 40X lens

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objective. A comparison of Mf counts in blood collected from the saphenous and femoral veins showed similar results.

[00223] *Detection of Mf in the Peripheral Blood by PCR.* PCR-based assays are more sensitive in detecting the presence of Mf in the blood samples (Mishra, et al. (2005) *Acta Trop.* 93:233-7; Tao, et al. (2006) *J. Clin. Microbiol.* 44:3887-93). Therefore, the PCR based assay was also used to confirm the presence of Mf in the blood samples of all macaques 20 weeks after challenge. Whole blood samples were centrifuged at 10,000 rpm for 5 minutes and the supernatant containing serum was stored at -20°C. DNA was isolated from the pellet using DNEASY Blood & Tissue Kit (Qiagen, Valencia, CA) according to the manufacturer's instruction. Primers were synthesized at Integrated DNA Technologies Inc., (Coralville, IA) for *HhaI* tandem repeats. Primer sequences for *HhaI* tandem repeats were: Forward 5'-GCG CAT AAA TTC ATC AGC-3' (SEQ ID NO:75) and Reverse 5'-GCG CAA AAC TTA ATT ACA AAA GC-3' (SEQ ID NO:76). PCR parameters were initial denaturation of 94°C for 5 minutes, followed by 40 cycles of 1 minute at 94°C, 1 minute at 56°C, 1 minute at 72°C and a final extension of 10 minutes at 72°C. Following PCR reaction, 10 µl of each PCR product was analyzed on a 1% agarose gel.

[00224] *PBMC Proliferations Assay.* PBMC collected 10 weeks post-challenge were cultured in 96-well tissue culture plates at a concentration of 1×10^6 cells/well in RPMI 1640 supplemented with 10% FCS. Cells were stimulated either with rBmHAT antigen (1 mg/ml) or Concanavalin A (1 mg/ml) or with medium alone (unstimulated) in triplicate wells. PBMC were stimulated in triplicate wells and the plates were incubated at 37°C in 5% CO₂. After 72 hours, cell proliferation was measured using cell counting kit (CCK-8)

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(Dojindo Molecular Technologies, Inc., Gaithersburg, MD). Stimulation index of PBMC proliferation was calculated using the formula: Absorbance of stimulated cells/Absorbance of unstimulated cells.

[00225] *Statistical Analysis.* Data are represented as the mean $\pm$ standard error. One-way ANOVA tests (Kruskal-Wallis) was performed for the antibody titer and T cell proliferation using GraphPad Prism software. Student T test was performed for protection studies. A probability (P) value of ≤ 0.001 was considered statistically significant.

[00226] *rBmHAT Vaccination Does Not Induce Any Adverse Reactions in Macaques.* The injection sites were monitored closely for signs of any adverse reactions (redness, swelling, etc.) for 7 days post-immunization. There were no adverse reactions in any of the vaccinated or control animals. Clinical monitoring showed no dramatic loss of body weight ($>10\%$ of the original weight), changes in eating habits or any other behavioral changes. Temperature measurements obtained daily following immunizations did not show any significant variations. Temperature measurements were also performed at regular intervals using implanted transponders. There were no significant variations in the body temperature in vaccinated and control animals.

[00227] The lymph nodes in the left and right leg of all animals were monitored weekly starting approximately 2 weeks prior to challenge (to establish a baseline) and throughout the challenge period. The lymph nodes were measured with a caliper and observed for edema. The measurements showed an overall increase in the mean size of the inguinal lymph nodes in both legs during the 5-8 week post-challenge period in all groups. Compared to the baseline (14.5 mm) the lymph node size in control animals were 22 ± 1 mm and rBmHAT group were 26.2 ± 1 mm. Following

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this period, the sizes of the lymph nodes decreased to near pre-challenge levels in all macaques.

[00228] Challenge with *B. malayi* L3 did not alter the body temperature in macaques. Analyses of the serum chemistry and hematology (CBC) values showed that they were all in the normal range for all cell types except for a slight increase in the eosinophil counts following L3 challenge in infected animals.

[00229] *All Three Antigens in the Multivalent Immunogenic Construct Were Immunogenic in Macaques.* Analysis of the IgG antibody titer in vaccinated macaques showed that all the macaques developed high titers (1:40,000) of IgG antibodies after third immunization against rBmHAT. The titer of antibodies against each of the three component antigens in the vaccine construct was then analyzed. All macaques developed high titers of IgG antibodies against rBmHSP12.6 (1:16,000), rBmALT2 (1:24,000) and rBmTSP-LEL (1:16,000). There were slight individual variations in the titer of antibodies between each vaccinated macaque. On a comparative basis, macaque #5242, #5258 and #5259 showed the highest titer of IgG antibodies against the component antigens (except anti-rBmHSP12.6 antibodies in macaque #5258 and anti-rBmTSP antibodies in macaque #5259). Macaque #4996 and 5254 developed only low titers of antibodies to rBmALT2 and rBmTSP (Table 14).

TABLE 14

Animal ID	Antibody Titer			
	rBmHSP12.6	rBmALT2	rBmTSP	rBmHAT
4996	6400	3200	16000*	40000
5242	16000*	24000**	16000*	40000
5254	6400	800	12800*	40000
5258	6400	24000**	16000*	40000
5259	16000*	24000**	6400	40000

Macaques were immunized with 200 µg of rBmHAT with alum adjuvant. Anti-rBmHAT antibodies against rBmHSP12.6,

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rBmALT2, rBmTSP LEL or rBmHAT were evaluated. Each animal differed in the antibody titer against each antigen. * $P < 0.05$ and ** $P < 0.001$ statistically significant antibody IgG antibody titer compared to other animals.

[00230] Isotype analysis showed that nearly all of the antibodies were of IgG1 isotype against all the four antigens tested (rBmHSP, rBmALT2, rBmTSP and rBmHAT). Levels of IgG2, IgG3, IgA and IgE did not show any significant difference from the background values.

[00231] *rBmHAT Responding Cells Were Present in the PBMC of Immunized Rhesus Macaques.* To determine the antigen specific proliferative responses, PBMC was collected four weeks after the final vaccination. Cell proliferation was determined after stimulating CFSE labeled PBMC with rBmHAT proteins for 5 days and counting the labeled cells in a flow cytometer. These results showed that the proliferation frequency of antigen-responding cells in the immunized animals were 3-fold higher (stimulation index 6.1 ± 0.86) compared to the control animals (stimulation index 2.2 ± 1.42). As expected, PBMC from all the animals showed robust proliferative responses (stimulation index 87.4 ± 0) upon stimulation with pan-T mitogen, PHA. PBMC cultured in control medium had only low-level proliferation following 5-day incubation. The proliferation frequency value for each sample was obtained by subtracting the medium alone control value.

[00232] Frequency of CFSE-labeled CD3+, CD4+ and CD8+ PBMC proliferating in response to antigen stimulation were determined by flow cytometry. These studies showed that there was an increase in the proliferation of antigen-responding T cells in all immunized macaques compared to control macaques. Subset analysis showed that in immunized animals approximately 12.7% of the antigen responding T

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cells were CD4+ cells and 7.9% of T cells were CD8+ subsets. Background proliferation in the presence of rBmHAT antigen in the PBMC of control animals were 1.4% for CD4+ cells and 2.3% for CD8+ cells.

[00233] *Antigen Responding Cells in the PBMC of Immunized Monkeys Secrete IFN- γ .* Antigen responding cells in the spleen of rBmHAT immunized mice and gerbils predominantly secreted high levels of IFN- γ . Therefore, it was determined whether macaques also show a similar response after immunization but before challenge. These studies showed that PBMC from three immunized macaques (#5242, #5258 and #5259) all secreted significant amounts of IFN- γ when stimulated with rBmHAT antigen (Table 15). Culture supernatants of PBMC from macaque #4996 and #5254 only had background levels of IFN- γ similar to that of the PBMC from control macaques.

TABLE 15

IFN- γ Secretion (pg/ml)			
Animal ID	Control (alum only)	Animal ID	rBmHAT + alum
4995	0	4996	0
5240	0	5242	62.5
5249	0	5254	0
5252	0	5258	62.5
5253	0	5259	62.5

[00234] *Anti-rBmHAT Antibodies in the Sera of Immunized Macaques can Participate in the Killing of B. malayi L3.* To determine the protective ability of anti-rBmHAT antibodies in the sera of immunized macaques, an in vitro ADCC assay was performed. Results showed that the PBMC from vaccinated macaque were able to participate in the killing of 35% of *B. malayi* L3 (Table 16). When sera from individual macaques were evaluated maximum killing potential in the ADCC was 45% in the sera of macaque #5258. Sera from macaque #5242 and #5259 also showed significant killing potential with

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38% and 35% killing respectively. Sera from macaque #4996 and #5259 had the least ADCC property with 25% and 31% killing respectively. No larval death occurred when sera from control macaques were used in these assays.

TABLE 16

Animal ID	Live L3 ^a	Dead L3 ^a	% Larval Death ^a	Mean % Larval Death
4995	10	0	0	0 (control)
5240	10	0	0	
5249	10	0	0	
5252	10	0	0	
5253	10	0	0	
4996	7.5±0.6	1.5±0.6	25±5.2*	35±6.1* (immunized)
5242	6.5±0.6	4±0.6	38±6.9*	
5254	6.5±1	3±0.6	31±7.4*	
5258	6.5±1.5	5±0.6	45±6.3*	
5259	7±1.2	3.5±1.2	35±11.5*	

^a Results are presented as Mean±SD of five wells. Significant larval death *(P<0.05) compared to other macaques. Control wells were L3 incubated with media, cells alone or sera alone.

[00235] Immunization with rBmHAT Conferred Partial Protection in Macaques. One month after the final vaccination, all 10 monkeys were challenged with 500 *B. malayi* L3 and screened for the appearance of Mf in the peripheral blood circulation. A Knott test and PCR analysis were used to detect Mf. The Knott test was performed weekly from week 5 post-challenge until the animals became positive. In these studies, challenged macaques became positive for Mf starting from week 10 post-challenge. During weeks 11-20 post challenge, three of the control macaques became positive for Mf. Unfortunately, the remaining two control macaques remained negative through the end of the study. In the vaccinated group, three of the macaques (#5242, #5254 and #5259) remained negative

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throughout the study. However, two of the vaccinated macaques (#4996 and #5258) became positive for *Mf*. To further confirm the infection, a PCR analysis was performed, where *HhaI* antigen-specific primers were used to amplify for the presence of *Mf*-specific DNA in the blood of infected monkeys. PCR analysis confirmed infections in macaque #5249 and #4996. The other three positive animals identified by Knott technique were negative by PCR.

[00236] *rBmHAT Responding Cells were Present in the PBMC of Immunized Rhesus Macaques After Challenge*. PBMC collected 10 weeks post challenge was stimulated with *rBmHAT* to determine the antigen-specific T cell response. PBMC of three animals #5242 (S.I. - 0.928 ± 0.01), #5258 (S.I. - 1.091 ± 0.16) and #5256 (S.I. - 1.0181 ± 0.13) from the vaccinated group that were negative for *Mf* showed significant proliferation upon *rBmHAT* stimulation. Whereas, two of the vaccinated animals #4996 (S.I. - 0.258 ± 0.12) and #5254 (S.I. - 0.379 ± 0.03) positive for *Mf* did not show significant proliferation upon *rBmHAT* stimulation. No significant proliferation was observed in any of the control animals #4995 (S.I. - 0.280 ± 0.03), 5240 (S.I. - 0.415 ± 0.09), 5249 (S.I. - 0.300 ± 0.26), 5252 (S.I. - 0.507 ± 0.03) or 5253 (S.I. - 0.475 ± 0.25). S.I. of PBMC stimulated with Concanavalin was in the range of 2.0-3.8.

[00237] *Eosinophil Numbers were High in Infected Macaques Showing Mf*. Microfilaremic individuals show high eosinophil counts in their blood (Pearlman, et al. (1993) *Exp. Parasitol.* 76:200-8; Pearlman, et al. (1993) *J. Immunol.* 151:4857-64). A similar finding was observed in rhesus macaques as well. Absolute counts of eosinophils were determined on weeks 13, 9, and 5 prior to challenge, on the day of challenge and on weeks 1, 5, 10, and 14 post-challenge. The results showed that there was an increase in

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the frequency of eosinophil numbers in the peripheral blood of microfilaremic macaques around 10 weeks post-challenges. One macaque (#5259) that was negative for Mf also showed some eosinophilia. Eosinophil counts were 10-fold higher in control macaques that had microfilariae in their peripheral blood.

[00238] *High Titer of Antigen-Specific IgG Antibodies and Elevated Antigen-Specific Secretion of IFN- γ from PBMC Correlated with Protection in the Immunized Macaques.* Since two of the macaques in the immunized group showed presence of infection following challenge, vaccine-induced immune responses were compared in the two infected macaques with similar responses in the three uninfected macaques within the immunized group. Values before and after challenge were compared. Values before challenge eliminated any bias due to the challenge of parasites. Comparative immunological values are presented in Table 17.

TABLE 17

Macaque Group	Animal ID	PBMC Proliferation, Mean S.I. $\pm$ S.D. (n=3)	
		Stimulated with ConA	Stimulated with rBmHAT
Control (immunized with alum)	4995	3.260 $\pm$ 0.01	0.280 $\pm$ 0.03
	5240	3.090 $\pm$ 0.58	0.415 $\pm$ 0.09
	5249	2.982 $\pm$ 0.24	0.300 $\pm$ 0.26
	5252	3.674 $\pm$ 0.83	0.507 $\pm$ 0.03
	5253	2.582 $\pm$ 0.72	0.475 $\pm$ 0.25
rBmHAT (immunized with rBmHAT + alum)	4996	3.874 $\pm$ 0.47	0.258 $\pm$ 0.12
	5242	2.170 $\pm$ 0.43	0.928 $\pm$ 0.001**
	5254	2.068 $\pm$ 0.18	0.379 $\pm$ 0.03
	5258	3.304 $\pm$ 0.64	1.091 $\pm$ 0.16**
	5259	2.883 $\pm$ 0.27	1.0181 $\pm$ 0.13**

**Significant proliferation of PBMC **($P < 0.001$) compared to PBMC from other macaques.

[00239] Results showed that the titer of IgG antibodies was significantly high in the three immunized macaques that did

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not develop the infection after the challenge. Similarly, PBMC from the same three macaques secreted higher levels of IFN- γ when stimulated with the rBmHAT antigen. PBMC from the two immunized macaques that developed the infection after challenge were unable to secrete similar levels of IFN- γ in response to rBmHAT stimulation. An ELISPOT assay was performed using PBMC from vaccinated and control macaques. Results showed that in all the infected macaques there was a significant increase in the number of antigen-specific IL-10 secreting cells compared to IFN- γ secreting cells. When the ratios of IFN- γ to IL-10 secreting cells in the PBMC of immunized macaques were compared, there was a significant increase in the IL-10 secreting cells in the two vaccinated macaques that showed infection (Table 18). These findings suggest a clear correlation between the type immune responses elicited and the failure to establish infection in the vaccinated macaques.

TABLE 18

Animal ID	Immunological values before L3 challenge				Immunological values after L3 challenge	
	Antibody titer of >12,000			IFN- γ	Mf	Ratio of IFN- γ :IL-10 secreting cells
	rBmHSP	rBmALT2	rBmTSP LEL			
4995 ^a	-	-	-	-	+	1:3
5240 ^a	-	-	-	-	-	1:1
5249 ^a	-	-	-	-	+	1:11
5252 ^a	-	-	-	-	-	1:0.01
5253 ^a	-	-	-	-	+	1:13
4996 ^b	-	-	+	-	+	1:4
5242 ^b	+	+	+	+	-	1:0.003
5254 ^b	-	-	+	-	+	1:2
5258 ^b	+	+	+	+	-	1:0.001
5259 ^b	+	+	-	+	-	1:0.02

^a Control, immunized with alum. ^b rBmHAT, immunized with rBmHAT + alum.

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Example 8: Valency Comparisons

[00240] Monovalent, bivalent and trivalent vaccination trials of recombinant heat shock protein 12.6 (rHSP12.6), abundant larval transcript-2 (rALT-2) and tetraspanin large extracellular loop (rTSP-LEL) proteins were compared. Recombinant proteins were prepared as described herein. The bivalent immunogenic compositions and multivalent immunogenic compositions (SEQ ID NO:70) were produced as fusion proteins. Mice (N=5) were immunized subcutaneously using a protein prime-boost vaccine regimen. Immunized and control animals were challenged with live third stage infective larvae (L3) of *B. malayi* using a micropore chamber method. After 48 hours of implantation, animals were sacrificed and the chambers were recovered from peritoneal cavity. Contents of each chamber were emptied and larvae were examined microscopically at 100X to assess larval death. The results of this analysis are presented in Table 19.

TABLE 19

Group	Protein Vaccine	Percent Larval Death (protection)
Control	Alum	9 ± 3.4
Monovalent	rHSP12.6 (rH)	58 ± 7.8
	rALT-2 (rA)	78 ± 3.7
	rTSP LEL (rT)	49 ± 2.2
Bivalent	rHA	81 ± 6.5
	rAT	72 ± 1.1
	rHT	68 ± 4.4
Multivalent	rHAT	95 ± 3.1

[00241] The results indicate that the multivalent immunogenic composition synergistically enhanced the protective immune responses in vaccinated animals compared to monovalent and bivalent compositions.

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[00242] *B. malayi* parasite does not mature into adults in mice. However, vaccine-induced protection against adult worm establishment can be determined in jirds. Therefore, monovalent, bivalent and trivalent vaccines were evaluated in jirds. Animals (N=10) were immunized subcutaneously with recombinant proteins. Jirds were challenged with 100 *B. malayi* L3s and worm establishment was determined on day 95 after challenge. Percent protection values were calculated as the percent reduction in worm establishment compared with control jirds. The results of this analysis are presented in Table 20.

TABLE 20

Group	Protein Vaccine	Percent Protection
Control	Alum	15.2 ± 3.3
Monovalent	rHSP12.6 (H)	70.0 ± 12.6
	rALT-2 (A)	72.7 ± 8.8
	rTSP LEL (T)	68.1 ± 2.4
Bivalent	rHA	83.3 ± 3.3
	rAT	77.1 ± 12.3
	rHT	70.2 ± 11.8
Multivalent	rHAT	90.2 ± 9.1

[00243] The results indicate that the multivalent immunogenic composition synergistically enhanced the protective immune responses in vaccinated animals compared to monovalent and bivalent vaccines.

Example 9: Vaccine Comparisons

[00244] Monovalent, bivalent and multivalent immunogenic compositions of this disclosure were compared in mice, jirds and mastomys. Animals were immunized as described, challenged with *B. malayi* L3 and worm establishment was determined. The results of these analyses are presented in Table 21. Of note, rBmHAX immunization gave 98% protection in mice and 97% protection in jirds. These findings show

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that both *rBmHAT* and *rBmHAX* are excellent vaccine candidates for lymphatic filariasis.

TABLE 21

Group	Mice*		Jirds		Mastomys	
	Test	Control	Test	Control	Test	Control
<i>rWbALT2</i> ^a	73+3.7%	2+0%	73+1%	0+1%	71.66+8.8%	4.2+1.3%
<i>rBmHSP</i> ^a	58+7.8%	0+0%	61+0%	4+0%	69.97+12.6%	2.1+0.2%
<i>rWbTSP</i> ^a	49+2.2%	3+1%	33+2%	1+1%	68.13+2.4%	1.1+1.1%
<i>rBmTPX</i> ^a	48+2.1%	0+0%	52+2.5%	0+0%	ND	ND
<i>rWbGST</i> ^a	49+3.1%	2+1%	61+ 1%	0+0%	ND	ND
<i>rWbHA</i> ^b	81+6.5%	3+3.2%	ND	ND	83.25+3.3%	7.2+1.1%
<i>rWbAT</i> ^b	72+1.1%	1+2.1%	ND	ND	77.13+12.3%	5.4+2.3%
<i>rWbHT</i> ^b	68+4.4%	6+3.8%	ND	ND	70.23+11.8%	7.1+3.3%
<i>rBmAX</i> ^b	74+3.3%	0+0%	80+3.5	0+0%	ND	ND
<i>rWbGA</i> ^b	68+2.5%	2+4.1%	72+3.3%	0+0%	ND	ND
<i>rBmHAT</i> ^c	98+2.1%	4+3.3%	95+3.5%	2+1%	95.23+9.1%	4.4+1.2%
<i>rBmHAX</i> ^{c**}	98+1.2%	3+1.0%	97+2.1%	0+0%	ND	ND

^aMonovalent vaccine. Wb, *W. bancrofti*. Bm, *B. malayi*.

^bBivalent vaccine. H, HSP. A, ALT2. T, TSP. X, TPX. G, GST.

^cTrivalent vaccine.

*Animals were immunized s/c with four injections of 15 µg of the vaccine antigen plus 15 µg of alum at 2-week intervals. Test animals were challenged with 100 L3 and worm establishment was determined on day 90 post-challenge. The micropore chamber challenge method was used in mice. In this method, 20 L3 were placed in a micropore chamber, which was implanted into the peritoneal cavity. After 48 hours the chambers were removed to determine live and dead larvae. Data mean + SD. N=10.

**Mice and jirds were immunized with 15 µg of *rBmHAX* plus 15 µg of alum with a total of four immunizations at 2 weeks interval. Blood was collected on day 0, 14, 28, 42, 49 and 70 to monitor the titer of antibodies against each of the component antigens. The following titers were observed on day 49 (ALT-2 1:60,000; HSP 1:40,000, TPX 1:40,000). All the animals were challenged on day 49 with 20 *B. malayi* L3 for mice and 100 *B. malayi* L3 for jirds. Worm establishment or worm death in immunized animals was observed at 48 hours after surgical implantation of L3 in mice or 90 days after infection in jirds. Percent protection was calculated as described herein.

Example 10: Tetravalent Fusion Protein (*rBmHAXT*) Vaccine Antigen Against Lymphatic Filariasis in a Mouse Model

[00245] Cloning, Expression and Purification of *rBmHAXT* Recombinant Protein. GenScript (Piscataway, NJ) supplied

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the sequences of *bmhsp12.6* (GENBNK Accession No. AY692227.1), *bmalt-2* (GENBNK Accession No. JF795950.1), *bmtpx-2* (GENBNK Accession No. AF319997.1) and *bmtsp* (GENBNK Accession No. JF795955.1) in the pUC57 vector. The genes were amplified using forward 5'-CGG GAT CCA TGG AAG AAA AGG TAG TG-3' (SEQ ID NO:31) and reverse 5'-CCC GAA TTC TTA ATG TTT CTC AAA ATA TGC TTT-3' (SEQ ID NO:89) with restriction sites for *Bam*HI and *Eco*RI. The PCR-amplified products were cloned into the pRSETA expression vector, transformed into competent BL21 (DE3) *Escherichia coli* cells for expression of the recombinant proteins with 6X histidine tag. Recombinant fusion proteins were purified using immobilized metal affinity Ni²⁺-charged agarose chromatography column sold under the tradename SEPHAROSE® (GE Healthcare Life Sciences, Pittsburgh, PA) and eluted with 300 mM imidazole. Endotoxin in the final purified protein preparation was removed using an endotoxin removal column (Thermo Fisher Scientific, Rockford, IL). The expression and purity of recombinant proteins was confirmed in 12% SDS-PAGE gel and western blot using anti-His antibodies (Qiagen, Valencia, CA). Protein concentration was determined using a Bradford reagent (Thermo Fisher Scientific).

[00246] *Adjuvants*. Three different adjuvant formulations were used with recombinant *BmHAXT*. Alum (AL007) and Alum plus GLA, a synthetic TLR4 agonist (AL019) was purchased from the Infectious Disease Research Institute, Seattle, WA and Mannosylated Chitosan (MCA) was a gift from Pacific GeneTech, Hong Kong.

[00247] *Animals and Parasite*. Six to eight weeks old Balb/c mice purchased from Taconic biosciences (Hudson, NY) were used in these experiments. Use of animal in this study was approved by the animal care committee of the University of

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Illinois, Rockford following the National Institutes of Health guidelines for the care and use of laboratory animals. The infective larval stage (L3) of *B. malayi* was obtained from the NIAID/NIH Filariasis Research Reagent Resource Center (University of Georgia, Athens, GA).

[00248] *Immunization of Balb/c Mice.* For the immunization, mice were randomly divided into seven groups of five mice per group: (1) rBmHAXT + AL007 given s/c, (2) rBmHAXT + AL019 given s/c, (3) rBmHAXT + MCA (first dose s/c and booster doses given orally), (4) AL007 control given s/c, (5) AL019 control given s/c, (6) MCA control (first dose s/c and booster doses given orally), (7) rBmHAXT + MCA control (all doses were given orally). Each mouse received three doses of 15 µg of rBmHAXT and 15 µg of respective adjuvant formulation at 15 days interval.

[00249] *Collection of Serum, Peritoneal Fluid and Spleen.* Blood samples were collected from the submandibular vein of each mouse on day 0 (pre-immune), and then two weeks after each immunization and kept at room temperature for 1 hour to clot. Serum was separated, and aliquots were kept frozen at -80°C for further use. Peritoneal cavity was washed with 500 µl of sterile saline solution and the fluid was collected from each mouse and processed. Spleen was then collected from each animal, washed three times with complete RPMI-1640 medium supplemented with 10% FBS and 1X antibiotic/mycotic solution (Sigma, St. Louis, MO).

[00250] *Titer of IgG Antibodies in the Serum and Peritoneal Fluids.* The titers of rBmHAXT-specific IgG antibodies in the sera samples and in the peritoneal fluids were evaluated using an indirect ELISA. Wells were coated with 1 µg/ml of rBmHAXT overnight at 4°C. After washing and blocking of the plates, diluted (1:100, 1:1,000, 1:5,000, 1:10,000, 1:20,000 and 1:40,000) sera or peritoneal fluid

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samples were added and incubated for 1 hour at room temperature. HRP-conjugated chicken anti-mouse IgG antibodies (Thermo Fisher scientific) were used as the secondary antibodies and color was developed using the 1-step Ultra TMB-ELISA substrate (Thermo Fisher Scientific). The reaction was stopped using 0.16 M H₂SO₄, and optical density was determined at 450 nm in a BioTek Synergy 2 ELISA reader.

[00251] *Levels of Antigen Specific Antibody Isotypes in the Serum and Peritoneal Fluids.* Levels of rBmHAXT-specific antibody isotypes (IgG1, IgG2a, IgG2b, IgG3, IgE, IgM) were determined in the sera and peritoneal fluid samples using an indirect ELISA. Respective isotype-specific biotinylated goat anti-mouse antibodies (Sigma) and streptavidin-HRP (1:20,000) were used as the secondary antibodies. Color was developed with 1-step Ultra-TMB. The reaction was stopped using 0.16 M H₂SO₄, and optical density was determined at 450 nm in a BioTek Synergy 2 ELISA reader.

[00252] *Challenge Studies.* To determine vaccine-induced protection, a micropore chamber challenge method was used as described previously (Dakshinamoorthy, et al. (2013) *Vaccine* 31(12):1616-22). Briefly, 20 L3s of *B. malayi* were placed in a micropore chamber and surgically implanted into the peritoneum of each mouse. Seventy-two hours after implantation, the micropore chambers were recovered. Contents of each chamber were emptied and larvae were counted and examined microscopically for adherence of cells and for larval death. Larvae that were clear, straight and with no movement were counted as dead. Larvae that were active, coiled and translucent were counted as live. The percentage of protection was expressed as the number of dead parasites/number of total parasites recovered x 100.

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[00253] *Levels of Secreted Cytokines in Culture Supernatant of Splenocytes.* A single cell suspension of spleen cells was prepared and stimulated with 1 µg/ml of rBmHAXT or ConA. Unstimulated spleen cells were kept as negative control for the assay. After a 72-hour incubation, culture supernatants were collected and levels of IL-2, IL-4, IL-6, IFN γ , TNF α , IL-10, and IL-17A were determined using a cytokine bead array kit (BD Bio Sciences, San Jose, CA).

[00254] *Analysis of T Cell Subsets by Flow Cytometer.* Spleen cells from the above cultures were then washed and labeled with fluorescent labeled anti-mouse CD3 (APC), CD4 (PE) and CD8 (PE/cya7) and the percent population of each cell type was determined in a flow cytometer. Briefly, cells were incubated with Fc γ II receptor blocker in staining buffer (2% FBS + 0.1% sodium azide) for 30 minutes at 4°C with subsequent wash in staining buffer. All three fluorescent-labeled antibodies were added to the cells and incubated for 1 hour at 4°C in the dark. After washing with staining buffer, cells were fixed in 4% paraformaldehyde and analyzed in a BD FACSCalibur™ (BD Biosciences) flow cytometer.

[00255] Another set of cells from the above experiment was stained with CD3 (APC) and within the CD3-gated population, the CD62L (PE/Cya7) and CCR7 (PE) positive T cells were identified as T-central memory cells. The cell population was also stained for intracellular IFN- γ (FITC) to determine the percent of IFN- γ positive T-central memory cells.

[00256] *Statistical Analysis.* Data presented are mean $\pm$ standard deviation (SD). Statistical significance of mean differences among different sample groups was analyzed using non-parametric Kruskal-Wallis test followed by Bonferroni correction for multiple tests using SPSS

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software (v24.0, IBM, NY). The significance level was defined as $P < 0.05$.

[00257] *Titer of rBmHAXT-Specific IgG Antibody.* Recombinant BmHAXT protein was prepared and expressed. On the SDS-PAGE gel, the molecular mass of rBmHAXT was approximately 60 kDa and appeared as a single band. Endotoxin levels in the final purified preparations was < 3 EU/0.1 mg of protein. The titer of rBmHAXT-specific IgG antibody was high (1:20000) in the sera of the rBmHAXT + AL007 group and in the rBmHAXT + AL019 group ($p < 0.05$). However, the titer was less (1:10000) in rBmHAXT + MCA group. In rBmHAXT + MCA group where all the doses were given orally, there was very little titer of antigen-specific antibodies, nearly same as AL007, AL019 and MCA adjuvant control groups. Similarly, when the peritoneal fluids were analyzed, high titer of antigen-specific IgG antibody in rBmHAXT + AL019 and rBmHAXT + AL007 vaccinated animals were observed compared to rBmHAXT + MCA group. The titer of IgG antibodies was less in the peritoneal fluids when compared to the respective sera samples from the same animals.

[00258] *Antibody Isotypes in Serum and Peritoneal Fluid.* To determine the type of humoral immune response generated against rBmHAXT, the antibody isotypes IgG1, IgG2a, IgG2b, IgG3, IgE, IgM and IgA were determined in serum and peritoneal fluid samples. The results showed that IgG1 was the predominant isotype of antibodies in all vaccinated groups ($p = 0.0001$) except rBmHAXT + MCA (all oral dose) group, which was similar to the controls. Titer of IgG2a and IgG2b antibodies were also significantly high in all vaccinated animals ($p < 0.05$) compared to controls except in rBmHAXT + oral MCA vaccinated group. Titer of IgG3, IgE, IgM, and IgA antibodies in the vaccinated animals did not show any significant changes compared to the controls.

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Significantly, high titers of IgG1 antibodies were present in the peritoneal fluids of *rBmHAXT* + AL007 and *rBmHAXT* + AL019 vaccinated animals ($p=0.0001$) compared to *rBmHAXT* + MCA subcutaneous group and controls. Titer of IgG2a and IgG2b antibodies in the peritoneal fluid of all vaccinated animals were not significantly different from the controls.

[00259] *Vaccination with rBmHAXT+AL019 Conferred Maximum Protection.* Vaccine-induced protection was determined using a micropore chamber challenge method. The results showed that maximum protection was observed in animals vaccinated with *rBmHAXT*+AL019 ($88.05 \pm 3.9\%$; $p=0.0001$) followed by *rBmHAXT*+AL007 ($79.47 \pm 2.6\%$; $p=0.0001$) and *rBmHAXT*+MCA ($78.67 \pm 5.47\%$; $p=0.0001$). Several cells were found attached to the surface of the dead larvae. These results indicate that AL019 may be a better adjuvant for *rBmHAXT* compared to AL007 ($p=0.0037$) and MCA ($p=0.02$). Vaccination with *rBmHAXT* + oral MCA conferred only $17.97 \pm 5.75\%$, which was similar to the adjuvant control groups (AL007, 20.55%; AL019, 24.19%; and MCA, 15.742%).

[00260] *Spleen Cells from rBmHAXT-Vaccinated Animals Secreted Both Th1 and Th2 Cytokines.* Cytokines level in the culture supernatants of spleen cells were determined using a cytokine bead array. The results showed that secreted levels of Th1 (IFN- γ , IL-2, IL-6, IL-17A) and Th2 (IL-4 and IL-10) cytokines were significantly ($p<0.05$) increased in the culture supernatants of spleen cells from *rBmHAXT*+AL019 and *rBmHAXT*+AL007 vaccinated animals compared to the respective adjuvant control animals. Spleen culture supernatants from *rBmHAXT*+MCA vaccinated animals had significantly high levels of IFN- γ ($p=0.01$) and IL-6 ($p=0.0001$) compared to the respective adjuvant control. However, there was no significant difference in the levels of the other cytokines measured. Cytokine levels in the

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culture supernatants from *rBmHAXT* + oral MCA group were similar to the adjuvant controls.

[00261] *T_{CM} Cells were Generated in the Spleen of rBmHAXT-Vaccinated Animals.* Spleen cells were cultured at 37°C for 72 hours, stimulated with 1 µg/ml of *rBmHAXT* protein. After 72 hours, cells were harvested and stained with CD3/CD4/CD8 antibodies and evaluated via flow cytometer. There was a slight but significant increase in the CD8⁺ cell population in the *rBmHAXT*+AL019-treated group ($p \leq 0.05$) compared to the other groups. To determine the percent of *T_{CM}* cells in the spleen, splenocytes were stained with CD62L/CCR7 antibodies and analyzed in a flow cytometer. Cells that were dual positive for CD62L/CCR7 were considered to be *T_{CM}* cells. The results showed that *rBmHAXT*-treated animals showed high percentage of *T_{CM}* cells irrespective of the adjuvant used ($p \leq 0.001$).

[00262] *T_{CM} Cells were Predominantly IFN γ ⁺.* IFN- γ secreting *T_{CM}* cells are believed to play a major role in vaccine-induced protection in parasitic infections (Maggioli, et al. (2016) *Front. Immunol.* 7:421). Therefore, the percentage of CD62L⁺ CCR7⁺ *T_{CM}* cells that expressed intracellular IFN- γ was measured. The results showed that cells from *rBmHAXT*+AL019-vaccinated animals had a significantly ($p < 0.01$) high percentage of IFN γ ⁺ *T_{CM}* cells compared to *rBmHAXT*+AL007- and *rBmHAXT*+MCA-vaccinated groups.

Example 11: Prophylactic Vaccine Against Human Lymphatic Filariasis in Non-Human Primates

[00263] *Non-Human Primates.* Forty male or female disease-free rhesus macaques (3 to 5 years old) were purchased from PrimGen (Hines, IL) and housed at the Bioqual's facility at Rockville, MD. All animals were screened for the absence of

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filarial infections prior to enrolling them in the study by analyzing the blood for the presence of microfilarial *Hha-1* by PCR (Hoti, et al. (2003) *Acta Trop.* 88:77-81; Rao, et al. (2006) *J. Clin. Microbiol.* 44:3887-3893) and serum for the presence of antibodies against rBmSXP-1 (Vasuki, et al. (2003) *Acta Trop.* 86:109-114; Abdul Rahman, et al. (2007) *Filaria J.* 6:10) and rBmHAXT proteins were analyzed using enzyme-linked immunosorbent assay (ELISA). Animals that were positive for any of the proteins were not enrolled in the study.

[00264] *Parasites.* *Brugia malayi* infective third stage larvae (L3) were obtained from the NIAID/NIH Filariasis Research Reagent Resource Center (University of Georgia, Athens, GA).

[00265] *Adjuvants.* Two different adjuvants were compared in this study. Alum (AL007) and Alum plus a synthetic TLR4 agonist GLA (AL019) purchased from Infectious Disease Research Institute, Seattle, WA.

[00266] *Cloning and Expression of Multivalent Recombinant Proteins.* rBmHAT protein was expressed in *Escherichia coli* BL21 (DE3), purified and analyzed as described herein. The coding sequence (CDS) of multivalent fusion protein rBmHAT (composed of *bmhsp* 12.6, *bmalt-2* and *bmtsp*) and rBmHAXT (composed of *bmhsp* 12.6, *bmalt-2*, *bmtpx2* and *bmtsp*) were synthesized at GenScript (Piscataway, NJ). The sequences were provided in pUC51 vector. Both CDS were PCR amplified using the same gene specific primers (Forward primer: 5'-CGG GAT CCA TGG AAG AAA AGG TAG TG-3', SEQ ID NO:31 & Reverse primer: 5'-CGG AAT TCT CAA TCT TTT TGA GAT GAA T-3', SEQ DI NO:36) with restriction sites for *BamHI* and *EcoRI* and cloned into the expression vector pRSETA (Invitrogen, Carlsbad, CA) with the 6X Histidine tag. The ligated constructs for both *bmhat* and *bmhaxt* were further

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transformed into the expression strain of *E. coli* BL21 (DE3). Expression of recombinant proteins was induced with 1 mM IPTG. The recombinant proteins were purified using nickel affinity column chromatography (GE Healthcare Life Sciences, Pittsburgh, PA) and the purity of the recombinant proteins was confirmed in 12% SDS PAGE gel and by western blot using anti-penta His antibodies (Qiagen, Velencia, CA). Endotoxin in the final prep was removed using an endotoxin removal column (Thermo Fisher Scientific, Rockford, IL). Final concentration of rBmHAT and rBmHAXT proteins was determined by Bradford assay (Qiagen).

[00267] *Immunization of Macaques.* This was a double-blinded vaccination trial. A total of 40 macaques were randomly divided into three treatment groups and one control group with 10 macaques per group. All the treated animals received four doses of 150 µg of the vaccine antigen and 2 mg of the adjuvant on days 0, 28, 56 and 84. Treatment group 1 received rBmHAT + alum, treatment group 2 received rBmHAT + AL019 and treatment group 3 received rBmHAXT + AL019. Control animals received AL019 adjuvant only. The injection sites were monitored daily for any adverse reactions (redness, swelling, etc.) for up to 7 days post-immunization. Blood samples were collected prior to each immunization and before challenge.

[00268] *Cell Counts, Serum Chemistry and Complete Blood Count (CBC) Analysis.* CBC and serum chemistries were analyzed using commercial automated hematology and serum chemistry analyzers by IDEXX. Samples collected prior to the initiation of the study served as a normal reference baseline for each animal.

[00269] *Antigen-Specific Antibody Levels in Macaque Sera.* Levels of rBmHAT-, rBmHAXT-, rBmHSP-, rBmALT-2-, rBmTPX-, or rBmTSP-specific total IgG, IgG1, IgG2, IgG3, IgM and IgE

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antibodies were determined in the sera of each rhesus macaque using an indirect ELISA as described elsewhere herein.

[00270] *Antibody-Dependent Cell-mediated Cytotoxicity (ADCC) Assay.* ADCC assay was performed as described elsewhere herein. Approximately ten live *B. malayi* L3 each were incubated at 37°C with 5% CO₂ in triplicate wells along with 2x10⁵ PBMC and 50 µl of sera samples. Seventy-two hours after incubation, viability of *B. malayi* L3 was determined. The percentage larval death was expressed as the ratio of the number of dead L3 to the total number recovered from each well multiplied by 100.

[00271] The culture supernatant from the ADCC assay was also collected to determine the level of myeloperoxidase (MPO) activity using a kit purchased from Biovision (Milpitas, CA) and the values are expressed as mU/minute in per ml of culture supernatant.

[00272] *Antigen-Specific Proliferation of Peripheral Blood Mononuclear Cells (PBMC).* PBMC (1x10⁷ cells/well in 1 ml) were incubated at 37°C in the dark for 15 minutes with 5 mM of carboxyfluorescein diacetate succinimidyl ester (CFSE). Following incubation, cells were washed, incubated for an additional 30 minutes at 37°C and plated at 2x10⁶ cells/well in 1 ml in a 24-well tissue culture plate. Five hundred µl of the medium was removed the next day and rBmHAXT (1 µg in 500 µl) was added to the wells. Cells incubated with RPMI medium alone served as negative controls and concanavalin A (1 mg/well)-stimulated cells served as positive controls. Cells were harvested on day five after culture, labeled with anti-CD3-APC antibody, fixed in 4% paraformaldehyde for 10 minutes at room temperature and data acquired on a BD FACSCalibur™ flow cytometer and analyzed using ModFit LT software (Verity Software House, Topsham, ME).

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[00273] Parallel cultures of cells incubated for 3 days were harvested, paraformaldehyde fixed and labeled with combinations of anti-CD3-APC, anti-CD4-FITC, anti-CD8-PE, anti-CD28-PE, or anti-CCR7-FITC. Intracellular IFN- γ and IL-4 were determined after fixing and permeabilization. Data was acquired on BD FACSCalibur™ flow cytometer and analyzed using Flow Jo v10.1 (FlowJo, LLC, Ashland, OR).

[00274] Secreted levels of cytokines (GM-CSF, IFN- γ , IL-12p70, IL-1 β , IL-4, IL-5, IL-6, IL-15, IL-16 and TNF- α) in the cell culture supernatants were measured using an antibody-based Rhesus Cytokine Quantibody Array GS1 (RayBiotech, Inc., Norcross, GA) according to manufacturer's protocol. The intensity of the fluorescence signals from the slide arrays was scanned and data analyzed after subtracting the background signals and normalization to positive controls.

[00275] *B. malayi* Infective Larval (L3) Challenge. One month after the last immunization, all macaques were challenged subcutaneously with 130-180 *B. malayi* L3. All the larvae were examined microscopically for their viability, counted, and only the viable larvae were used for challenge. Following challenge, all the macaques were monitored routinely for any possible alterations in the clinical biochemistry panel (serum chemistry, hematology, complete blood count analysis and CD4⁺/CD8⁺ T-cell counts), physical parameters (signs of adverse reactions at the site of challenge, body weights, body temperature, body condition, lymphoedema and lymph node measurements) and behavioral patterns.

[00276] *Confirming the Establishment of Challenge Infection in Macaques.* It is practically difficult to count the number of adult worms established in each macaque. However, several pieces of evidences were used to confirm the

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presence of active infection in macaques including microscopic and *Hha-I* PCR analyses. For microscopic analysis, on week 5, 10, 15 and 18 post-challenge, 10 ml of blood was collected from each macaque between 6-10 pm and screened for the presence of microfilariae using a modified Knott technique. For *Hha-I* PCR analysis, DNA isolated from 200 µl of blood samples using the Gen Elute blood genomic DNA kit (Sigma-Aldrich) were PCR amplified for *Hha-I* tandem repeat genes as described previously (Hoti, et al. (2001) *Bull. Entomol. Res.* 91:87-92) and the amplified PCR products were sequenced to confirm the *Hha-I* sequence.

[00277] *Titer of Anti-rBmSXP-1 Antibodies in Sera.* *BmSXP-1* is a highly sensitive and specific diagnostic antigen for *B. malayi* infections. Typically, a single sex infection will not have any Mf in the peripheral circulation. Thus, microscopy and PCR approach may not detect these dormant infections. However, presence of active worm in infected subjects or animals can be confirmed by determining the titer of IgG4 antibodies against *BmSXP-1* antigen. An ELISA was used to determine the titer of these antibodies in the sera of macaques. Since no reliable commercial anti-macaque IgG4 antibodies were obtainable, titer of anti-r*BmSXP-1* IgG antibodies was used as a marker to detect dormant infections.

[00278] *Lymphoscintigraphy Analysis.* The lymphoscintigraphic analysis was carried out as described elsewhere herein.

[00279] *Statistical Analysis.* Data presented are mean $\pm$ standard deviation (SD). Statistical significance of mean differences among different sample groups was analyzed using non-parametric Kruskal-Wallis test followed by Bonferroni correction for multiple tests using SPSS software (v24.0, IBM, NY). The significance level was defined as $P \leq 0.05$. To analyze the vaccine-induced

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protection, Chi-square test was used to compare the proportions across the groups and Fisher's exact test was used where appropriate. Odds ratios (OD) were calculated to determine the differences between groups.

[00280] *Immunization with the Vaccine Candidates Generated High Titer of Antigen-Specific IgG Antibodies and Their Isotypes.* Molecular mass of rBmHAT is approximately 39 kDa and rBmHAXT is approximately 60 kDa. Both proteins were prepared to over 95% purity with endotoxin levels <10 EU/ μ g of the protein. Immunization of macaques with the purified proteins generated high titer of antigen-specific IgG antibodies. The IgG antibodies were specific to each component of the fusion protein. Maximum IgG antibody titer was achieved after the second dose of immunization (Table 22) indicating that two doses of vaccine is sufficient to achieve maximum antibody titer.

TABLE 22

Macaque Groups (n=10)	Immunizations			
	First	Second	Third	Fourth
rBmHAT+AL007	1:1250	1:20000	1:20000	1:20000
rBmHAT+AL019	1:10000	1:20000	1:20000	1:20000
rBmHAXT+AL019	1:1250	1:20000	1:20000	1:20000
AL019	1:125	1:125	1:125	1:125

rBmHAT, recombinant *Brugia malayi* HSP12.6+ALT-2+TSPLEL;
rBmHAXT, recombinant *B. malayi* HSP12.6+ALT-2+TPX-2+TSPLEL.

[00281] IgG1 and IgG2 were the most predominant isotype of IgG antibodies in the sera of all immunized animals. Levels of IgG3 antibodies were significantly elevated in the sera of rBmHAXT plus AL019 immunized group compared to the control animals. IgM and IgE antibodies were not significantly different from controls in the sera of vaccinated animals.

[00282] *Antigen Responding Memory Cells were Present in the Blood of Vaccinated Macaques.* Proliferation index of PBMCs

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from vaccinated animals was high in response to the respective antigens compared to controls. Cells from control group replicated only once during the five days in culture compared to the vaccinated group where the cells divided up to eight generations. Evaluation of the memory cell population within the dividing antigen-responding CD4⁺ and CD8⁺ T cells showed that both CD28⁺CCR7⁻ effector memory T cells (T_{EM}) and CD28⁺ CCR7⁺ central memory T cells (T_{CM}) were selectively expanded in rBmHAXT plus AL019 and rBmHAT plus AL007 immunized macaques. The T_{EM} cells predominantly were positive for intracellular IFN-γ and T_{CM} cells predominantly positive for intracellular IL-4. Analysis of the culture supernatants of the PBMCs showed a marked increase in the secreted levels of cytokines (GM-CSF, IFN-γ, IL-12p70, IL-1β, IL-4, IL-5, IL-6, IL-15, IL-16 and TNF-α) compared to AL019 controls. PBMCs from rBmHAXT+AL019 vaccinated animals secreted nearly 10-fold higher levels of IFN-γ compared to AL019 controls.

[00283] *Immunization with rBmHAXT Conferred Maximum Protection.* Ten weeks after challenge with *B. malayi* L3, seven out of 10 control animals (70%) showed Mf in their peripheral blood and they continued to be positive for Mf until completion of the experiment (18 weeks post-challenge). However, only 3 out of 10 macaques (30%) in the rBmHAXT plus AL019 group showed Mf in their blood (FIG. 4). These findings were further confirmed by PCR analyses of the blood samples for the presence of *B. malayi*-specific *Hha-1* and by an ELISA for IgG antibodies against SXP-1 antigen. Repeat examination of the blood did not show any evidence challenge of infection in any of the negative animals until completion of the experiment (18 weeks post) indicating that immunization with rBmHAXT plus AL019 conferred 57.14% protection after adjusting the 30% of

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amicrofilaremic macaques in the control group ($p=0.073$, odds ratio=0.18). Five out of 10 animals in the *rBmHAT*+AL019 group ($p=0.649$, odds ratio=0.42) and 7 out of 10 animals in the *rBmHAT*+AL007 group ($p=1.0$, odds ratio=1.0) were positive for Mf. Statistical correlation between different groups showed that *rBmHAXT*+AL019 conferred better protection than other vaccinated groups and AL019 control (*rBmHAXT*+AL019 vs AL019 control - $p=0.073$; *rBmHAXT*+AL019 vs *rBmHAT*+AL019 - $p=0.649$; *rBmHAXT*+AL019 vs *rBmHAT*+AL007 - $p=0.073$ and *rBmHAT*+AL019 vs *rBmHAT*+AL007 - $p=0.649$). Thus, based on the odds-ratio, the odds that the AL019 control group would be positive for Mf were 2.33 times higher than the odds that *rBmHAT*+AL019 group would be Mf positive. The odds that the AL019 control group would be positive for Mf were 5.43 times higher than the odds that the *rBmHAXT*+AL019 group would be Mf positive. The odds that the *rBmHAT*+AL019 group would be positive for Mf were 1.95 times higher than the odds that the *rBmHAXT*+AL019 group would be Mf positive. These statistical analyses indicate that protection conferred by *rBmHAXT*+AL019 immunization was significantly better than *rBmHAT*+AL007 and *rBmHAT*+AL019 immunizations.

[00284] An antibody dependent cellular cytotoxicity (ADCC) assay was also performed as an *in vitro* surrogate for determining vaccine-induced protection. These assays also confirmed that sera samples from macaque vaccinated with *rBmHAXT*+AL019 were more efficient in killing the *B. malayi* L3 *in vitro* compared to the sera samples from the other two vaccinated groups (FIG. 5). Several cells were found attached to the dead larvae. In fact, many of the dead larvae were totally covered by cells within 24 hours after incubation. In this study the morphology of the cells was not identified. However, previous studies suggest that the

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bound cells are predominantly monocytes. To determine the activation status of these cells, levels of myeloperoxidases (MPO) in the culture supernatants from these ADCC assays were measured. The results showed an increase in the secreted levels of MPO (2.08 to 2.78 mmol/min/ml) in the wells with sera from vaccinated animals and PBMCs compared to the wells with sera from control animals (1.99 mmol/min/ml), indicating activation of MPO producing cells.

[00285] *Mf-Negative Vaccinated Animals did not Develop Lymphatic Pathology.* Adult filarial parasites living within the lymphatic vessels cause severe inflammation leading to lymphedema and blockage of lymph flow. The presence of lymphatic blockage in this study was determined by lymphoscintigraphy. Lymph flow was compared between the right and left leg in the same animal. Challenge infections were given on the right leg. The results showed that on week 16 post-challenge, there was a significant reduction in the lymph flow in the right leg of all Mf positive animals compared to their left leg indicating lymph blockage. Lymph flow did not show any significant differences between the right and left leg in all Mf negative animals in the vaccinated group. These findings thus demonstrate that lymphatic pathology was minimal or was absent in vaccinated and challenged macaques that did not show Mf in their peripheral blood.

Example 12: Prophylactic Vaccine Against *Dirofilaria immitis* Infection in Dogs

[00286] *Immunization Protocol.* Six dogs were divided into two groups of three animals per group. Each animal of the first group received three rounds of 100 µg dose of rBmHAXT vaccine plus 400 µl of AL019 adjuvant (40 µg TLR4 agonist +

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800 µg alum) s/c. Each animal of the second group was used as a control and received three rounds of 400 µl of AL019 adjuvant only s/c. Injections were performed on days 0, 30, and 60. In addition, at days 0, 30, 60, and 90, 20 mL of blood was collected in EDTA tubes from the saphenous vein of each dog prior to immunization. All animals were monitored for adverse reactions including injection site reactions, fever, loss of appetite, allergy, hair loss and weight loss.

[00287] *Antigen-Specific Antibody Levels in Dog Sera.* Levels of rBmHAXT-specific total IgG, IgG1, IgG2, IgG3, IgM and IgE antibodies were determined in the sera of each dog using an indirect ELISA as described elsewhere herein.

[00288] *Antibody-Dependent Cell-mediated Cytotoxicity (ADCC) Assay.* ADCC assay was performed as described elsewhere herein. Eight to ten live *D. immitis* L3 each were incubated at 37°C with 5% CO₂ in duplicate wells along with 0.5 million PBMC isolated from normal dog blood, 200 µl RPMI 1640 medium and 100 µl of sera samples. Plates were monitored under light microscope every 24 hours for viability of *D. immitis* L3. Larvae that were limpid, non-motile or slowly motile were considered dead. The percentage larval death was expressed as the ratio of the number of dead L3 to the total number recovered from each well multiplied by 100.

[00289] *Immunization with rBmHAXT Vaccine Generated High Titer of Antigen-Specific IgG Antibodies and Their Isotypes.* Immunization of dogs with the purified rBmHAXT protein generated high titer of antigen-specific IgG antibodies (over 1:20000). There was also a significant increase in IgG1, IgG2 and IgA antibodies in the serum of dogs after three immunizations compared to the control group, with IgG1 and IgG2 being the most predominant

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isotype of IgG antibodies. Analysis of the sera samples for the presence of protective antibodies against *D. immitis* infective larvae showed that significant levels of protective memory antibodies were present in the sera of vaccinated animals. These protective antibodies proliferated in response to rBmHAXT and were able to kill both drug-sensitive (~60%) and drug-resistant (~85%) of infective larvae after two to three immunizations (FIG. 6). Several cells were found attached to the dead larvae. Further, culture supernatants of spleen cells from the vaccinated dogs showed elevated levels of TNF- α and IL-10. These findings suggest that rBmHAXT is an excellent vaccine candidate against heartworm infections in animals such as dogs and cats.

[00290] All dogs were challenged s/c with 50 drug-sensitive *D. immitis* infective larvae. Six months after the challenge, all animals were euthanized to recover the established adult worms from each dog. The results showed that the mean worm load in rBmHAXT vaccinated animals was 7 ± 1.73 compared to the AL019 control group, which had a mean worm load of 29.3 ± 3.51 . This study demonstrated that vaccination with rBmHAXT in dogs, conferred 76.11% protection against a challenge infection with drug-sensitive *D. immitis*. Following challenge infection, fewer male and female worms were established in the rBmHAXT vaccinated dogs.

Example 13: Comparison of rBmHAXT and rDiHAX Vaccines Against *Dirofilaria immitis* Infection in Mice

[00291] Cloning, Expression and Purification of rBmHAXT Recombinant Protein. GenScript (Piscataway, NJ) supplied the sequences of *bmhsp12.6* (GENBNAK Accession No. AY692227.1), *bmalt-2* (GENBNAK Accession No. JF795950.1),

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bmtpx-2 (GENBNK Accession No. AF319997.1) and *bmtsp* (GENBNK Accession No. JF795955.1) in the pUC57 vector. The genes were amplified using forward 5'-CGG GAT CCA TGG AAG AAA AGG TAG TG-3' (SEQ ID NO:31) and reverse 5'-CCC GAA TTC TTA ATG TTT CTC AAA ATA TGC TTT-3' (SEQ ID NO:89) with restriction sites for *Bam*HI and *Eco*RI. The PCR-amplified products were cloned into the pRSETA expression vector, transformed into competent BL21 (DE3) *E. coli* cells for expression of the recombinant proteins with 6X histidine tag. Recombinant fusion proteins were purified using immobilized metal affinity Ni²⁺-charged agarose chromatography column sold under the tradename SEPHAROSE® (GE Healthcare Life Sciences, Pittsburgh, PA) and eluted with 300 mM imidazole. Endotoxin in the final purified protein preparation was removed using an endotoxin removal column (Thermo Fisher Scientific, Rockford, IL). The expression and purity of recombinant proteins was confirmed in 12% SDS-PAGE gel and western blot using anti-His antibodies (Qiagen, Valencia, CA). Protein concentration was determined using a Bradford reagent (Thermo Fisher Scientific).

[00292] *Cloning, Expression and Purification of rDiHAX Recombinant Protein.* The contig nucleotide sequence of *DiHSP* 12.6 (gene=nDi.2.2.2.g00663), *DiALT-2* (gene=nDi.2.2.2.g08197) and *DiTPX-2* (gene=nDi.2.2.2.g06574) were obtained from Wormbase ParaSite by blasting *BmHSP* 12.6, *BmALT-2* and *BmTPX-2* sequences. *BmHSP* 12.6, *BmALT-2* and *BmTPX-2* proteins were found to share 97%, 63% and 96% sequence similarity with *DiHSP* 12.6, *DiALT-2* and *DiTPX-2* proteins, respectively. The nucleotide and amino acid sequence of *DiHSP* are provided in SEQ ID NO:90 and SEQ ID NO:91, respectively. The nucleotide and amino acid sequence of *DiALT-2* are provided in SEQ ID NO:92 and SEQ ID NO:93,

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respectively. The nucleotide and amino acid sequence of *DiTPX* are provided in SEQ ID NO:94 and SEQ ID NO:95, respectively. The nucleotide sequences of *DiHSP* 12.6, *DiALT*-2 and *DiTPX*-2 were linearly combined and the resulting *dihax* gene was synthesized by Invitrogen Life Technologies™. The chimeric gene (SEQ ID NO:96) was provided in pET100/D-TOPO® vector (ThermoFisher Scientific, Rockford, IL), transformed into competent BL21*DE3 *E. coli* and the *rDiHAX* fusion protein (SEQ ID NO:97) was expressed. Briefly, an overnight seed culture was inoculated into 500 mL sterile LB broth and allowed to grow under the optimized conditions and selection pressure until the OD₆₀₀ was reached. The bacterial cells were then induced with 1 mM IPTG (Research Products International, Mt. Prospect, IL) and allowed to grow for an additional 4 hours. The cells were then pelleted down by centrifuging at 12,000 rpm for 30 minutes at 4°C. For protein purification, the pellet was re-suspended in 20 mL Tris-Buffered Saline (TBS) and 150 µl of lysozyme was then added to the solution and incubated for 30 minutes in a shaker platform at room temperature. Following incubation, the pellet was sonicated for 4 cycles at 1 minute each with a pause of 30 seconds in between. Following sonication, the lysates were centrifuged at 12,000 rpm for 30 minutes at 4°C. The supernatant was discarded, the pellet was washed and 15 mL of 8M Urea was then added to the pellet and incubated overnight at 4°C with constant mixing. After incubation, the lysate was centrifuged at 12,000 rpm for 30 minutes at 4°C and the supernatant was collected into a fresh 50 mL conical centrifuge tube over ice. The recombinant protein was expressed with an N-terminal six histidine residue tag. This allowed for purification of the *rDiHAX* protein by Immobilized Metal Affinity Chromatography (IMAC). In

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particular, the extracted protein was incubated with 2 mL cobalt resin for 30 minutes in a shaker at room temperature and packed into a 10 ml column. After washing the column with 10 ml TBS, the column was washed with 30 mL of 10 mM Imidazole prepared in TBS. The bound protein was then eluted with 300 mM Imidazole containing 10% glycerol in TBS. Purity and molecular size of the rDiHAX protein was assessed on a 14% SDS-PAGE gel. The molecular weight of the recombinant protein was approximately 60 kDa. After desalting, endotoxin from the purified protein was removed by passing the protein solution through a High Capacity Endotoxin removal resin column (ThermoFisher Scientific). The level of endotoxin in the concentrated protein sample was analyzed using a Pierce™ LAL Chromogenic Endotoxin Quantitation Kit. The final amount of endotoxin in the purified rDiHAX preparation was 3 EU per mg of protein.

[00293] *Experimental Design.* Balb/c mice (male 4-6 weeks of age) were grouped into 10 mice per group and immunized subcutaneously with 15 µg of rBmHAXT or rDiHAX antigen along with 10 µg of AL019 (Alum plus GLA, a synthetic TLR4 agonist) as adjuvant. Four immunizations were given at 2-week intervals. Control animals received AL019 adjuvant only. Blood samples were collected from each mouse prior to each immunization and 2 weeks after the last immunization to analyze the serum levels of antigen-specific IgG, IgG1, IgG2a, IgG2b and IgG3. An ADCC assay was performed by incubating 10-15 *D. immitis* L3 with 50 µl of sera from immunized mice and 1x10⁵ peritoneal cells from control mice. A challenge experiment was also performed by placing a micropore chamber containing 15-20 *D. immitis* L3 in the peritoneal cavity of all mice. Larval viability was determined 72 hours post-challenge and spleen cells and

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peritoneal fluid/cells were analyzed for immunological correlates of vaccine-induced protection.

[00294] *Immunization with rBmHAXT and rDiHAX Vaccines Generated High Titer of Antigen-Specific IgG Antibodies and Their Isotypes.* Immunization of mice with the purified rBmHAXT and rDiHAX proteins generated high titer of antigen-specific IgG antibodies. In particular, the results showed that immunized animals developed high titers (1:10000 titer) of IgG1, IgG2a, IgG2b and IgG3 antibodies against rBmHAXT or rDiHAX compared to controls ($p < 0.05$).

[00295] Results from the ADCC experiments showed that sera samples from rBmHAXT immunized mice killed $93 \pm 8.83\%$ larvae and sera samples from rDiHAX immunized mice killed $76 \pm 5.69\%$ larvae compared to the sera samples from the AL019 group that gave $(20 \pm 5.93\%)$ larval death. In the challenge experiment, larval death was $83 \pm 4.14\%$ and $71 \pm 8.99\%$ for rBmHAXT and rDiHAX immunized mice, respectively, compared to the control ($7.3 \pm 2.42\%$). Notably, there was significant ($p < 0.05$) cross-reactivity of antibodies in the sera samples from rBmHAXT and rDiHAX vaccinated animals with rBmHAXT and rDiHAX proteins as determined by ELISA and western blot analysis.

[00296] Analysis of the cellular immune response showed that there was an increase in the antigen-specific CD3⁺CD62L⁺CCR7⁺ memory T cells in the spleen of vaccinated animals compared to AL019 controls. The culture supernatants of spleen cells from both rBmHAXT and rDiHAX groups showed elevated levels of IL-17A, IL-6, IFN- γ and IL-10.

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Example 14: Intramuscular Injection of rBmHAXT Provides Protection Against *Dirofilaria immitis* Infection in Dogs

[00297] *Immunization Protocol.* Six dogs were divided into two groups of three animals per group. Each animal of the first group received three rounds of 100 µg dose of rBmHAXT vaccine plus 40 µg of alum adsorbed GLA-SE (AL019; TLR4 ligand GLA formulated as an oil-in-water emulsion) on days 0, 28 and 56 given i/m on the left flank region. Each animal of the second group was used as a control and received three rounds of adjuvant only on days 0, 28 and 56 given i/m on the left flank region. In addition, at days -1, 0, 28, 56, and 84, blood samples were collected in EDTA tubes from the saphenous vein of each dog prior to immunization. Serum samples were analyzed for antibody titer (IgG, IgG1, IgG2, IgA, IgM and IgE). Peripheral blood mononuclear cells were analyzed for vaccine-induced memory cells and for their cytokine production. Protective antibodies were determined by performing an ADCC assay. All animals were challenged with 50 drug-sensitive *D. immitis* larvae to determine protection. Vital signs and clinical laboratory parameters (CBC, urinalysis, liver function) were monitored as was injection site reaction (swelling, redness, pain).

[00298] *Antigen-Specific Antibody Levels in Dog Sera.* Levels of rBmHAXT-specific total IgG1, IgG2, IgGA, IgM and IgE antibodies were determined in the sera of each dog using an indirect ELISA as described elsewhere herein.

[00299] *Antibody-Dependent Cell-mediated Cytotoxicity (ADCC) Assay.* ADCC assay was performed as described elsewhere herein. Eight to ten live *D. immitis* L3 each were incubated at 37°C with 5% CO₂ in duplicate wells along with 0.5 million PBMC isolated from normal dog blood, 200 µl RPMI 1640 medium and 100 µl of sera samples. Plates were

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monitored under light microscope every 24 hours for viability of *D. immitis* L3. Larvae that were limpid, non-motile or slowly motile were considered dead. The percentage larval death was expressed as the ratio of the number of dead L3 to the total number recovered from each well multiplied by 100.

[00300] *Immunization with rBmHAXT Vaccine Generated High Titer of Antigen-Specific IgG Isotype Antibodies.* Twenty-eight days after the third vaccination, dogs vaccinated with rBmHAXT antigen showed significant increases ($p < 0.01$) in IgG antibody titers (1:10,000) compared to the adjuvant control group. There was also a significant increase in IgG1, IgG2 and IgA antibodies in the serum of dogs after three immunizations compared to the control group, with IgG1 and IgG2 being the most predominant isotype of IgG antibodies. While no change was observed in the levels of IgE and IgM antibodies, this analysis demonstrated a balanced Th1/Th2 immune response generated against the vaccine antigens in the vaccinated animals. ADCC showed that sera samples from rBmHAXT vaccinated animals killed $69 \pm 16.82\%$ drug-sensitive larvae ($p < 0.05$) compared to the AL019 control group ($20 \pm 12.17\%$). Similarly, ADCC showed that sera samples from rBmHAXT vaccinated animals killed $86 \pm 7.50\%$ drug-resistant larvae ($p < 0.05$) compared to the AL019 control group ($38.2 \pm 22.80\%$). In rBmHAXT vaccinated animals, drug-sensitive worm load was 7 ± 1.73 ($P = 0.0025$) compared to the AL019 control group (29.3 ± 3.51). This represents a 76.11% reduction in worm establishment in vaccinated animals. Indeed, worm recovery after challenge infection with drug-sensitive *D. immitis* L3s indicated a significant reduction in rBmHAXT vaccinated animals compared to the AL019 control group (6.67 vs. 29.33). The results of these analysis indicate that after three doses

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of vaccinations with *rBmHAXT*, protective antibodies were generated, and these antibodies were effective in killing both drug-resistant and drug-sensitive *D. immitis* infective larvae *in vitro*. In addition, challenge studies showed that vaccination significantly reduced worm establishment. Thus, the *rBmHAXT* vaccine is safe for use in canines.

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What is claimed is:

1. A multivalent immunogenic composition comprising two or more antigens from *Dirofilaria immitis*.

2. The multivalent immunogenic composition of claim 1, wherein the antigens are protein-based, DNA-based, or a combination thereof.

3. The multivalent immunogenic composition of claim 1, wherein the antigens comprise an Abundant Larval Transcript, Small heat shock protein (HSP) 12.6, Thioredoxin Peroxidase 2, or fragments thereof.

4. The multivalent immunogenic composition of claim 3, wherein the Abundant Larval Transcript comprises SEQ ID NO:98 or SEQ ID NO:99; the Small heat shock protein 12.6 comprises SEQ ID NO:100 or SEQ ID NO:101; and the Thioredoxin Peroxidase 2 comprises SEQ ID NO:83 or SEQ ID NO:101.

5. The multivalent immunogenic composition of claim 4, wherein the Abundant Larval Transcript comprises SEQ ID NO:93; the Small heat shock protein 12.6 comprises SEQ ID NO:91; and the Thioredoxin Peroxidase 2 comprises SEQ ID NO:95.

6. The multivalent immunogenic composition of claim 1, wherein the antigens are covalently attached.

7. A recombinant vector comprising nucleic acids encoding the multivalent immunogenic composition of claim 1.

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8. A recombinant host cell comprising the recombinant vector of claim 7.

9. The multivalent immunogenic composition of claim 1 further comprising an adjuvant.

10. A method for inducing a protective immune response in a subject comprising administering the multivalent immunogenic composition of claim 1 to a subject thereby inducing a protective immune response in the subject.

11. The method of claim 10, further comprising administering one or more additional doses of the multivalent immunogenic composition to the subject.

12. The method of claim 10, wherein the immunogenic composition is administered by subcutaneous or intramuscular injection.

13. The method of claim 10, wherein the multivalent immunogenic composition is administered with an adjuvant.

14. A method for immunizing an animal against dirofilariasis comprising administering to a subject a multivalent immunogenic composition comprising two or more antigens, wherein said antigens are selected from an Abundant Larval Transcript antigen comprising SEQ ID NO:121 or SEQ ID NO:122; a Small heat shock protein 12.6 antigen comprising SEQ ID NO:81 or SEQ ID NO:123; a Tetraspanin antigen comprising SEQ ID NO:82; and a Thioredoxin Peroxidase 2 antigen comprising SEQ ID NO:83 or SEQ ID

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NO:124 thereby immunizing the subject against dirofilariasis.

15. The method of claim 14, further comprising administering one or more additional doses of the multivalent immunogenic composition to the subject.

16. The method of claim 14, wherein the immunogenic composition is administered by subcutaneous or intramuscular injection.

17. The method of claim 14, wherein the multivalent immunogenic composition is administered with an adjuvant.