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BALB/c Mice Deficient in CD4⁺ T Cell IL-4Rα Expression Control Leishmania mexicana Load although Female but Not Male Mice Develop a Healer Phenotype

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Abstract

Immunologically intact BALB/c mice infected with Leishmania mexicana develop non-healing progressively growing lesions associated with a biased Th2 response while similarly infected IL-4Rα-deficient mice fail to develop lesions and develop a robust Th1 response. In order to determine the functional target(s) for IL-4/IL-13 inducing non-healing disease, the course of L. mexicana infection was monitored in mice lacking IL-4Rα expression in specific cellular compartments. A deficiency of IL-4Rα expression on macrophages/neutrophils (in LysMcreIL-4Rαlox/lox animals) had minimal effect on the outcome of L. mexicana infection compared with control (IL-4Rαlox/lox) mice. In contrast, CD4⁺ T cell specific (LckcreIL-4Rαlox/lox) IL-4Rα⁻/⁻ mice infected with L. mexicana developed small lesions, which subsequently healed in female mice, but persisted in adult male mice. While a strong Th1 response was manifest in both male and female CD4⁺ T cell specific IL-4Rα⁻/⁻ mice infected with L. mexicana, induction of IL-4 was manifest in males but not females, independently of CD4⁺ T cell IL-4 responsiveness. Similar results were obtained using pan-T cell specific (iLckcreIL-4Rαlox/lox) IL-4Rα⁻/⁻ mice. Collectively these data demonstrate that upon infection with L. mexicana, initial lesion growth in BALB/c mice is dependent on non-T cell population(s) responsive to IL-4/IL-13 while progressive infection is dependent on CD4⁺ T cells responsive to IL-4.

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Introduction

New world cutaneous leishmaniases resulting from infection with Leishmania mexicana is under different genetic and immunoregulatory controls to those controlling L. major infection [1]. Also, unlike L. major, the majority of mouse strains are susceptible to L. mexicana infection [2–3]. As with the other Leishmania species, protective immunity against L. mexicana is the result of a STAT-4 dependent type-1 immune response, although this can be generated independently of IL-12 [4]. While the immunological pathways resulting in non-healing L. major infections in susceptible BALB/c mice remain somewhat controversial, IL-4 plays the major role in promoting non-healing L. mexicana infections in this mouse strain [5–7]. Thus, mice lacking IL-4 develop small lesions that heal while those lacking IL-4Rα fail to develop lesions [6]. This also indicates some input from IL-13 in the non-healing response to L. mexicana infection as IL-4 and IL-13 receptors share the IL-4Rα sub unit [6]. However, IL-4 and IL-13 are pleiotropic cytokines and numerous cell types of both the innate and adaptive immune responses produce these cytokines as well as express their receptors.

In order to better differentiate both the cellular sources and targets of IL-4/IL-13 initiating lesion growth and facilitating progressive non-healing disease, we have previously examined parasite growth in SCID mice reconstituted with IL-4⁻/-, IL-4Rα⁻/-, or wild type splenocytes [5–6]. These studies indicated that non-lymphocyte sources of IL-4/IL-13 may contribute to early lesion growth during L. mexicana infection. However, the non-healing disease phenotype was dependent on a lymphocyte source of IL-1 and, in its absence, IL-4-deficient splenocyte-reconstituted SCID mice generated a healing response [5]. In addition, SCID mice reconstituted with IL-4Rα⁻/- splenocytes demonstrated that initial lesion development was also dependent upon cells from this source responding to IL-4/IL-13 [6].

In order to better differentiate the specific role of IL-4/IL-13 responding cells from global effects in vivo, tissue specific IL-4Rα⁻/- mice have been produced. So far macrophage/neutrophil specific (LysoMCreIL-4Rαlox/lox) [8] and CD4⁺ T cell specific (LckCreIL-4Rαlox/lox) [9] IL-4Rα⁻/- mice have been generated and the consequences for L. major infection studied. In contrast to susceptible BALB/c mice, BALB/c LysoMCreIL-4Rαlox/lox mice showed a significantly delayed disease progression after infection with L. major, concomitant with normal Th2 and type 2 antibody immune responses but with improved macrophage leishmanicidal activities [8]. These results suggest that alternatively activated macrophages were contributing to the susceptible phenotype in non-healer BALB/c mice. Furthermore T cell-specific LckCreIL-4Rαlox/lox BALB/c mice infected with L. major were significantly...
Author Summary

Leishmania species are parasites, transmitted by sandflies which are of extensive public health importance in the tropical and subtropical regions of the world. A large number of distinct Leishmania species cause cutaneous disease and the vast majority of studies utilize the causative agent of Old World cutaneous leishmaniasis, L. major. Other species, for example, L. mexicana, are associated with quite different patterns of disease following infection of mice when compared with L. major. Thus, while susceptible BALB/c mice deficient in the ability to respond to the cytokines IL-4/IL-13 are not protected against development of cutaneous leishmaniasis caused by L. major they are totally resistant to infection with L. mexicana. Here we describe the outcome of L. mexicana infection in BALB/c mice with cell-specific deletion of the receptor for IL-4/IL-13 on macrophages/neutrophils or T helper cells. Infections develop in both mutants but lesion growth is controlled only in T cell specific knockouts and female but not male mice heal. Male but not female T cell specific knockouts maintain a strong IL-4/IL-13 response. This highlights the role of IL4/IL-13 in driving a non-healing disease phenotype and clinical immunity similar to genetically susceptible mice. L. mexicana parasites and infection

L. mexicana [MYNC/BZ/62/M579] was maintained by serial passage of amastigotes inoculated into the shaven rumps of BALB/c mice. Amastigotes for use in infections were isolated from lesions and enumerated as described below. Two sites of infection were examined and either 5 × 10^5 L. mexicana amastigotes in a final volume of 50 μl were inoculated subcutaneously into the shaven base of the tail, or 2 × 10^7 L. mexicana amastigotes in a final volume of 25μl were inoculated subcutaneously into the hind footpad. 6–8 week old male or female LysMcreIL-4Rαlox and LckcreIL-4Rαlox mice were used in each experiment, with age and sex matched cre negative IL-4Rαlox littermates used as controls. The lesion diameter was measured using a sliding gauge micrometer at weekly intervals.

Enumeration of parasites

Lesions were excised from L. mexicana infected LysMcreIL-4Rαlox, LckcreIL-4Rαlox and IL-4Rαlox mice and disrupted through a metal mesh with 5μl of RPMI 1640 (Cambrex Bio Science Verviers, Belgium). The parasites were washed twice at 550g in RPMI and then enumerated using an improved Naubauer haemocytometer. Alternatively parasite numbers were quantified by limiting dilution, as previously described [11].

Splenocyte stimulation and cytokine detection

Splenocytes were isolated from infected mice and cultured for 72 hours in 96-well plates (Corning-Costar, NY, USA) in the presence or absence of L. mexicana antigenic lysate, as previously described [6]. IFN-γ and IL-4 levels were detected in the supernatants by capture ELISA. Briefly the wells of Immulon 1B flat-bottomed microtitre plates (ThermoLabsystems, MA, USA) were coated with 50μL of 1μg ml⁻¹ purified anti-mouse IFN-γ capture antibody R4-6A2 (BD Biosciences, Oxford, UK) or 500ng ml⁻¹ IL-4 capture antibody 11B11 (BD Biosciences) in PBS (pH 9.0) overnight at 4°C. Supernatants were then added to the individual wells and either 30μL recombinant mouse IFN-γ (R&D Systems, Abington, UK) or recombinant mouse IL-4 (Genzyme, Cambridge, UK) added to individual wells in duplicate in a doubling dilution with a solution of pH 7.4 PBS supplemented with 10% v/v FCS (Harlan Sera-Lab Ltd., Crawley, UK), ranging from 20ng ml⁻¹ to 0.01ng ml⁻¹ (IFN-γ) or 2ng ml⁻¹ to 0.977pg ml⁻¹ (IL-4). The plates were then incubated for 2 hours at 37°C. The bound cytokines were incubated with either biotinylated rat anti-mouse IFN-γ monoclonal antibody XMG1.2 or biotinylated rat anti-mouse IL-4 antibody BVD6-24G2 (both BD Biosciences) and detected with either conjugated streptavidin-alkaline phosphatase or conjugated streptavidin-horseradish peroxidase (BD Biosciences). The appropriate substrate was then added to the wells, p-nitrophenyl-phosphate (Sigma-Aldrich, Poole, UK) or tetramethylbenzidine in pH 5.5 sodium acetate buffer, containing 0.0005% hydrogen peroxide (BDH, Poole, UK). Finally the plates were read at an absorbance of 405nm for IFN-γ or at 450nm for IL-4.

Detection of Leishmania mexicana specific -IgG1, -IgG2a and total IgE

L. mexicana specific-IgG1 and -IgG2a were detected in the plasma of infected mice by ELISA, as previously described [12].
Briefly, Immulon 1B flat-bottomed microtitre plates were coated with 100μL of 10μg ml⁻¹ *Leishmania mexicana* lyase (lyase preparation previously described [13] in PBS (pH 9.0) overnight at 4°C. Plasma samples were serially diluted in duplicate, followed by a 1 hour incubation at 37°C. Bound *Leishmania* specific antibodies were detected with a 1 hour incubation with horseradish peroxidase conjugated goat anti-mouse IgG1 or goat anti-mouse IgG2a (Southern Biotechnology Associates Inc., AL, USA). The substrate tetrathylbenzidine in pH 5.5 sodium acetate buffer, containing 0.0063% hydrogen peroxide, was then added to the wells and, following colour development, the reaction stopped by the addition of 10% sulphuric acid, absorbance measured at 450nm using a SOFTmax PRO (Molecular Devices, CA, USA) and the endpoint dilution was determined. Total IgE was detected in the plasma of infected mice by capture ELISA as previously described [12], using R35–72 capture IgE mAb (BD Biosciences)

Flow cytometry

Draining lymph node cells were activated for 4 hours with 50 ng ml⁻¹ PMA and 500 ng ml⁻¹ Ionomycin (both Sigma-Aldrich) along with GolgiPlug (BD Biosciences). Following stimulation, cells were harvested and washed, resuspended in FACSc Buffer containing Fc Block (2.4G2 hybridoma supernatant) together with the appropriate combinations of the following antibodies: CD4-APC, CD8-PerCP or B220-FITC (all from BD Biosciences). Intracellular cytokine staining was carried out using PE-conjugated anti-IL-4 or IFN-γ with Cytofix/Cytoperm solution (all from BD Biosciences). Data was obtained using FACScanto (BD Bioscience) and analysed using FlowJo (Tree Star Inc., CA, USA).

Statistical analysis

Antibody analysis was performed using the Mann-Whitney U test and all other analysis used an unpaired Student’s t test.

Results

IL-4Rx signaling via macrophages/neutrophils plays little role in the susceptibility of BALB/c mice to *L. mexicana*

To compare the progression of *L. mexicana* lesion growth in LysM<sup>cre/lox</sup>IL-4Rx<sup>+</sup> mice with IL-4Rx<sup>-/lox</sup> littermate control and global IL-4Rx<sup>−/−</sup> mice, animals were infected with 5 x 10<sup>6</sup> amastigotes into the shaven base of the tail. While no discernible lesions were identified in infected global IL-4Rx<sup>−/−</sup> mice, as previously demonstrated [6], rapidly growing non-healing lesions were observed in both LysM<sup>cre/lox</sup>IL-4Rx<sup>+/lox</sup> and IL-4Rx<sup>-/lox</sup> mice (Figure 1A). Parasite burdens were also similar in LysM<sup>cre/lox</sup>IL-4Rx<sup>−/lox</sup>, and IL-4Rx<sup>-/lox</sup> mice and significantly higher (p<0.0001) than those recorded from global IL-4Rx<sup>−/−</sup> animals (Figure 1B). In line with the non-healing progressive disease phenotype displayed by macrophage/neutrophil IL-4Rx<sup>−/−</sup> mice, parasite antigen induced spleen cell IFN-γ production was similar to IL-4Rx<sup>-/lox</sup> mice and significantly less (p<0.01) than that of global IL-4Rx<sup>−/−</sup> mice (Figure 1C). Antigen induced spleenocyte IL-4 production was similar in all 3 strains (Figure 1D), demonstrating once again that IL-4 induction can be independent of IL-4Rx signaling [6,14–16]. Further studies demonstrated that the close similarities in the disease phenotypes of LysM<sup>cre/lox</sup>IL-4Rx<sup>−/lox</sup> and IL-4Rx<sup>-/lox</sup> mice were independent of site, dose of inoculum, and life cycle stage initiating infection (data not shown). These data suggest that the expression of IL-4Rx by a macrophage/neutrophil population is not important in determining susceptibility to *L. mexicana* infection.

IL-4Rx signaling via CD4<sup>+</sup> T cells is essential for progressive non-healing disease following infection with *L. mexicana*

In subsequent studies, infection of CD4<sup>+</sup> T cell specific (Lck<sup>cre/lox</sup>IL-4Rx<sup>-/lox</sup>) IL-4Rx<sup>−/−</sup> mice with 5 x 10<sup>6</sup> *L. mexicana* amastigotes into the shaven base of the tail resulted in control of the lesion growth observed in control IL-4Rx<sup>-/lox</sup> mice (wild-type equivalent). Interestingly, in one experiment using male mice, lesions in Lck<sup>cre/lox</sup>IL-4Rx<sup>-/lox</sup> mice did not heal completely, while experiments utilizing female mice fully resolved (Figure S1). Consequently, to confirm and further investigate this apparent gender-dependent difference in control of *L. mexicana* infection male and female Lck<sup>cre/lox</sup>IL-4Rx<sup>-/lox</sup>, control IL-4Rx<sup>-/lox</sup>, and global IL-4Rx<sup>-/−</sup> mice were infected in parallel with 5 x 10<sup>6</sup> *L. mexicana* amastigotes into the shaven base of the tail (Figure 2A–D). While infected global IL-4Rx<sup>−/−</sup> mice displayed a non-lesion growth phenotype, lesion growth was progressive in control IL-4Rx<sup>-/lox</sup> mice (Figure 2A and B). These disease phenotypes were independent of gender. By comparison *L. mexicana* infected female CD4<sup>+</sup> T cell specific (Lck<sup>cre/lox</sup>IL-4Rx<sup>-/lox</sup>) IL-4Rx<sup>−/−</sup> mice developed lesions which completely healed after 4–5 weeks (Figure 2A), while male CD4<sup>+</sup> T cell specific (Lck<sup>cre/lox</sup>IL-4Rx<sup>-/lox</sup>) IL-4Rx<sup>−/−</sup> mice developed lesions which failed to fully heal (Figure 2B). Indeed in agreement with lesion size parasite burdens up until week 6 were similar in both male Lck<sup>cre/lox</sup>IL-4Rx<sup>-/lox</sup> and IL-4Rx<sup>-/lox</sup> mice (Figure S2).

Parasite numbers at the termination of the study at week 12 were of a similar order of magnitude in both female and male control IL-4Rx<sup>-/lox</sup> mice while global IL-4Rx<sup>−/−</sup> mice of both sexes were equally able to control infection with *L. mexicana* (Figure 2C and D). By contrast while infected CD4<sup>+</sup> T cell specific (Lck<sup>cre/lox</sup>IL-4Rx<sup>-/lox</sup>) IL-4Rx<sup>−/−</sup> mice of both sexes were able to significantly control parasite growth (p<0.0001 and p<0.01 respectively for female and male mice), male mice (Figure 2D) were significantly limited in this ability and had significantly higher parasite burdens (p<0.001) than female mice (Figure 2C).

IL-4Rx signaling via CD4<sup>+</sup> T cells inhibits the production of a specific Th1 response following infection with *L. mexicana*

*L. mexicana* infection of CD4<sup>+</sup> T cell specific (Lck<sup>cre/lox</sup>IL-4Rx<sup>-/lox</sup>) IL-4Rx<sup>−/−</sup> mice resulted in an enhanced Th1 response in both male and female Lck<sup>cre/lox</sup>IL-4Rx<sup>-/lox</sup> mice compared with control IL-4Rx<sup>-/lox</sup> mice, as demonstrated by significantly enhanced antigen induced splenocyte IFN-γ production (Figure 3A and B; p<0.025 for females; p<0.01 for males). As previously described, antigen stimulated splenocyte IFN-γ production from infected global IL-4Rx<sup>−/−</sup> mice was significantly higher than for wild-type equivalent (IL-4Rx<sup>-/lox</sup>) mice and this was true whether examining female or male mice (p<0.02). Antigen stimulated splenocytes from infected female but not male Lck<sup>cre/lox</sup>IL-4Rx<sup>-/lox</sup> mice produced significantly more IFN-γ than antigen stimulated splenocytes from infected global IL-4Rx<sup>−/−</sup> animals. An expanded Th1 response was also indicated by enhanced antigen specific IgG2a production compared with control IL-4Rx<sup>-/lox</sup> mice, and in magnitude similar to that generated by global IL-4Rx<sup>−/−</sup> mice (Figure 3C and D). However, while specific IgG2a production in the absence of IL-4Rx signaling via CD4<sup>+</sup> T cells in female Lck<sup>cre/lox</sup>IL-4Rx<sup>-/lox</sup> mice was significantly greater (p<0.025) than in...
infected control IL-4Rα−/lox mice as early as week 6 post-infection (Figure 3C) it was not until week 12 post-infection that male LckcreIL-4Rα−/lox mice were producing significantly more IgG2a (p<0.025) than their infected control IL-4Rα−/lox counterparts (Figure 3D). Similar results were recorded in 3 separate experiments.

IL-4Rα signaling via CD4+ T cells promotes the induction of a Th2 response following infection with L. mexicana differentially in male and female mice

A clear dichotomy in antigen-induced splenocyte IL-4 production was identified between infected female and male LckcreIL-4Rα−/lox mice both compared with each other and compared with their wild-type equivalent counterparts (Figure 4A and B). Splenocyte IL-4 production was barely detectable in female LckcreIL-4Rα−/lox mice, and significantly less than IL-4 production by male LckcreIL-4Rα−/lox mice (p<0.01). On the other hand, antigen induced splenocyte IL-4 production was similar in all infected male mice, independent of IL-4Rα expression (Figure 4B). Similar results were obtained with another Th2 cytokine, IL-5 (Figure 4C and D), as well as IL-10 (Figure 4E and F), with production of both cytokines significantly lower in female but not male LckcreIL-4Rα−/lox compared with similarly infected sex matched control IL-4Rα−/lox mice. Similarly, Th2 associated antigen specific IgG1 production was significantly less in infected female (p<0.05 week 12) but not infected male LckcreIL-4Rα−/lox mice compared with their respective control IL-4Rα−/lox counterparts (Figure S2). Minimal IgG1 production was detected in the serum of infected global IL-4Rα−/lox mice. Total IgE levels in infected female and male LckcreIL-4Rα−/lox mice were similar.

Figure 1. IL-4Rα deficiency in macrophages/neutrophils does not influence L. mexicana growth or the immune response. Mean lesion growth (Figure 1A), parasite burdens (Figure 1B), and L. mexicana antigen induced (25 μg/ml) splenocyte IFN-γ (Figure 1C), and IL-4 (Figure 1D) produced from IL-4Rα intact (IL-4Rα−/lox), macrophage/neutrophil specific (LysMcreIL-4Rα−/lox) IL-4Rα−/−, and global IL-4Rα−/− mice infected subcutaneously with 5×10⁶ amastigotes of L. mexicana. At 12 weeks post infection parasite burdens were significantly less in IL-4Rα−/− mice than IL-4Rα−/lox or LysMcreIL-4Rα−/lox mice (**p<0.0001) and IFN-γ production significantly greater (**p<0.01). Results are mean +/- s.e. 5 mice. Representative of 3 independent experiments. doi:10.1371/journal.pntd.0000930.g001
Figure 2. IL-4Rα deficiency in CD4+ T cells enables control of L. mexicana parasite growth. Mean lesion growth (Figure 2A and B) and parasite burdens at week 12 (Figure 2C and D) in female (Figure 2A and C) and male (Figure 2B and D) IL-4Rα intact (IL-4Rα+/lox), CD4+ T cell specific (LckcreIL-4Rα+/lox) IL-4Rα+/−, and global IL-4Rα+/− mice infected sub-cutaneously with 5×10⁶ amastigotes of L. mexicana. Results are mean ± s.e. 5 mice. Representative of 4 separate experiments. Parasite burdens in IL-4Rα+/− male and female mice were significantly less than IL-4Rα intact mice (**p<0.0001) for both male and female mice. Parasite burdens were also significantly less in male and female CD4+ T cell specific IL-4Rα+/− compared with IL-4Rα intact mice (****p<0.0001) for females and (**p<0.01) for males. Male CD4+ T cell specific IL-4Rα+/− had significantly higher parasite burdens than females on the same background (p<0.001).
doi:10.1371/journal.pntd.0000930.g002

Discussion

We have previously demonstrated that signaling via IL-4Rα plays the major role in the non-healing response of BALB/c mice following infection with L. mexicana [6] and that IL-4Rα+/− mice, unlike their wild-type counterparts that produce progressively growing non-healing lesions, display a non-lesion growth disease phenotype associated with an enhanced type-1 response. In the course of the present study using macrophage/neutrophil specific IL-4Rα−/− mice (LysMcreIL-4Rα−/−) we failed to identify any significant role for IL-4Rα signaling via macrophages/neutrophils in the normal non-healing response of BALB/c mice infected with L. mexicana. In contrast, following early lesion growth, CD4+ T cell specific IL-4Rα−/− mice were able to inhibit disease progression. However, while lesions in female CD4+ T cell specific IL-4Rα−/− mice healed those in male CD4+ T cell specific (LckcreIL-4Rα−/−) IL-4Rα−/− mice.
Persisted. Furthermore, although both female and male CD4$^+$ T cell specific (LckcreIL-4R$^\alpha_{2/lox}$) IL-4R$^\alpha_{2/2}$ mice had significantly enhanced type-1 responses compared with IL-4R$^\alpha_{2/2}$ intact (IL-4R$^\alpha_{2/2}$) mice, male CD4$^+$ T cell specific (LckcreIL-4R$^\alpha_{2/lox}$) IL-4R$^\alpha_{2/2}$ mice maintained strong type-2 responses compared with their female counterparts.

Although signaling via IL-4R$^\alpha$ plays a significant role in the outcome of infection with *L. mexicana* as well as *L. major* [6,8–9,15] the cell targets for IL-4/IL-13 activity and whether they promote or inhibit the disease process differ significantly between species.

Figure 3. IL-4R$^\alpha$ deficiency in CD4$^+$ T cells results in enhanced Th1 responses after *L. mexicana* infection. *L. mexicana* antigen induced (10 μg/ml) splenocyte IFN-γ (Figure 3A and B), and 6 and 12 week serum IgG2a levels (Figure 3C and 3D) produced from female (Figure 3A and C) and male (Figure 3B and D) IL-4Rx intact (IL-4R$^\alpha_{2/2}$), CD4$^+$ T cell specific (LckcreIL-4R$^\alpha_{2/lox}$) IL-4R$^\alpha_{2/2}$, and global IL-4R$^\alpha_{2/2}$ mice infected subcutaneously with $5\times10^6$ amastigotes of *L. mexicana*. *p<0.05, **p<0.01 compared with IL-4R$^\alpha$ intact mice. Representative of 4 separate experiments.

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IL-4Rx<sup>CD4</sup> T Cells Promote *Leishmania mexicana*
infected with arginase null mutant \textit{L. mexicana} parasites while pharmacological inhibition of arginase during \textit{L. major} infection did not inhibit the Th2 immune response [22].

CD4$^+$ T cell specific (Lck$^{cre}$IL-4R$\alpha^{2/loxp}$) IL-4R$\alpha^{-/-}$ mice are more resistant than global IL-4R$\alpha^{-/-}$ mice to infection with \textit{L. major}, indicating that in the absence of a polarized Th2 response, there is a role for an IL-4/IL-13 responsive non-CD4$^+$ T cell in early resistance to infection [9]. Conversely CD4$^+$ T cell specific (Lck$^{cre}$IL-4R$\alpha^{2/loxp}$) IL-4R$\alpha^{-/-}$ mice are more susceptible than global IL-4R$\alpha^{-/-}$ mice to infection with \textit{L. mexicana}, indicating a role for an IL-4/IL-13 responsive non CD4$^+$ T cell population in early susceptibility. We have now studied the course of \textit{L. mexicana} infection in newly generated iLck$^{cre}$IL-4R$\alpha^{2/loxp}$ female and male mice that have IL-4R$\alpha$ deleted on all T cell populations [23]. These produce the same disease and immunological phenotypes as CD4$^+$ T cell specific (Lck$^{cre}$IL-4R$\alpha^{2/loxp}$) IL-4R$\alpha^{-/-}$ mice (data not shown). Consequently IL-4 responsive CD8$^+$ T cells do not play a role in early susceptibility or the non-healing response following infection with \textit{L. mexicana}. Studies utilizing macrophage specific BALB/c IL-4R$\alpha^{-/-}$ mice have demonstrated that IL-4/IL-13 operates through this population to enhance \textit{L. major} parasite growth via alternative macrophage activation [8] and consequently these are unlikely to be the population driving a Th1 response in CD4$^+$ T cell specific (Lck$^{cre}$IL-4R$\alpha^{2/loxp}$) IL-4R$\alpha^{-/-}$ mice. However, IL-4 treatment of BALB/c mice prior to T cell priming has previously been demonstrated to instruct dendritic cells to produce IL-12 and facilitate a protective Th1 response against \textit{L. major} [24] and is required for protective type-1 responses to \textit{Candida} [25]. In addition IL-13 is able to prime monocytes for IL-12 production[26], which is also observed in listeriosis [27].

![Figure 4. IL-4R$\alpha$ deficiency in CD4$^+$ T cells results in decreased specific Th2 responses in female mice. \textit{L. mexicana} antigen induced (10 $\mu$g/ml) splenocyte IL-4 (Figure 4A and B), IL-5 (Figure 4C and D) and IL-10 (Figure 4E and F) produced from female (Figure 4A, C and E) and male (Figure 4B, D and F) IL-4R$\alpha$ intact (IL-4R$\alpha^{-/-}$), CD4$^+$ T cell specific (Lck$^{cre}$IL-4R$\alpha^{2/loxp}$) IL-4R$\alpha^{-/-}$, and global IL-4R$\alpha^{-/-}$ mice infected sub-cutaneously with 5 x 10$^6$ amastigotes of \textit{L. mexicana}. *$p<0.05$, **$p<0.01$ compared with IL-4R$\alpha$ intact mice. Representative of 4 separate experiments. doi:10.1371/journal.pntd.0000930.g004](https://www.plosntds.org/doi/10.1371/journal.pntd.0000930.g004)
Figure 5. IL-4Rα deficiency in CD4+ T cells results in decreased non-specific Th2 responses in female mice. ConA and anti-CD3 induced (10 μg/ml) splenocyte IL-4 produced from female (Figure 5A) and male (Figure 5B) IL-4Rα intact (IL-4Rα+/lox), CD4+ T cell specific (LckcreIL-4Rα+/lox) IL-4Rα−/−, and global IL-4Rα−/− mice infected sub-cutaneously with 5 × 10^6 amastigotes of L. mexicana 12 weeks previously. *p<0.05, **p<0.01 compared with IL-4Rα intact mice. IL-4 production from female LckcreIL-4Rα−/lox mice was significantly less than similarly treated male LckcreIL-4Rα−/lox mice (p<0.02 for ConA and p<0.05 for anti-CD3 respectively). Results are mean±s.e. of 5 mice. Representative of 2 separate experiments.

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Furthermore both IL-4 and IL-13 promote CD40L-induced IL-12 production in macrophages and dendritic cells [28]. This would indicate that dendritic cells may be the IL-4/IL-13 responsive cells facilitating protection against L. major in the absence of IL-1Rα responsive CD4+ T cells in BALB/c mice. As no distinct disease phenotype could be discerned in macrophage/neutrophil specific (Ly6M+/−IL-4Rα−/lox) IL-4Rα−/− mice compared with IL-4Rα intact animals infected with L. mexicana, no IL-4/IL13 responsive non-T cell population can easily be ruled out in promoting early infection against this parasite. While a role for B cells and antibody production in the non-healing response to infection against this parasite is well established (as reviewed in [29–30]), the fact that IL-4Rα−/− BALB/c mice are more resistant to this parasite than IL-4−/− mice suggests that IL-13 responsive cells and consequently non-lymphoid cells via IL-4Rα signaling play a role in disease susceptibility during L. mexicana infection [6].

Unlike the epidemiological and experimental reports on L. major and L. tropica which identify females as more susceptible, females are more resistant than males to cutaneous infection with L. mexicana (humans and mice) [5,12,31–33] and visceral leishmaniasis caused by L. donovani (humans) [34–35] or L. infantum (dogs) [36]. Female DBA/2 mice infected with L. mexicana develop much stronger Th1 responses, as measured by IFN-γ production, delayed-type hypersensitivity and IgG2a antibody levels, than similarly infected male mice [12,32]. Similarly, in humans infected with L. mexicana, females generally have increased Th1 responses as measured by DTH reactions and decreased Th2 responses as measured by IgE production than males [33]. The present studies using CD4+ T cell specific IL-4Rα−/− BALB/c mice have revealed a previously undetected, underlying male susceptibility to L. mexicana involving T cells. Thus, unlike female mice, male mice were unable to resolve infection and overall had a less polarized Th1 response and more polarized Th2 than their female counterparts. This was associated with IL-4 production independently of IL-4Rα signaling in male but not female CD4+ T cell specific (LckcreIL-4Rα−/lox) IL-4Rα−/− BALB/c mice. The L. mexicana induced IL-4 producing Th2 phenotype in male LckcreIL-4Rα−/lox BALB/c mice was not the result of differential Cre-mediated deletion efficiency of IL-4Rα in male mice as compared with female mice, as no CD4+ T cell population expressing IL-4Rα was detected from either gender (data not shown). While IL-4 production independently of IL-4Rα signaling has been observed in a number of immunological models previously [6,14–15] this is the first time a sex associated influence on this ability has been identified. How significant this could be with regard to the numerous gender related differences observed in inflammatory and infectious diseases is an intriguing question but outside the scope of the present study.

To conclude in this study utilising tissue specific IL-4Rα−/− mice we demonstrate that upon infection with L. mexicana initial lesion growth is dependent on a non-CD4+ T cell population responsive to IL-4/IL-13, while progressive infection is dependent on CD4+ T cells responsive to IL-4. Furthermore whether lesions heal or not is gender determined, suggesting a subtle but
significant effect of sex hormones on CD4+ T cell function whereby infected male but not female CD4+ T cell specific IL-4Rα-/- mice can drive IL-4 production independently of IL-4Rα signaling.

Supporting Information

Figure S1  Female but not male T cell specific IL-4Rα-/- mice heal following L. mexicana infection. Mean lesion growth (Figure 1A and B) in female (Figure 1A) and male (Figure 1B) IL-4Rα intact (IL-4Rα+/lox), CD4+ T cell specific (Lckcre IL-4Rα+/lox) IL-4Rα-/-, and global IL-4Rα-/- mice infected sub-cutaneously with 5 x 10⁶ amastigotes of L. mexicana. These are the results from 2 separate experiments carried out at different times the first using females (Figure 1A), the second using males (Figure 1B). While lesions healed in female CD4+ T cell specific (Lckcre IL-4Rα+/lox) mice they persisted in male CD4+ T cell specific (Lckcre IL-4Rα+/lox). Results are mean+/− s.d. 5 mice. Representative of 2 separate experiments.

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Figure S2  Similar parasite burdens in wild-type and T cell specific IL-4Rα-/- male mice 6 weeks post-infection. Mean lesion parasite burden ± s.e. at week 6 post-infection in male IL-4Rα intact (IL-4Rα+/lox), and CD4+ T cell specific (Lckcre IL-4Rα+/lox) IL-4Rα-/- mice infected sub-cutaneously with 5 x 10⁶ amastigotes of L. mexicana.

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Figure S3 Less IgG1 production in infected female T cell specific IL-4Rα−/− mice. L. mexicana-specific IgG1 levels (Figure, 2A and B) and total IgE levels (Figure, 2C and D) in female (Figure 2A and C) and male (Figure 2B and D) IL-4Rα intact (IL-4Rα+/+), CD4 T cell specific (LckcreIL-4Rα+/+), IL-4Rα−/−, and global IL-4Rα−/− mice infected sub-cutaneously with 5×10⁶ amastigotes of L. mexicana. *p<0.05, and ***p<0.001 compared with IL-4Rα intact mice. Representative of 4 separate experiments.

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Author Contributions
Conceived and designed the experiments: FB JA. Performed the experiments: KJB ORM TM HAM JA. Analyzed the data: KJB ORM HAM JA. Contributed reagents/materials/analysis tools: FB JA. Wrote the paper: ORM FB JA.

References