**Toxoplasma Polymorphic Effectors Determine Macrophage Polarization and Intestinal Inflammation**

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**SUMMARY**

European and North American strains of the parasite *Toxoplasma gondii* belong to three distinct clonal lineages, type I, type II, and type III, which differ in virulence. Understanding the basis of *Toxoplasma* strain differences and how secreted effectors work to achieve chronic infection is a major goal of current research. Here we show that type I and III infected macrophages, a cell type required for host immunity to *Toxoplasma*, are alternatively activated, while type II infected macrophages are classically activated. The *Toxoplasma* rhoptry kinase ROP16, which activates STAT6, is responsible for alternative activation. The *Toxoplasma* dense granule protein GRA15, which activates NF-κB, promotes classical activation by type II parasites. These effectors antagonistically regulate many of the same genes, and mice infected with type II parasites expressing type I ROP16 are protected against *Toxoplasma*-induced ileitis. Thus, polymorphisms in determinants that modulate macrophage activation influence the ability of *Toxoplasma* to establish a chronic infection.

**INTRODUCTION**

*Toxoplasma gondii* is an obligate intracellular parasite capable of infecting a wide range of mammalian hosts including humans. Most *Toxoplasma* strains isolated in Europe and North America belong to just three distinct clonal lineages, the type I, II, and III strains. These strains differ in virulence in mice and likely cause different sequelae in humans (Boothroyd and Grigg, 2002). *Toxoplasma* effectors secrete molecules from two secretory organelles, rhoptries and dense granules, into the host cytosol which modulate host signaling pathways and dictate virulence (Reese et al., 2011; Rosowski et al., 2011; Saeij et al., 2006, 2007; Taylor et al., 2006). A major aim in the field is to understand the genetic basis underlying *Toxoplasma* strain differences in virulence and how secreted effector molecules work to achieve chronic infection for the parasite.

A possible strategy to establish a chronic infection is through the modulation of the host’s Th1 response, which culminates in the production of IFN-γ, the main mediator of resistance against *Toxoplasma*. However, the Th1 response must also be tightly regulated, otherwise a lethal inflammatory response develops. For example, mice lacking the regulatory cytokines IL-10 or IL-27 die of severe immune pathology when infected with type II strains (Gazzinelli et al., 1996; Stumhofer et al., 2006). Th1 type cytokines (e.g., IFN-γ) synergize with pattern recognition receptors on macrophages to signal for the classical activation (or M1) of macrophages, which exert antimicrobial functions against intracellular pathogens and require the activity of NF-κB, IRF, and C/EBPβ transcription factors (Medzhitov and Hong, 2009). Macrophages are necessary for host protection to *Toxoplasma* (Dunay et al., 2008), and the IL-12 response by infected macrophages is greatly influenced by the strain type (Robben et al., 2004). The molecular mechanism underlying parasite strain differences in proinflammatory cytokine induction by macrophages has not been resolved.

In contrast, alternatively activated macrophages (or M2) develop in a Th2 cytokine environment (IL-4, IL-13) and are inhibited by Th1 type cytokines (Martinez et al., 2009). M2 macrophages secrete anti-inflammatory molecules that can downregulate Th1 immune processes and are important in the immune response against worm infections. M2 activation is promoted by STAT6 and PPARγ transcription factors (Odegard et al., 2007), and mice deficient in IL-4, a potent mediator of M2 polarization, are more susceptible to acute *Toxoplasma* infection (Roberts et al., 1996). IL-4 treatment, as well as TLR stimulation (El Kasmi et al., 2008), alters L-arginine metabolism in macrophages through the induction of the arginase enzyme. L-arginine and the arginase catabolite ornithine can be scavenged by parasites to generate ATP (Cook et al., 2007) and assist their replication (Iniestra et al., 2001). Thus, the ability of *Toxoplasma*, or other protozoan parasites, to induce specific macrophage activation states could have immediate consequences on virulence, local parasite burden, and inflammatory-related pathologies.

Given that *Toxoplasma* elicits a strong Th1 response, it is not known whether the parasite actively counteracts collateral damage following inflammation or if there are strain differences in such a response. In this report, we show that mouse macrophages infected with type I and III *Toxoplasma* strains are
polarized toward an M2 activation state, while type II infected macrophages resemble aspects of M1 activation. This difference is due to polymorphisms in the Toxoplasma rhoptry kinase ROP16 and dense granule protein GRA15, which activate STAT6 and NF-κB signaling pathways, respectively. Finally, type II strains that express ROP16 from the type I strain fail to cause intestinal inflammation in susceptible C57BL/6 (B6) mice. This report provides direct evidence that Toxoplasma-infected macrophages can be alternatively activated, and describes parasite-specific factors that work independently of pattern recognition receptors to achieve M1 or M2 activation.

RESULTS

**Toxoplasma Type I and III Strains Induce M2 Activation, while the Type II Strain Induces M1-like Cells**

Toxoplasma strain differences in the modulation of host cells at the site of infection might lead to variation in their ability to disseminate, replicate, or survive. In agreement with an earlier report studying the type I and II strains (Mordue and Sibley, 2003), we observed that all three strains equally infected macrophages during the first 3 days of intraperitoneal (i.p.) infection, and this cell type accounted for approximately 60% of the total infected peritoneal exudate cells (PECs) (see Figure S1 available online). Neutrophils were the next most abundant cell type infected by Toxoplasma (15% of the total infected PECs). However, it was the macrophage that provided a niche permissive for parasite replication, because when compared to neutrophils they exhibited a higher GFP intensity (parasites express GFP) (Figure S1) and had more parasites per vacuole when FACS sorted and analyzed under a microscope (≥ 4 compared to 1 parasite per parasitophorous vacuole, macrophages versus neutrophils, data not shown). No differences were observed in cellular recruitment, or infectivity of these or other cell types, over the first 3 days of infection (Figure S1, data not shown).

These observations suggest that parasite differences in virulence might be due in part to how these strains modulate or interact with macrophages. To explore this further, two mouse macrophage cell lines, RAW264.7 and J774, were infected with either the type II or III strain, and gene expression profiles were analyzed by oligonucleotide arrays 18 hr after infection. Dendritic cells are an important link between the innate and adaptive T cell response by infected BMDMs as determined by ELISA (Figure 1D). Not all aspects of M1 activation were observed in type II infected cells (Table 1), compared to LPS/IFN-γ-stimulated infection. Although we found iNOS message (Table 1), compared to LPS/IFN-γ-stimulated BMDMs, infection with the type II strain induced a small but significant increase of arginase activity compared to noninfected cells.

In contrast, the type II strain induced the expression of genes that are associated with the M1 phenotype, including many proinflammatory cytokines (Table 1). As has been previously noted (Robben et al., 2004), compared to other strain types, the type II strain highly induces the expression of transcripts for the proinflammatory cytokines IL-1β, IL-6, and IL-12p40/35 in infected bone marrow-derived macrophages (BMDMs). Our transcriptional profiling largely confirmed these results, and also suggested that IL-23 was consistently induced by the type II strain in all three cell lines tested (Table 1). In agreement with these observations, the type II strain, but not the type I or III strains, elicited a strong IL-23 (p40/p19) and IL-12 (p40/p35) response by infected BMDMs as determined by ELISA (Figure 1D). Not all aspects of M1 activation were observed in type II infected cells. For example, M1 cells are known to produce high amounts of reactive oxygen and nitrogen intermediates. Although we found iNOS message (Nos2) to be enriched in type II infected cells (Table 1), compared to LPS/IFN-γ-stimulated BMDMs, infection with the type I, II, or III strains generated little to no amounts of nitric oxide (NO) (data not shown). The inability of Toxoplasma to directly induce iNOS protein has similarly been observed (Mordue and Sibley, 2003).

**Toxoplasma Rhopty Kinase ROP16 Promotes M2 Activation**

Previously, using human foreskin fibroblasts (HFFs), we demonstrated that the type I and III strains, but not the type II strain,
Table 1. Macrophages and Dendritic Cell Lines Infected with Type II or Type III Parasites Have Gene Expression Profiles Consistent with either a Classical or an Alternative Activation Program

<table>
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<th>Gene Symbol</th>
<th>Type II versus Type III Fold Change</th>
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<th>DC</th>
<th>J774</th>
<th>Average ALT/CLASS</th>
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Gene symbols are depicted for a subset of genes (36 out of 184) that were similarly regulated in a strain-specific manner (at least 2-fold average difference) between the mouse macrophage cell lines RAW264.7 and J774, and the DC2.4 dendritic cell line. The fold difference in expression comparing type II and III infected cells is indicated, where positive numbers indicate the fold increase in type II over III infection and negative values indicate the fold increase of type III over type II infections. Genes were grouped according to their expression level in either alternatively or classically activated macrophages (Biswas and Mantovani, 2010; Gordon, 2003; Martinez et al., 2006, 2009). ND indicates that the gene was not detected above background in that particular cell type. The experiment was performed in duplicate. See also Figure S2 and Table S1 for molecular pathway and TFBSs analysis of these gene sets, respectively.

Constitutively activate STAT6, a difference due to polymorphisms in the secreted Toxoplasma rhoptry kinase ROP16 (Saeij et al., 2007). Furthermore, ROP16 can directly phosphorylate the critical Y641 residue required for STAT6 activation (Ong et al., 2010), thus making ROP16 a likely candidate driving strain differences in M2 activation. To investigate this further, we analyzed whether a type I strain that has the ROP16 gene deleted (type I Δrop16) (Ong et al., 2010) can induce M2 cells. Unlike wild-type type I (and III) strains, the type I Δrop16 strain failed to induce the expression of any of the M2-associated markers (arginase, CD206, and Mgl2) (Figure 2), which correlated with its inability to phosphorylate STAT6 at any time point investigated (0.5, 1, 2, 4, 8, and 18 hr, data not shown; 24 hr shown in Figures 2C and 2D).

Gene expression profiling of BMDMs infected with the type I or type I Δrop16 strains indicated that ROP16 controlled the expression (≥2-fold) of 538 unique annotated genes. Indeed, the most differentially regulated genes were those associated with the M2 phenotype, with Arg1 at the top of the list of ROP16-induced genes (132-fold) (Table S2A). Other M2 markers including Cd206, Mgl2, and Cdh1 (E-cadherin) were also dependent on ROP16. Surface receptors that were induced by ROP16 were confirmed by FACS, which included the B7 family members (Pdcd1lg2) and B7-H1 (Cd274), as well as the C-type lectin Dectin-1 (Clec7a) (Figure 2E). The M2 signature could clearly be seen in a TFBS analysis of ROP16-regulated genes, which implicated STAT6 and other M2 transcriptional regulators (Table S2B). In summary, the M2 activation program induced by Toxoplasma is controlled by ROP16.

To confirm that ROP16-mediated differences in macrophage activation occur in vivo, we infected BALB/c mice i.p. with type I, type II, or type I Δrop16 parasites and stained for phospho-STAT6 (Figures 2F and 2G). These data show that strain-specific induction of M2 cells is apparent in vivo and that the rhoptry kinase ROP16 plays a fundamental role in this process.

Toxoplasma Dense Granule Protein GRA15 Promotes M1 Activation

Recently, we identified a dense granule protein GRA15, encoded by the type II strain (GRA15b), that is secreted into the host cytosol and causes the activation and nuclear translocation of host p50/REL-A NF-κB heterodimers (Rosowsky et al., 2011). Furthermore, GRA15b accounted for most of the IL-12p40 response by infected macrophages in vitro, which prompted us to explore in greater detail the role of GRA15b in M1 activation. Therefore, gene expression profiles of type II and type II Δgra15-infected BMDMs were analyzed. Genes that were dependent (≥2-fold) on the expression of Toxoplasma GRA15 were those typically induced in M1 cells (Table S3A) and included many proinflammatory cytokines (Il12a, Il6, Il12a, Il12b, Il1a, and Tnf), ligands for T cell costimulatory receptors (Cd40, Cd80, Cd70, Tnfsf9, and Tnfsf4), NF-κB modulators (Nfkbi1e, Nfkbi1b, Nfkbi2),
and some of the M1-associated chemokines (Cxcl1 and Cxcl11). Transcripts for Il10 and the IL-27/35 subunit Ebi3, which are necessary to prevent inflammatory damage following Toxoplasma infection (Gazzinelli et al., 1996; Stumhofer et al., 2006), were also highly dependent on the expression of GRA15II (Table S3A). Interestingly, Il23a was the most differentially regulated gene transcript between these stains (58-fold), and secretion of IL-23 (p40/19), IL-12 (p40/35), and IL-10 by infected BMDMs was entirely dependent on the expression of type II GRA15 (Figure 3C). TFBS analysis of the 710 genes that were regulated by GRA15II also revealed a significant enrichment of TFBSs for transcription factors known to be activated in M1 macrophages (Medzhitov and Horng, 2009), which include NF-κB, IRF, C/EBP, PU1, and ATF (Table S2B). GRA15II also repressed many genes that are associated with M2 activation (Mrc1, Mgl1, Ccl24, Ear11, Ptgs1) (Table S3A). In particular, PPARG, which encodes a transcription factor that promotes M2 activation (Odegaard et al., 2007), was the gene most repressed by GRA15II. In summary, many aspects of M1 activation by the type II strain were largely controlled by GRA15.

Inducing the M2 Phenotype with Type II-Engineered Parasites
To test whether a simple combination of GRA15 and ROP16 will determine the M1/M2 phenotype of infected macrophages, a series of type II parasites was generated that expressed or lacked the STAT3/6- and/or NF-κB-activating versions of these genes. Gene expression profiles, proinflammatory cytokine secretion, and arginase activity of BMDMs infected with type II, type II +ROP16I, type II Δgra15, and type II Δgra15 +ROP16I parasites were analyzed. Type II +ROP16I-infected macrophages possessed significantly higher arginase activity than type II infected RAW264.7 cells (data not shown) and BMDMs (Figure 3B), but lower than the response elicited by the type III
Figure 2. Toxoplasma-Secreted Rhoptry Kinase ROP16 Mediates Alternative Macrophage Activation

(A) RAW264.7 macrophages were mock infected (control) or infected (moi = 5) with type I, type I Δrop16, or type II parasites, and 24 hr later arginase activity was determined (Student’s t test, *p < 0.05, type I versus type I Δrop16 or type II). Error bars, ±SD.

(B) As in (A), except the macrophages were fixed and stained with antibodies to the parasite surface antigen SAG-1 (green) and the M2 markers CD206 or mMgl. Hoechst dye was used to stain nuclei (blue).

(C) Western blot of infected RAW264.7 cell lysates using antibodies against mMgl1/2, tyrosine-phosphorylated STAT6 (pSTAT6), or total STAT6. Antibodies against GAPDH and SAG-1 were used for host cell and parasite loading controls, respectively.

(D) One day after infection with the indicated strain types, RAW264.7 macrophages were fixed, permeabilized, and stained with antibodies against pSTAT6 and SAG-1. Nuclei were stained with Hoechst (blue).

(E) BMDMs were infected with GFP-expressing type I or type I Δrop16 parasites and stained with PE-labeled antibodies to the surface receptors B7-H1 (PD-L1), B7-DC (PD-L2), Dectin-1 (Clec7a), or CD86 (which is not regulated by ROP16). Histogram plots depict the relative surface expression of these markers on infected GFP+ (black lines) and noninfected GFP- (blue lines) BMDMs in the same well. Isotype staining with Rat IgG2a antibodies is also shown (shaded histogram).

(F) BALB/c mice were infected i.p. with type I, type I Δrop16, or type II parasites. Twenty-one hours postinfection, PECs were harvested and stained for CD11b and the SAG-1 parasite surface antigen. Infected (toxo+) and uninfected (toxoneg) CD11b+ PECs were analyzed for their expression of pSTAT6 or CD206 by histogram (gray, “minus one” staining control, where cells are stained with all staining reagents except the anti-STAT6 or CD206 primary antibodies; red, type I; blue, type II; green, type I Δrop16; black, PECs from an uninfected mouse stimulated with recombinant murine IL-4 for 10 min at 37°C). Data are representative of two independent experiments (n = 3).

(G) Bar graphs depict the percentage of positively staining CD11b+ PECs as analyzed in (F) (KO, type I Δrop16). N.D., not detected. Error bars, ±SD. ANOVA one-way analysis of variance was used to determine statistical significance. The percentage of infected CD11b+ cells was similar in type I, type II, and type I Δrop16-infected mice (data not shown).

See Table S2A for a list of genes regulated by ROP16, as well as Table S2B for a TFBS analysis of this gene set.
strains, the gene expression profiles of BMDMs in the macrophage arginase response. Importantly, strain differences in urea production were absent in parasites were compared. Indeed, there was significant overlap between ROP16- and GRA15-regulated genes, as many genes were either synergistically or antagonistically regulated by both GRA15 and ROP16 (Table S3B). For example, M1 cytokines that were highly induced by GRA15 were downregulated following type II + ROP16 infection (Figure 3C), likely because ROP16 can inhibit the activation of NF-κB by type II strains (Rosowski et al., 2011). Conversely, many M2 markers were more highly expressed in BMDMs infected with type II Δgra15 + ROP16 than with type II + ROP16, parasites (Figures 3A and 3B), indicating that activation of NF-κB can inhibit the expression of M2 markers, possibly through its effect on PPARγ. Finally, GRA15 and ROP16 retained the ability to induce M1 or M2 markers in polarizing environments in vitro and in vivo (see discussion in Figure S3). Thus, a combination of GRA15 and ROP16 can control macrophage activation along the M1/M2 axis.

Arginase Promotes Toxoplasma Replication

Recently, it was demonstrated that arginase-I expression in macrophages is a susceptibility factor during Toxoplasma infection and that Arg1−/− macrophages produce more NO in response to inflammatory stimuli (El Kasmi et al., 2008). iNOS, like arginase, uses L-arginine as its substrate, but converts it to L-citrulline and NO, which is required for long-term control of Toxoplasma infection (Scharton-Kersten et al., 1997). We therefore investigated whether the induction of arginase by Toxoplasma ROP16 has a similar effect on the production of NO by macrophages. By adding different concentrations of L-arginine to L-arginine-free medium, it was determined that below ~40 mg/L of L-arginine there is a rapid decline in NO production by mouse macrophages stimulated with LPS and IFN-γ (Figure 4A) (commercial DMEM contains 84 mg/L L-arginine, mouse serum

To obtain a complete picture of the macrophage response to these strains, the gene expression profiles of BMDMs infected with type II, type II Δgra15, type II + ROP16, and type II Δgra15 + ROP16 parasites were compared. Indeed, there was significant overlap between ROP16- and GRA15-regulated genes, as many genes were either synergistically or antagonistically regulated by both GRA15 and ROP16 (Table S3B). For example, M1 cytokines that were highly induced by GRA15 were downregulated following type II + ROP16 infection (Figure 3C), likely because ROP16 can inhibit the activation of NF-κB by type II strains (Rosowski et al., 2011). Conversely, many M2 markers were more highly expressed in BMDMs infected with type II Δgra15 + ROP16 than with type II + ROP16, parasites (Figures 3A and 3B), indicating that activation of NF-κB can inhibit the expression of M2 markers, possibly through its effect on PPARγ. Finally, GRA15 and ROP16 retained the ability to induce M1 or M2 markers in polarizing environments in vitro and in vivo (see discussion in Figure S3). Thus, a combination of GRA15 and ROP16 can control macrophage activation along the M1/M2 axis.

Arginase Promotes Toxoplasma Replication

Recently, it was demonstrated that arginase-I expression in macrophages is a susceptibility factor during Toxoplasma infection and that Arg1−/− macrophages produce more NO in response to inflammatory stimuli (El Kasmi et al., 2008). iNOS, like arginase, uses L-arginine as its substrate, but converts it to L-citrulline and NO, which is required for long-term control of Toxoplasma infection (Scharton-Kersten et al., 1997). We therefore investigated whether the induction of arginase by Toxoplasma ROP16 has a similar effect on the production of NO by macrophages. By adding different concentrations of L-arginine to L-arginine-free medium, it was determined that below ~40 mg/L of L-arginine there is a rapid decline in NO production by mouse macrophages stimulated with LPS and IFN-γ (Figure 4A) (commercial DMEM contains 84 mg/L L-arginine, mouse serum

To obtain a complete picture of the macrophage response to these strains, the gene expression profiles of BMDMs infected with type II, type II Δgra15, type II + ROP16, and type II Δgra15 + ROP16 parasites were compared. Indeed, there was significant overlap between ROP16- and GRA15-regulated genes, as many genes were either synergistically or antagonistically regulated by both GRA15 and ROP16 (Table S3B). For example, M1 cytokines that were highly induced by GRA15 were downregulated following type II + ROP16 infection (Figure 3C), likely because ROP16 can inhibit the activation of NF-κB by type II strains (Rosowski et al., 2011). Conversely, many M2 markers were more highly expressed in BMDMs infected with type II Δgra15 + ROP16 than with type II + ROP16, parasites (Figures 3A and 3B), indicating that activation of NF-κB can inhibit the expression of M2 markers, possibly through its effect on PPARγ. Finally, GRA15 and ROP16 retained the ability to induce M1 or M2 markers in polarizing environments in vitro and in vivo (see discussion in Figure S3). Thus, a combination of GRA15 and ROP16 can control macrophage activation along the M1/M2 axis.
RAW264.7 macrophages were infected for 24 hr with type I or type I \( \Delta \text{rop16} \) parasites and activated with LPS and IFN-\( \gamma \) for 24 hr. Although high arginase activity was induced only in macrophages infected with type I parasites, both strains inhibited NO production equally well at L-arginine concentrations of 15, 40, and 80 mg/L (data not shown). Since Toxoplasma-infected cells are refractory to IFN-\( \gamma \) signaling (Zimmermann et al., 2006), infection and stimulation were performed concurrently to bypass this refractory state. Indeed, NO production was restored under these conditions. NO production by stimulated macrophages was dependent on the concentration of L-arginine and multiplicity of infection (moi); however, no significant difference in NO production was observed between cells infected with type I or type I \( \Delta \text{rop16} \) parasites (Figure 4B), even though type I parasites induced high levels of arginase under these conditions (Figure 4C).

Arginase converts L-arginine to urea and ornithine, the latter of which can be utilized in a variety of metabolic pathways including...
amino acid and polyamine synthesis. Toxoplasma lacks arginase activity and is a polyamine auxotroph (Cook et al., 2007). Induction of host arginase could therefore be a strategy to increase the availability of host polyamines to support Toxoplasma replication. Since DC2.4 cells are extremely responsive to induction of arginase-I (Figure 1C), we assayed parasite growth in these cells cultured in 35 mg/L L-arginine and either stimulated with IL-4 to induce arginase-I and/or treated with the arginase-I inhibitor nor-NOHA. In general, parasite replication for all strains was enhanced in IL-4-treated cells. The difference was apparent at 48 hr for the type II/III strains and at 24 hr for the type I strains (Figures 4D and 4E). Proliferative enhancement was through IL-4-induced host arginase, since IL-4-stimulated cells treated with nor-NOHA elicited a proliferative response that was similar in magnitude to parasite growth in nontreated cells (Figures 4D and 4E). Strains that express ROP16, grew slightly faster (in particular type II +ROP16, compared to type II), and nor-NOHA inhibited parasite replication of all strains tested. These results suggest that Toxoplasma could use the arginase metabolic pathway to promote its own growth, possibly through the action of ROP16.

**ROP16 Promotes Host Survival and Quells Toxoplasma-Induced Ileitis in C57BL/6 Mice**

Following natural peroral infection with the type II strain, C57BL/6 mice rapidly die during the acute phase of infection, which correlates with severe intestinal pathology (Liesenfeld et al., 1996). Toxoplasma-induced ileitis can be cured by removing a variety of proinflammatory cytokines including IFN-γ (Liesenfeld et al., 1996), IL-23, and IL-22 (Munoz et al., 2009). Given the anti-inflammatory capacity of the Jak-STAT6 and -STAT3 signaling pathways to regulate these mediators, we decided to explore the role of ROP16 in inflammatory modulation at the site of infection.

To this end, B6 mice were perorally challenged with type II +ROP16, or +ROP16, parasites, or with the type II or III strains. With high-dose infection (800 cysts), the majority of mice survived infection with the type II ROP16, strains, and those that died did so at a much later time point than mice infected with the type II strain (Figure 5A). Survival following type II+ROP16 infection correlated with reduced intestinal inflammation across the entire length of the intestine (Figure 5D). By day 8, cellular infiltrate into the lamina propria, villi blunting, and necrosis were nearly absent in type II+ROP16-infected mice (Figures 5B and 5D). Protection also correlated with reduced submucosa thickening (type II, 72 μM; versus type II +ROP16, 56 μM, average over 400 measurements p < 10^-7, data not shown). Whereas the type II strain elicited a significant influx of granulocytes into the villi and Peyer’s patches, as detected by Gr-1 and myeloperoxidase (MPO) staining, granulocyte recruitment was significantly reduced in type II +ROP16-infected animals (Figure 5E). Villus expression of iNOS (NOS2) in type II +ROP16-infected mice was reduced but not significantly different from type II infection. Lympohocytes isolated from the Peyer’s patches of type II +ROP16-infected animals produced less IL-22 and IFN-γ when stimulated with plate-bound anti-CD3 and anti-CD28 antibodies compared to lymphocytes from type II infected mice (Figure 5C), while lamina propria lymphocytes from type II +ROP16-infected animals produced less IL-22 but similar amounts of IFN-γ compared to lymphocytes from type II infected animals. Thus, type I/III ROP16 expression correlates with a general dampening of Toxoplasma-induced ileitis after oral infection in B6 mice.

**DISCUSSION**

In this report, we have demonstrated that Toxoplasma type I and type III strains can induce the M2 phenotype, while the type II strain induces M1-like macrophages. The alternative activation of macrophages is dependent in large part on the Toxoplasma polymorphic protein kinase ROP16, while the classical activation of macrophages by the type II strain is due to the unique ability of its GRA15 protein to activate the NF-κB pathway and elicit proinflammatory cytokines. In total, polymorphisms in these two factors account for ~25%–50% of the gene expression differences between type II- or III infected cells (data not shown).

Interestingly, ROP16 and GRA15 seem to affect signaling pathways that are themselves differentially “wired” between different hosts. For example, there is considerable mouse strain variation in the ability to generate M1 or M2 cells (Mills et al., 2000). One hypothesis is that parasite effectors from different Toxoplasma strains evolved to work optimally in hosts predisposed to certain types of immune responses, such as those along the Th1/Th2/Th17 or M1/M2 axes. Conversely, ending up in the wrong host might lead to severe disease and failure to establish chronic infection. Evidence surrounding this idea include (1) C57BL/6, but not BALB/c, mice challenged orally with type II strains, but not type III strains (data not shown), can develop severe immune pathology caused by high levels of proinflammatory cytokines in the small intestine (ileitis) (Liesenfeld et al., 1996); (2) chronic infections with type II strains, but not other strains, can cause severe pathology in the brain (encephalitis) of susceptible mice (Suzuki and Joh, 1994); (3) type I or type III recombinant strains are more often sampled in patients that present severe ocular toxoplasmosis (Grigg et al., 2001); and (4) although the type I strain is lethal in laboratory mice, rats are extremely resistant to Toxoplasma infection in general (Sibley and Ajika, 2008). Whether the type II or other strains are uniquely suited to spread in nature is an unresolved question; however, the type II strain is the most abundant strain identified in livestock and in humans in North America and Europe.

The fact that type I and III parasites initially induce M2 macrophages seems to contradict the well-established fact that Toxoplasma infections with the type I strain induce a strong Th1 response (Mordue et al., 2001). We favor the hypothesis that early alternative activation of macrophages, decreased macrophage IL-12 secretion (Robben et al., 2004), and reduced dendritic cell expansion following type I infection (Tait et al., 2010) contribute to a lower IFN-γ and cytotoxic host response against the parasite. Later during infection, the higher type I parasite burden could lead to increased levels of proinflammatory cytokines (Mordue et al., 2001). This could be due to “danger signals” released from lysing parasites such as profilin that can directly stimulate dendritic cells to produce high levels of IL-12 (Yarovinsky et al., 2005).
If both the type I and III strains induce alternative macrophage activation, why then are type III strains avirulent? The major Toxoplasma locus responsible for the difference in virulence between type I and III strains encodes another rhoptry protein kinase, ROP18 (Saeij et al., 2006; Taylor et al., 2006), which can phosphorylate and thereby inactivate mouse p47 GTPases, which are crucial for IFN-γ-mediated killing of Toxoplasma (Fen-tress et al., 2010; Steinfeldt et al., 2010). Type III strains express extremely low levels of ROP18 due to an insertion in its promoter (Saeij et al., 2006), and the addition of the type I ROP18 locus to a type III strain causes this strain to be as virulent as type I strains (Taylor et al., 2006). In contrast, we recently demonstrated that the virulence differences in mice between type II and III strains is multifactorial, with five Toxoplasma loci being involved, including ROP18, ROP16 (Saeij et al., 2006), ROPS (Reese et al., 2011), and most likely GRA15 (Rosowski et al., 2011). With the exception of ROP5, evidence now exists that these virulence factors can directly manipulate macrophage function, and the likelihood that other Toxoplasma effectors, polymorphic or not, would do likewise seems probable, especially considering the findings presented here.

We recently reported that following i.p. infection with type II Δgra15 parasites, a lower host production of IL-12p70 and IFN-γ at 1–2 days of infection preceded a higher parasite burden at day 5 compared to the type II strain (Rosowski et al., 2011). It is possible that M1 activation by GRA15 helps drive IFN-γ production to keep parasite numbers low, thus facilitating chronic infection. The induction of IL-12 by GRA15 may be especially important in hosts that do not express TLR11, as in humans (Roach et al., 2005). With respect to the in vivo effects of...
ROP16, we previously observed that the type II +ROP16+, or +ROP16+, strains were less virulent following i.p. infection compared to the parental type II parasites (Saej et al., 2006). We have extended this analysis to the oral model, and found that ROP16 prevents Toxoplasma-induced ileitis. The mechanism by which ROP16 promotes host survival is currently under investigation, but it is unlikely that ROP16 mediates its effect by inhibiting macrophage NO production. L-arginine depletion by arginase-1 also inhibits T cell responses (Pese et al., 2009). Thus, ROP16-induced arginase activity, suppression of IL-12 family members, and its induction of the T cell coinhibitory molecules B7-DC and B7-H1 might all feed into a general dampening of the CD4 T cell response, which is implicated in driving Toxoplasma-induced intestinal inflammation.

In conclusion, Toxoplasma appears unique in that strains of the same species can elicit polar opposite responses in infected macrophages. The rationale for alternative activation by Toxoplasma might be 2-fold: (1) to limit inflammatory damage in the infected host by quelling the Th1 response aimed at parasite elimination, and (2) to scavenge polyamines or other metabolites for energy consumption. On the other hand, the promotion of M1 cells could assist the host to develop a better Th1 response required for parasite clearance, and paradoxically allow the establishment of chronic infection. It appears that the survival of both the host and the parasite hangs in the delicate balance between opposing pro- and anti-inflammatory responses. Understanding how Toxoplasma regulates these immune decisions may provide important clues to their widespread success in establishing chronic infection.

EXPERIMENTAL PROCEDURES

Mice, Parasites, and Cells Six- to ten-week-old female BALB/c, C57BL/6J, or B6.129S2(C)-Stat6tm1Gru/J (Jackson Laboratories) mice were used in all experiments. All mice were maintained in specific pathogen-free conditions in accordance with institutional and federal regulations. The Toxoplasma strains used in this study are described in the Supplemental Experimental Procedures. RAW264.7, J774, and DC2.4 cell lines were maintained in the same medium as HFFs with an additional 10 mM HEPES (GIBCO Invitrogen). BMDMs were generated by culturing bone marrow cells in 20% L929 cell-conditioned medium, as previously described (Rosowski et al., 2011). This method yielded a highly pure population of CD11b+ F4/80+ macrophages (>99%) by FACS. All parasite strains and cell lines were routinely checked for mycoplasma contamination, and it was never detected.

Ex Vivo Phospho-STAT6 Assay and FACS Analysis BALB/c mice were infected i.p. with 3 x 10^6 parasites; 21 hr later, PECs were harvested, and all manipulations were done in the presence of Phosphatase Inhibitor Cocktail 2 (Sigma) and 1 x Roche protease inhibitor (Roche). PECs were blocked with 4% FBS, FcBlock (BD PharMingen), and normal rat and mouse sera (Caltag Laboratories) and stained with α-CD11b M1/70 PE or Pacific Blue (eBioscience), washed, fixed in 4% paraformaldehyde, and permeabilized with 0.5% saponin in blocking solution, stained with rabbit α-SAG-1, α-C206 M55D3 biotin or PE (Serotec), and α-pSTAT6 pY641 J71-773.58.11 Alexa Fluor 647 (BD PharMingen), washed and detected with goat α-rabbit Alexa Fluor 488 (Invitrogen) and streptavidin PerCP (BD PharMingen) in all permeabilization solution. For the staining of infected BMDMs (moi = 0.5), cells were blocked with 10% normal mouse and hamster sera (Jackson ImmunoResearch) and FcBlock and stained with PE-labeled antibodies to CD66 (eBioscience), B7-H1, B7-DC (BD PharMingen), Dectin-1, or a RatIgG2a isotype control (R&D Systems), followed by washing. Cells were fixed with 2% formaldehyde and washed before FACS analysis.

Arginase and Nitric Oxide Assays Parasites (moi of 20, 10, 5, or 1) were added to cells (10^5 cells/well) grown in 96-well plates, and arginase activity was measured 20–24 hr after infection as described (Corraliza et al., 1994). Wells with similar numbers of viable parasites were compared between parasite strains as inferred from a plaque assay. To measure the NO response, RAW264.7 cells were grown in DMEM without L-arginine complemented with 10% dialyzed serum and defined concentrations of L-arginine (MP Biomedicals). Nitrite was measured by using the Griess reaction.

Microarray Analysis Mouse macrophage (RAW264.7 and J774) and dendritic (DC2.4) cell lines were grown in a T75 to 80% confluency and were infected with the Me49 or CEP strains (moi = 7). BMDMs were plated at 3 x 10^6 cells per well (6-well plate) infected (moi = 3) for 18 hr, after which RNA was isolated using TRizol (Invitrogen). RNA was labeled and hybridized to a mouse Affymetrix array (Mouse 430 2.0 or Mouse 430A 2) and analyzed as described (Rosowski et al., 2011).

Immunofluorescence Assay Cells were fixed with 3% formaldehyde, treated with methanol, blocked, and permeabilized with 3% bovine serum albumin, 5% goat serum, 0.2% Triton X-100 in PBS. Coverslips were incubated in permeabilization solution with antibodies specific for Mrc1/CD206 sc-56109, mMgl sc-56109, or polyclonal antibodies against p-STAT6 sc-11762 (Santa Cruz Biotechnology) and a mouse monoclonal antibody against the surface antigen SAG-1, DGS2. Alexa Fluor 488 or 594 (Molecular Probes)-coupled secondary antibodies and Hoechst dye were used for antigen and DNA visualization with a fluorescence microscope.

Western Blot Lysates were prepared from infected (moi = 10 for 24 hr) macrophages grown in a 6-well plate. Western blots were performed as described (Rosowski et al., 2011) using antibodies against GAPDH sc-32233 (Santa Cruz Biotechnology), p-STAT6 558241 (BD PharMingen), mMgl AF-4297 (R&D systems), and SAG-1.

Parasite Growth Assay in DC2.4 Cells DC2.4 cells were cultured in DMEM containing 10% dialyzed serum and 35 mg/ml L-arginine and infected with an moi of ~1 and simultaneously treated with 50 ng/ml mouse IL-4 (PeproTech) and/or 100 μM nor-NOHA (Nomega-hydroxy-nor-Arginine) (Cayman Chemical) to induce or inhibit arginase, respectively. After 24–48 hr, cells were fixed, blocked, permeabilized, and stained as described above. The number of parasites per vacuole for 50 vacuoles was counted per each condition.

Oral Infection, Tissue Sections, and Ex Vivo Cytokine Analysis Brain homogenate of chronically infected mice was stained with dolichos biflorus–FITC (Vector Laboratories), and cysts were enumerated by microscopy. B6 mice were orally gavaged with 800 cysts and monitored for survival. Compared to the ME49 strain, the Pru strain is less virulent, and higher cyst numbers are needed to cause intestinal inflammation. For tissue sectioning, 8 days after infection the entire length of the small intestine (duodenum to ileum) was cut longitudinally, fixed in 10% buffered formalin, rolled into a “jelly roll,” sliced in two, mounted into cassettes, and processed for sectioning and hematoxylin and eosin staining. Antibodies to Gr-1 (Ly6C/G) RB6-8Cs (BD), MPO Ab-1 RB-373-A (Neo Marker), and iNOS sc-650 (Santa Cruz Biotechnology) were detected with HRP-linked secondary antibodies (Dako, BD). For ex vivo cytokine analysis, the Peyer’s patches were dissected, and lymphocytes were obtained by crushing. Pieces of the small intestine were then incubated in 5 mM EDTA in HBSS, washed, and digested with 1.25 mg/ml collagenase V and 50 U/ml DNase, and lamina propria lymphocytes were purified over a 40%/80% Percoll (GE) gradient. Cells were washed, and 3 x 10^6 cells were plated in 96-well bottom plates (Costar) coated with plate-bound α-CD3s: and α-CD28 (5 μg/ml) in RPMI medium with 10% FBS, supplements, and antibiotics. Twenty hours later, supernatant was analyzed by ELISA for mouse IFN-γ or IL-22 (eBioscience).

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REFERENCES


