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Authors
Jensen, Kirk DC
Camejo, Ana
Melo, Mariane B
et al.

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Toxoplasma gondii Superinfection and Virulence during Secondary Infection Correlate with the Exact ROP5/ROP18 Allelic Combination

Kirk D. C. Jensen,a,‡ Ana Camejo,a Mariane B. Melo,a Cynthia Cordeiro,a Lindsay Julien,a Gijsbert M. Grotenbreg,b Eva-Maria Frickel,c Hidde L. Ploegh,a Lucy Young,a Jeroen P. J. Saeij,a

Department of Biology, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA; Department of Microbiology, Department of Biological Sciences, and Immunology Programme, Life Sciences Institute, National University of Singapore, Singapore; Division of Parasitology, MRC National Institute of Medical Research, London, United Kingdom; Whitehead Institute for Biomedical Research and Massachusetts Institute of Technology, Cambridge, Massachusetts, USA; Department of Ophthalmology, Massachusetts Eye and Ear Infirmary, Boston, Massachusetts, USA

* Present address: Kirk D. C. Jensen, School of Natural Sciences, University of California, Merced, Merced, California, USA.

ABSTRACT The intracellular parasite Toxoplasma gondii infects a wide variety of vertebrate species globally. Infection in most hosts causes a lifelong chronic infection and generates immunological memory responses that protect the host against new infections. In regions where the organism is endemic, multiple exposures to T. gondii likely occur with great frequency, yet little is known about the interaction between a chronically infected host and the parasite strains from these areas. A widely used model to explore secondary infection entails challenge of chronically infected or vaccinated mice with the highly virulent type I RH strain. Here, we show that although vaccinated or chronically infected C57BL/6 mice are protected against the type I RH strain, they are not protected against challenge with most strains prevalent in South America or another type I strain, GT1. Genetic and genomic analyses implicated the parasite-secreted rhoptry effectors ROP5 and ROP18, which antagonize the host’s gamma interferon-induced immunity-regulated GTPases (IRGs), as primary requirements for virulence during secondary infection. ROP5 and ROP18 promoted parasite superinfection in the brains of challenged survivors. We hypothesize that superinfection may be an important mechanism to generate T. gondii strain diversity, simply because two parasite strains would be present in a single meal consumed by the feline definitive host. Superinfection may drive the genetic diversity of Toxoplasma strains in South America, where most isolates are IRG resistant, compared to North America, where most strains are IRG susceptible and are derived from a few clonal lineages. In summary, ROP5 and ROP18 promote Toxoplasma virulence during reinfection.

IMPORTANCE Toxoplasma gondii is a widespread parasite of warm-blooded animals and currently infects one-third of the human population. A long-standing assumption in the field is that prior exposure to this parasite protects the host from subsequent reexposure, due to the generation of protective immunological memory. However, this assumption is based on clinical data and mouse models that analyze infections with strains common to Europe and North America. In contrast, we found that the majority of strains sampled from around the world, in particular those from South America, were able to kill or reinfect the brains of hosts previously exposed to T. gondii. The T. gondii virulence factors ROP5 and ROP18, which inhibit key host effectors that mediate parasite killing, were required for these phenotypes. We speculate that these results underpin clinical observations that pregnant women previously exposed to Toxoplasma can develop congenital infection upon reexposure to South American strains.

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Address correspondence to Jeroen P. J. Saeij, jsaeij@mit.edu.

Toxoplasma gondii is an intracellular zoonotic pathogen that chronically infects a wide range of vertebrate species, including sea and land mammals, a variety of birds, and an estimated one-third of the human population. In intermediate hosts, there are two developmental life stages: the fast-dividing tachyzoite stage, which is responsible for acute disease, dissemination, and pathology, and the slow-growing bradyzoite stage, which is responsible for chronic infection and tissue cyst formation. Once infected, most intermediate hosts are chronic carriers for life and develop immunological memory responses that protect the host against reinfection (1) and keep the parasite in its semidormant, chronic stage (2). Members of the cat family are the definitive host and shed infectious oocysts into the environment. Transmission between hosts occurs following ingestion of either tissue cysts or oocysts. Toxoplasma oocysts are initially diploid and undergo one round of meiosis during sporulation in the environment, a characteristic of coccidian parasites (3). Because Toxoplasma can selfmate, the resultant sporozoites are clonal if a cat ingests one par-
asite strain, but recombinant progeny can be produced when a cat is infected with two or more different strains.

Despite the potential for genetic recombination, this appears to be a rare event on certain continents (4). For example, in North America and Europe, the population structure of *T. gondii* is remarkably clonal, with four lineages (the clonal or canonical types I, II, and III and type 12) accounting for the majority of isolated strains (4–6). In contrast, *T. gondii* strains from other parts of the world (often called atypical or exotic strains), and in particular those from South America, lack a clonal population structure and exhibit genetic diversity. Atypical strains can be clustered into haplogroups (HGs) 4 to 15, but most HGs are not clonal (7–11), and there is evidence for increased sexual recombination in South American strains (10, 12). It is unclear why the population structure is linked to geography, but several hypotheses have been put forward, including selective sweeps driven by advantageous whole chromosomes (4), the disappearance of cats in North America during the Great Ice Age extinction event (8), clonal outbreaks due to self-mating in the cat (13), and diversification within the species-rich jungles of South America (14). Given that *Toxoplasma* is a globally ubiquitous parasite and infection rates can be high in certain locales, *T. gondii* likely encounters hosts with prior immunity to *T. gondii*. However, little is known regarding parasite survival within an immune host and whether there are specialized virulence factors that promote reinfection. Because secondary infection may significantly impact the *Toxoplasma* population structure, we decided to explore the pathogenesis of a panel of *T. gondii* strains isolated from around the world by infecting chronically infected hosts.

Studies on the pathogenesis of *Toxoplasma* have mainly focused on primary infection mouse models and *Toxoplasma* strains isolated from North America and Europe. Type I strains are highly virulent (100% lethal dose [LD100], 1 parasite) but rarely isolated, while types II, III, and 12 are less virulent (LD50 so of ~103, ~105, and ~107 parasites, respectively) and frequently observed (5). Using these strains, key virulence factors that inhibit downstream toxoplasmal mechanisms elicited by the proinflammatory cytokine gamma interferon (IFN-γ) have been found to explain the relative differences in virulence during primary infection. IFN-γ induces the expression of two classes of GTPases, the immunity-regulated GTPases (IRGs) and guanylate-binding proteins (GBPs), which are important host resistance factors to pathogens that reside in vacuoles, like *Toxoplasma, Chlamydia*, and *Mycobacterium* species (15). When *Toxoplasma* infects a cell previously stimulated with IFN-γ, the absence of regulatory GMS IRGs (16) on the parasitophorous vacuole membrane (PVM) leads to PVM localization of the GSK class of effectors IRGs (17) and many GBPs (18), causing PVM destruction and rapid parasite death (19–22). The *Toxoplasma* rhoptry (ROP) kinases ROP18 and ROP17, the dense granule GRA7, and the ROP5 pseudokinases are secreted into the host cell upon invasion and subsequently traffic back to the PVM, where they cooperatively inhibit the localization and function of IRGs (23–30) and GBPs (21, 31). Differences in virulence between the clonal lineage strains are the result of polymorphisms in the ROP5 (32, 33) and ROP18 effectors (34, 35), with smaller contributions from other genetic loci (36). The type I strains encode virulent alleles of the ROP5 and ROP18 effectors, while the type II and III strains encode combinations of less virulent alleles that render them more susceptible to IRG-mediated killing and therefore less virulent in mice. The few atypical strains that have been studied are extremely virulent in naive mice (37), and most encode combinations of the ROPS/ROP18 alleles that are predicted to confer IRG resistance (26). Whether atypical strains have novel virulence factors is unknown.

The majority of studies on secondary infection have also focused on clonal lineage strains. Whereas naive mice are extremely susceptible to the type I RH strain or high-dose infections with type II strains, chronically infected or vaccinated mice are not (38). In mouse models of chronic infection, *T* cells and IFN-γ play pivotal roles in preventing reactivation of the dormant form (2, 39). These results mirror clinical observations of HIV/AIDS patients, in whom deterioration of memory T cells correlates with toxoplasmic encephalitis. In mouse vaccination studies, CD8+ T cells are the main mediators of protection against lethal secondary challenges (40–43). Protective CD8+ T cells require CD4+ T cell help (42, 44, 45) and interleukin-12 (IL-12) during priming (46, 47), and protection is dependent on IFN-γ (41) and possibly tumor necrosis factor alpha (TNF-α) and lymphotoxin-alpha (48), but not perforin (49). The importance of cytolsis and inducible nitric oxide synthetase appears to be limited to chronic infection (50–52).

Several studies have aimed to understand how well infection with one strain protects against reinfection with another, i.e., “heterologous immunity.” In regions of endemicity, for example, in Brazil and France, approximately 50 to 80% of the human population has been exposed to the parasite, and multiple exposures are likely the norm. However, because of the genetic diversity in South America and dominance of type II strains in Europe, secondary infections in South America will more often occur with a different strain type. In mouse models of reinfection, a study of 124 isolates from North and Central America, Europe, and the Pacific Islands demonstrated significant heterologous immunity (53). Likewise, vesper mice chronically infected with a type II strain were protected from congenital infection with a type I strain (54). Large parts of the type I and III genome are derived from the type II strain, and there is evidence for genomic introgression of the type II strain into South American strains (8, 55). Heterologous immunity may thus be achieved because immunodominant antigens are encoded by shared genomic regions or because *Toxoplasma* strains are generally ~99% similar. In contrast, type I-vaccinated rats were not protected against congenital *T. gondii* infection following oral ingestion of tissue cysts from several strains (56), and in mice chronic infection with certain strains did not generate heterologous immunity to congenital infection (57) or lethal oral challenge with a different strain (58). A few studies have addressed what happens to the challenging strain during heterologous challenge, and those investigators noted that with certain strains and host genetic backgrounds, successful coinfection in the brain can occur (59–61). Thus, the outcome of secondary exposure could be the result of several factors, including the ability of memory cells to recognize the second strain, the type of intermediate host, and unique virulence attributes of the strain causing the secondary infection.

Very little is known about requirements for host immunity to atypical strains. This is important because there is evidence that the severity of human toxoplasmosis is influenced by the parasite genotype and geographic location. Congenitally infected Brazilian children or South American patients with ocular toxoplasmosis present a more severe form of eye disease than those in other locales (62–64), and PCR-based strain typing methods suggest
atypical strain infections in Brazil or type I/atypical infections in Europe and North America are associated with more severe ocular toxoplasmosis (65–68). Additionally, severe congenital infection in North America is associated with non-type II strains (69). Importantly for this current study, there have been cases where sero-positive healthy women developed acute toxoplasmosis and congenital infection during pregnancy; in one instance when the responsible strain was genotyped it was an atypical strain (70, 71). Whether type I or atypical strains possess unique virulence factors that make them highly virulent in human populations is unknown.

Since most studies on T. gondii strain differences in virulence have focused on primary infection models using the European-North American strains, we asked whether Toxoplasma strains differ in virulence during secondary infection and sampled a broad spectrum of T. gondii strains isolated from around the world. Here we present evidence that the majority of Toxoplasma strains are able to kill chronically infected or vaccinated C57BL/6 (B6) mice, including mice vaccinated and subsequently challenged with the same strain type. Toxoplasma expression of the virulent alleles of ROP5 and ROP18 is a requirement for secondary infection virulence and superinfection of chronically infected mice. We hypothesize that superinfection through IRG resistance promotes outcrossing, because two strains would be present in a single rodent meal for the cat. This would make it difficult to maintain a clonal population structure.

RESULTS

The atypical strain MAS is virulent during secondary infection. We first explored whether chronic infection conferred protective immunity to secondary infection by working with a nonclonal lineage strain, the atypical strain MAS (haplogroup 4). The MAS strain was originally isolated from a patient with disseminated congenital infection (72) and is highly virulent in naïve mice (37). C57BL/6 mice were infected with an avirulent type III strain (CEP) and allowed to progress to chronic infection for 35 to 60 days before secondary infection. While the majority of mice survived a secondary infection (i.e., challenge) with the type I RH strain, as expected, approximately 50% of chronically infected mice succumbed to secondary infection with the atypical strain MAS (Fig. 1A). Moreover, surviving and nonsurviving mice experienced significant weight loss and morbidity during secondary challenge with the MAS strain (Fig. 1B). In contrast, mice challenged with the type I RH strain experienced little weight loss or morbidity following secondary infection.

Since the clonal strain types (I, II, and III) and atypical strains may express different antigens, we wondered whether strain-specific immunity was generated by the previous immunization regimen. Therefore, C57BL/6 mice were vaccinated with the MAS strain. This was achieved by treating mice with the antiparasitic drugs pyrimethamine and sulfadiazine 1 day after initial infection and giving subsequent “priming” injections with live MAS parasites during drug administration. Two weeks after drug removal, MAS-vaccinated mice survived challenge with the type I RH strain but not the atypical strain MAS (Fig. 1C). MAS-challenged mice were less able to control parasite replication than were type I RH-challenged mice, as evidenced by bioluminescence imaging (luciferase-expressing MAS-Luc and RH-Luc strains) (Fig. 1D and E) and experienced significant weight loss (Fig. 1F). Thus, two different priming conditions that generated protective immuno-

logical memory to the type I RH strain failed to do so for the atypical strain MAS.

The CD8 T cell IFN-γ response to the atypical strain MAS is unimpaired. Given the central role of CD8 T cells and IFN-γ in mediating host immunity to secondary Toxoplasma infection (38), we tested whether the CD8 T cell IFN-γ response to the MAS strain was impaired. To this end, peritoneal exudate cells (PECs) and splenocytes from type III chronically infected mice were infected in vitro with either the atypical strain MAS or the type I strain (“recall infection”), and the CD8 T cell IFN-γ response was measured 16 h later by intracellular cytokine staining and fluorescence-activated cell sorting (FACS) analysis. No differences in the frequencies of IFN-γ+ CD8 T cells were observed following recall infections with the various Toxoplasma strains (Fig. 2A). Total amounts of IFN-γ, IL-2, and TNF-α were measured in the supernatants following recall infections, and no differences in cytokine production were observed between MAS and clonal strain type infections (data not shown). We noted that type III chronic infection elicited a robust peritoneal but not splenic CD8 T cell IFN-γ recall response (Fig. 2A and C). In contrast, type II chronic infection elicited a detectable CD8 T cell IFN-γ recall response from both compartments (Fig. 2B and C). Nonetheless, similar frequencies of IFN-γ+ CD8 T cells were also observed from the spleens and PEC compartments of type II chronically infected mice following recall infections with different parasite strains (Fig. 2C). CD8-negative CD3+ T cells, the majority of which are CD4 T cells, were also analyzed in these experiments, and similar results were obtained (data not shown).

IFN-γ-producing CD8 T cells from chronically infected mice in combination can approximate effector memory T cells (TEM; CD62L− CD44+ IL7ra− KLRG1+/−) and central memory CD8 T cell (TCM; CD62L+ CD44+ IL7ra+ KLRG1−) populations. CD8 T cells expressing these markers have different turnover rates (73), homing characteristics (74), priming requirements (46), and T cell receptor (TCR) repertoire functions (75), and hence they may vary in their responses to the MAS and type I strains, leading to differences in host susceptibility. Although the relative frequency of CD62L+ and/or KLRG1+ IFN-γ+ CD8 T cell PECs varied between individual type III chronically infected mice, at an individual mouse level the frequencies of these populations were equivalent following recall infections with the MAS and clonal parasite strains (see Fig. S1A in the supplemental material). Additionally, IFN-γ+ CD8 T cells from the spleens of type II chronically infected mice had similar IL-7ra expression following recall infections with type I and MAS strains (Fig. S1B). These results suggest that memory CD8 T cells expressing markers that approximate the TEM and TCM memory pools are not initially biased in their IFN-γ response to different T. gondii strains.

In the experiments described above, we analyzed polyclonal memory CD8 T cells with unknown antigen specificities. In the C57BL/6 background (H-2b haplotype), a peptide epitope recognized by CD8 T cells has been identified and is derived from a Toxoplasma protein, TGD057 (TgME49_215980), with unknown function (76). Mice have been cloned from the nucleus of a single Toxoplasma-specific CD8 T cell (“transnuclear mice”) bearing T cell receptor specificity for the TGD057_96–105 Peptide in complex with the Kb major histocompatibility complex (MHC) class I molecule, and adoptive transfer of CD8 T cells (Tg77 cells) from these transnuclear mice confers increased host resistance to infection.
with type II strains (77). Therefore, the naive T57 CD8 T cell cytokine responses to bone marrow-derived macrophages (BMDMs) infected with different parasite strains were measured in an enzyme-linked immunosorbent assay (ELISA), including the response to BMDMs infected with a type I strain in which the TGD057 gene was removed by double homologous recombination (1 Δtgld057) (see Fig. S2 in the supplemental material). The T57 IFN-γ and IL-2 responses were 5 to 10 times greater to BMDMs infected with the MAS strain than those infected with the type I strain, and as expected, no response was observed to BMDMs infected with type I Δtgld057 parasites (Fig. 2D). Of note, the TGD057 96–103 peptide epitope is conserved between parasite strains. In conclusion, the atypical strain MAS elicits a robust naive and memory CD8 T cell IFN-γ response, suggesting that immunological failure during secondary challenge does not correlate with impaired CD8 T cell recognition or the IFN-γ response to the atypical strain MAS.

**Toxoplasma ROP5 and ROP18 are major virulence determinants during secondary infection with atypical strains.** To investigate whether compromised host immunity occurred with other atypical strains, we chronically infected C57BL/6 mice with the avirulent type III strain as described before and then challenged these mice 35 to 65 days later with a panel of atypical strains that are highly virulent in naive mice (Fig. 3A) and can be loosely grouped according to their genotype as follows (haplogroups are in parentheses): CASTELLS (HG 4); GUY-KOE (HG 5); FOU, BOF, and GPHT (HG 6); CAST (HG 7); TgCATBr5 (HG 8); P89 (HG 9); GUY-DOS and VAND (HG 10); COUGAR (HG 11). We noted that atypical strains that resisted IRG-mediated killing in IFN-γ-stimulated mouse embryonic fibroblasts (MEFs; “IRG resistant”) caused between 50% and 100% mortality during secondary infection (Fig. 3B). In contrast, P89, CASTELLS, COUGAR, and BOF, which do not prevent IRG-mediated killing mechanisms in MEFs (“IRG susceptible”) (26), caused 0% mortality.
(P89, BOF, and CASTELLS) or 22% mortality (COUGAR) during secondary infection (Fig. 3C). In the case of P89 and CASTELLS, these strains do not express ROP18, whereas BOF has the virulent ROP18 allele but has very low expression of ROP5 (26). COUGAR expresses the virulent allele of ROP18 and some members of the ROP5 locus, but possibly because it lacks the ROP5C allele this strain remains sensitive to IFN-γ-mediated killing (26). Thus, there is a positive correlation between atypical Toxoplasma strains that inhibit IRG function through ROP5 and ROP18 and killing of chronically infected mice.

To test whether restoration of IRG resistance in an atypical strain can promote virulence during a secondary infection, mice were chronically infected with the type III strain as before and challenged with an atypical BOF strain engineered to express the entire ROP5 locus of the type I strain (BOF/ROP5s). Compared to the parental strain, BOF/ROP5s survives significantly better in IFN-γ-stimulated MEFs and inhibits IRGB6-PVM coating (26). Unlike the BOF strain, challenge with the BOF/ROP5s strain caused host death (40% of the cohort) and morbidity, as evidenced by weight loss (>5% weight loss) during secondary infection (Fig. 3D and E). These results underpin the notion that IRG resistance during a heterologous challenge is an important attribute for parasite virulence.

The Toxoplasma ROP5/SAG3 locus correlates with virulence during secondary infections with F1 progeny derived from clonal lineage strains. The type I RH strain is highly virulent in naive mice due to expression of the virulent ROP5 and ROP18 alleles (28, 33, 78, 79), but RH was the only IRG-resistant strain that failed to induce morbidity in chronically infected mice (Fig. 1A). This strain has a long laboratory passaging history (80) of at least 50 years prior to the experiments performed in this study, and over time it has accumulated hundreds of mutations and gene expression differences compared to other type I strains (80, 81). Thus, chronically infected mice were challenged with another type I strain called GT1, which was originally isolated from a deceased goat in North America (82). Importantly, the GT1 strain killed type III chronically infected mice (Fig. 4A). To test whether GT1 could also kill mice vaccinated with a type I strain, mice were immunized with the replication-deficient uracil auxotroph type I RH Δomp16 Δup vaccine strain (83) and chal-
Effect plots revealed that type I alleles at the (Fig. 4C), which is the genetic marker closest to the via cosmid integration (BOF were infected with the type III strain (CEP) and allowed to progress to chronic infection. Seventy days later, mice were challenged (i.p.) with 5 P 6 P 35% survival; 0% survival [mean ± standard deviation]; type III allele, 80% ± 35% survival; P < 0.0001) (Fig. 4D; see also Fig. S3 in the supplemental material).

To determine genetic loci underlying the ability of Toxoplasma to kill an immune host, type III chronically infected CTG strains (I) and ROP18 (III) that expresses virulent ROP18II (S22 strain, an F1 progeny derived from a cross between a strain and virulent type III ROP18 allele, which is not expressed due to an insertion in its promoter (34, 35). In this screen of 16 F1 I × III progeny (which all are virulent for naive mice), mouse survival significantly correlated with the SAG3 marker (LOD, 4.1; P < 0.05) on Toxoplasma chromosome XII (Fig. 4C), which is the genetic marker closest to the ROP5 locus. Effect plots revealed that type I alleles at the SAG3 locus significantly correlated with mouse mortality during secondary infection (type I allele, 0% ± 0% survival [mean ± standard deviation]; type III allele, 80% ± 35% survival; P < 0.0001) (Fig. 4D; see also Fig. S3 in the supplemental material).

Toxoplasma ROP5 and ROP18 promote superinfection in chronically infected mice. To extend the analysis of the role of Toxoplasma resistance to IRG-mediated killing in virulence during a secondary infection, a panel of ROP5and/or ROP18-expressing parasite strains was screened for virulence in type III chronically infected mice. First, the IRG-sensitive type II and type III strains engineered to become IRG resistant through ROP5 (II + ROP5) and ROP18 (III + ROP18) expression, respectively, induced morbidity during secondary infection but failed to kill chronically infected mice (Fig. 5A and B), even though these strains are virulent in naive mice (26, 84). Second, the highly virulent S23 strain, an F1 progeny derived from a cross between a type II and a type III strain (II × III) that expresses virulent ROP5*I and virulent ROP18*I alleles (85), induced morbidity during secondary infection but did not kill chronically infected mice (Fig. 5A and B), even though these strains are virulent in naive mice (26).
grees of sickness, as evidenced by weight loss after challenge. In contrast, challenge with the parental control or IRG-susceptible strains led to no appreciable morbidity or weight loss (Fig. 5B). Importantly, IRG-resistant BOF/H11001 ROP5/I, S22/H11001 ROP5/I, and III/H11001 ROP18/I strains and the virulent S23 strain could be detected in parasite cultures generated from the brains of the challenged survivors (termed “superinfection” here), whereas the parental strains could not be rederived (Table 1). Heterologous brain infections were observed in other challenge experiments, including chronically infected animals challenged with GUY-KOE, but not after challenge with the IRG-susceptible COUGAR or P89 strains. MAS and type I RH strains were rarely rederived from the brains of chronically infected mice; however, both strains are poor at forming cyst walls (37), which perhaps contributes to this phenotype. A positive correlation between day 8 parasite burden, weight loss, and the ability to superinfect was observed (Fig. 5C to E). These results suggest that IRG resistance through ROP5 and ROP18 is required for Toxoplasma to promote morbidity during a heterologous challenge and superinfection, but additional factors are necessary to endow a strain with the ability to kill a chronically infected host.

**FIG 4** The *T. gondii* type I ROP5/SAG3 locus is correlated with lethal secondary infection. (A) Type III (CEP) chronically infected C57BL/6 mice (day 37 of chronic infection) were challenged with $5 \times 10^4$ tachyzoites of either the RH (*n* = 2) or GT1 (*n* = 5) type I strains; cumulative survival is plotted. (B) C57BL/6 mice were vaccinated with $10^6$ tachyzoites of the uracil auxotroph type I RH Δku80 ΔompDΔup vaccine strain (83), and 34 days later mice were challenged with either $5 \times 10^6$ tachyzoites of the type I RH (*n* = 4) strain or $5 \times 10^5$ tachyzoites of the type I GT1 strain (*n* = 5). Cumulative survival is plotted. (C) Type III chronically infected C57BL/6 mice (day 34 of chronic infection) were challenged with $5 \times 10^4$ tachyzoites of 16 different F1 progeny derived from a cross between the GT1 (type I) and CTG (type III) strains. The chosen progeny have the type I CS6 marker on *Toxoplasma* chromosome VIIa, a marker which detects an informative SNP in the ROP18 allele; thus, these F1 progeny express ROP18 and are 100% lethal in naive mice (34). The running LOD score for each of the 176 markers on the various *Toxoplasma* chromosomes and mouse survival (%) at 26 days after challenge is plotted (red line). The SAG3 marker on *Toxoplasma* chromosome XII returned the highest LOD score (4.1; *P* < 0.05). Significance was estimated based on 1,000 permutations at each marker; thresholds of *P* = 0.05 and *P* = 0.1 are shown. (D) Effects of the type I and type III SAG3 locus on mouse survival at 26 days. *, significant *P* value based on Student’s *t* test.
DISCUSSION

The results reported here call into question the general assumption that healthy *T. gondii*-seropositive mice are protected from disease following reexposure and underpin several clinical observations that otherwise healthy seropositive women can develop congenital toxoplasmosis during pregnancy upon secondary infection (70). In these situations, the strain type likely matters. In our model, we searched for *Toxoplasma* virulence loci that promoted virulence during a secondary infection. The central message from these studies is that evasion of the host’s IFN-γ response through *T. gondii* virulence factors is central to host and parasite survival during a secondary infection.

Parasite genetic determinants that influence host susceptibility to reinfection. As observed in naive mouse infection studies, the *Toxoplasma* ROP5 and ROP18 virulence factors, which antagonize IFN-γ-induced IRGs, are important for parasite virulence during a secondary infection. In nearly every case when *Toxoplasma* expressed the virulent alleles of ROP5 and ROP18, morbidity ensued in the challenged animals, and this correlated with the parasite burden. Importantly, strain differences in virulence that are not observed in naive animals (because many strains have an LD100 of 1 parasite) can be teased apart in chronically infected mice. Genetic linkage analysis using the F1 progeny derived from the type I GT1 and type III CTG strains implicated the type I SAG3/ROP5 locus in mediating GT1 virulence during secondary infection in type III chronically infected B6 mice. The causative mutation underlying this quantitative trait locus (QTL) peak is the subject of ongoing investigation, but this is not the locus responsible for...
differences in virulence between the GT1 and RH type I strains, since genes in this region were similarly expressed and did not encode nonsynonymous single nucleotide polymorphisms (SNPs) between these two strains (data not shown) (81). Although type III ROP5 gene products are highly functional and able to synergize with ROP18 to antagonize the IRG system (84), the type I ROP5 locus has extra copies of ROP5A and ROP5B (33, 86), perhaps allowing for greater GTase antagonism in immune mice, which mount an earlier and greater IFN-γ response from the T cell compartment than do naive animals. Additionally, SAG3 is a glycosylphosphatidylinositol-linked surface protein that binds surface glycans (87) on the host cell and is required for virulence of the type I strain (88). SAG3 polymorphisms (5 nonsynonymous SNPs between type I and type III SAG3 alleles [data not shown]) may cause differences in cellular tropisms between strains, resulting in different immune evasion properties. SAG3 and ROP5 are also vaccine antigen candidates (89, 90), and a ROP5-derived peptide epitope in B6 mice was recently described (91). This polymorphic epitope is recognized by CD8 T cells after infection with type II but not type I or III strains, and immunization with dendritic cells loaded with the ROP5 epitope did not confer protection to high-dose challenges with the type II strain. Whether an alternative type III or type I ROP5-derived epitope is recognized by CD8 T cells and confers protection to type I secondary infections is unknown.

In addition to the SAG3/ROP5 locus, it is apparent that other genetic loci are responsible for virulence in vaccinated or chronically infected animals. By analyzing recombinant F1 progeny and various strains engineered to express virulent alleles of ROP5, complete penetrance of the ROP5 locus in causing a lethal secondary infection was not observed. Whether the latter result reflects interference between cosmid-expressed and endogenous ROP5 gene products is unknown. It should be noted that the BOF strain encodes a single ROP5 gene (26) that is expressed at low levels (92). Therefore, the BOF strain may be the best strain to circumvent potential interference between cosmid-expressed and endogenous ROP5 gene products. This may not be the case with the II + ROP5 and S22 + ROP5 + ROP18a strains that express ROP5 from the endogenous ROP5 locus, which has copy number variations and divergent ROP5 isoforms compared to the closely related type I and type III ROP5 isoforms (33). Nonetheless, of the three ROP5 engineered strains, the BOF + ROP5 strain is the most resistant to IRGB6-PVM coating (26) and the only strain that was able to kill some mice during secondary infection. The identity of additional genes that promote virulence in chronically infected mice and whether they are bona fide virulence factors or contain important immune epitopes remain to be determined.

C8 T cells and IFN-γ are absolute requirements for host immunity to the type I RH and type II ME49 strains (38), and CD8 T cells were able to generate IFN-γ in response to MAS-infected cells (Fig. 2). Whether additional CD8 T cell effector mechanisms, such as cytolyis, or other memory cell types (B and CD4 T cells) are required for host immunity to atypical T. gondii strains remains to be investigated. For example, loss of CD8 T cell polyfunctional activity (i.e., the ability to produce more than one cytokine or granzyme) correlates with host susceptibility to chronic infection (93), and perforin-dependent cytolysis is apparently one of these required functions (52). In contrast to chronic infection with ME49 type II strains, the perforin pathway is not required for vaccine-induced protection against RH secondary infection (49). Whether these differences reflect stage-specific (tachyzoite versus bradyzoite) or

### TABLE 1

Superinfection of chronically infected mice challenged with IRG-resistant *T. gondii* strains

| Challenge strain | ROP18b | ROP5c | Chronic infection strain | Fraction of mice superinfected |
|------------------|--------|-------|--------------------------|-------------------------------|
| CEP (III) hxgprt- GFP dLUC | N | VIR | CEP (III) hxgprt- | 0/5 |
| CEP (III) hxgprt- GFP dLUC + ROP18 | VIR | VIR | CEP (III) hxgprt- | 3/5d |
| Pru (II) GFP LUC | VIR | AVIR | CEP (III) hxgprt- | 0/4 |
| Pru (II) GFP LUC + ROP5 | VIR | AVIR + VIR | CEP (III) hxgprt- | 3/5d |
| RH (I) GFP dLUC | VIR | VIR | CEP (III) hxgprt- | 0/5 |
| S22 (II × III) | N | AVIR | CEP (III) hxgprt- | 0/5 |
| S22 (II × III) + ROP5 | VIR | AVIR + VIR | CEP (III) hxgprt- | 5/5d |
| S22 (II × III) + ROP5 + ROP18a GFP | VIR | AVIR + VIR | Pru (II) hxgprt- | 2/2e |
| S22 (II × III) + ROP5 + ROP18a GFP | VIR | AVIR + VIR | CEP (III) hxgprt- | 2/2d |
| BOF (HG 6) | N | VIR | CEP (III) hxgprt- | 0/5 |
| BOF (HG 6) + ROP5 | VIR | VIR | CEP (III) hxgprt- | 1/3f |
| MAS (HG 4) GFP dLUC | VIR | VIR | CEP (III) hxgprt- | 1/10d |
| GUY-KOE (HG 5) | VIR | VIR | CEP (III) hxgprt- | 1/1d |
| P89 (HG 9) | N | VIR | CEP (III) hxgprt- | 0/2 |
| COUGAR (HG 11) | VIR | AVIR | CEP (III) hxgprt- | 0/2 |

* a C57BL/6 mice were chronically infected with either a type III or type II strain (genotype indicated) and challenged with atypical strains (haplotypic group indicated in parentheses), clonal strains (strain type indicated in parentheses), F1 progeny derived from a type II × type III cross, or strains engineered to become IRG resistant through either introduction of the type I ROP5 locus by cosmid integration or transgenic expression of type I or type II ROP18 genes (genotypes are indicated). At 35 to 50 days after secondary challenge, brains from surviving mice were homogenized in PBS and used to inoculate HFF monolayers. The ensuing parasite cultures were then tested for the presence of the challenging strain (superinfection of the brain). Data indicated are the fractions of mice in which the challenging strain was detected (with the number of mice tested as the denominator).

* b VIR, expression of ROP18, which is equated to possessing the virulent allele from either the type II or type I strain; N, the type III strain does not express ROP18.

* c VIR, the ROP5 locus of the type I and III strains promotes virulence in naive mice; AVIR, the type II ROP5 alleles are less virulent; N, BOF has very low expression of ROP5; AVIR, it is unclear why COUGAR is IRG sensitive, but it lacks certain ROP5C isoforms.

* d GFP-positive parasites were observed in the parasite culture.

* e RFLP analysis of GRAP determined that the parasite culture had the S22 GRAPII allele.

* f Parasite growth was observed in mycophenolic acid-xanthine medium, which selects for parasites that carry a functional HXGPRT gene (e.g., the challenge BOF strain).

* g GFP-negative parasites were observed in the parasite culture.
strain-specific (RH versus ME49) requirements for host immunity remains an open question, especially since most strains are virulent during secondary infection, as reported here. It is clear that some aspect of the memory CD8 T cell response but not the CD4 T cell response is necessary for protection against RH secondary infection (42), even though both cell types make ample amounts of IFN-γ after challenge (data not shown). In addition to their cytolytic activity, which can destroy the host cell that Toxoplasma needs for replication, CD8 T cells express a variety of TNF superfamily members which have dynamic effects on Toxoplasma. For example, parasite death can be triggered following CD40-CD40L interactions (94, 95) and egress following FAS-FASL interactions (96). Additionally, host resistance to infection is promoted by lymphotixin-alpha (48). A careful dissection of how CD8 T cells restrict Toxoplasma may yield insights into other requirements for host immunity and point to new immune pathways that potentially intersect Toxoplasma virulence factors, in particular those of atypical strains.

**Potential effect of superinfection on Toxoplasma population structure.** Although heterologous immunity to ROP5- and ROP18-expressing Toxoplasma strains is achieved in certain mouse genetic backgrounds, “sterile heterologous immunity” may rarely occur. IRG-resistant strains were observed via bioluminescence imaging days after the initial challenge and eventually superinfected the brain of chronically infected mice. These events may have a significant effect on the population structure. Heterologous tissue infection in intermediate hosts could assist parasite sexual recombination in nature by allowing two strains to be present during a single meal consumed by a felid, the definitive host species for Toxoplasma. Mixed infections in the wild have been noted in humans (97) and in sheep (98, 99), and heterologous brain infections have been experimentally verified in laboratory mice (59). Here, we linked these events to allelic combinations of ROP5 and ROP18 that resulted in resistance to IRGs, which can be disadvantageous in naive mice because they die before the infectious tissue cysts are formed, but advantageous in niches where most intermediate hosts are chronically infected, thus facilitating superinfection and the generation of novel parasite genotypes upon feline infection. Although oocysts can infect cats, they are less infectious than tissue cysts and have a much longer (3 to 10 days versus 18 to 30 days) prepatent period (or time to shed oocysts) (100). Thus, heterologous tissue infection in intermediate hosts may be the most efficient means to produce recombiant progeny in nature.

Superinfection may be a major mechanism impacting the population structures observed on the different continents and is likely a consequence of parasite coevolution with local rodents and their IRGs. Unlike the clonal strains of North America and Europe, where the vast majority of isolates are IRG sensitive, most South American strains of the various haplogroups are not clonal and are IRG resistant. The geographical distribution of these phenotypes is the subject of speculation. Certainly, the *M. m. domesticus* house mouse that is common to North America, Western Europe, and Africa and is highly susceptible to the type I strain has likely shaped the dominance of the IRG-sensitive type II and III strains in these locales. Of course, “IRG sensitive” and “IRG resistance” are terms used to define the interaction between different *T. gondii* strains and the IRGs of various *M. m. domesticus* laboratory mouse strains. However, the murine IRG locus is extremely diverse, rivaling that of the MHC, and mouse subspecies from different geographic locations have unique IRG haplotypes that interact with virulent *Toxoplasma* strains differently (101). For example, the South-Southeast Asian *M. m. castaneus* subspecies of mice does not die from type I infection, due to polymorphisms in Irgb2-b1, and instead they form a life-long chronic infection (101). Perhaps this is why the type I strain is frequently isolated in Asia (5). Less is known regarding the IRG haplotypes of South American rodents (e.g., capybara, tuco-tuco, guinea pigs), but presumably South American *Toxoplasma* strains have coevolved with these hosts to achieve maximal chronic infection. Here, we hypothesize that once IRG resistance or optimal IRG antagonism is selected, maintaining a clonal population structure of such strains may be difficult when reexposure to *Toxoplasma* is common, for example, in South America.

Furthermore, today in North America, approximately half of wild mammals are now chronic carriers for *Toxoplasma* (6), and the domesticated cat is now highly abundant. If IRG-resistant South America strains invade North America, as is thought to have occurred for the generation of the type I and type III strains (8), then changes in the clonal population structure will likely occur as chronically infected North American hosts become superinfected with South American strains. Cats feeding on those superinfected intermediate hosts may yield strains with enhanced virulence properties, perhaps suited to infect an immune host or a naturally resistant host, like *M. m. castaneus*, but strains maladapted for other hosts or species irrespective of prior exposure to *Toxoplasma*.

**Toxoplasma virulence factors may also impact human disease.** Finally, given the lack of testing in the United States and the proximity to South America, perhaps closer attention should be paid to the possibility of reexposure to *Toxoplasma* and whether an individual has consumed food from South American locales. Although humans do not express the expanded small GTPase IRG family that is antagonized by most South American strains, they do express the large 65-kDa IFN-γ-induced GBPs, which are inhibited by virulent versions of ROP5 and ROP18 (31, 102). Furthermore, ROP18 induces ATF6 degradation, a conserved host transcription factor that is required for *T. gondii*-infected dendritic cells to elicit CD8 T cell activation (78). Whether ROP5/18 alleles promote virulence in humans is unknown; however, type I and atypical strain types have been associated with multiple forms of human toxoplasmosis (62–69). In conclusion, the selective forces that have shaped the *Toxoplasma* population structure may have the unintended consequence of generating strains that cause severe disease in certain intermediate hosts, and we conclude that *T. gondii* may be more virulent than previously appreciated.

**MATERIALS AND METHODS**

**Parasite strains.** *T. gondii* strains were passaged in human foreskin fibroblasts (HFFs; originally obtained from the Boothroyd lab, Stanford University) in Toxo medium (4.5 g/liter t-glucose, t-glutamine in Dulbecco’s modified Eagle’s medium [DMEM; Life Technologies] supplemented with 1% fetal bovine serum [FBS; Omega Scientific] and antibiotics). The following atypical strains were used (haplogroups are shown in parentheses): CASTELLS and MAS (HG 4); GUY-KOE (HG 5); FOU, BOF, and GHPT (HG 6); CAST (HG 7); TgCATB5 (HG 8); P89 (HG 9); GUY-DOS and VAND (HG 10); COUGAR (HG 11). The clonal types used in this study were type I RH Δhxgprt, RH Δ1UC (1-1), and RH Δhxgprt Δku80; type II Pru Δhxgprt Δku80, Pru A7 fLUC Δhxgprt/ΔHXGPRY (5-8 B+) (103); and type III CEP Δhxgprt, CEP Δhxgprt/Δ-CUC (C22), CL14 ΔUC. The avirulent S22 (ROP5/I, ROP18/I) and virulent S23-ΔUC (ROP5/I
 III strains (II and IV) are endogenously rearranged TCR additional times with 6 on drug therapy for 18 days. During this time, mice were boosted two liters (pH 7.2) of sulfadiazine plus 320 mg/kg drinking water 1 day following injection of 105 MAS tachyzoites and kept on this diet for 19 days prior to secondary challenge. During this time, mice exhibited no signs of active infection and experienced weight gain, suggesting the overall health of the animals. For vaccination with the atypical MAS strain, mice were given 400 mg/kg of drug every other day for a total of 4 days. For vaccination with the type III strain, mice were injected i.p. with 105 live syringe-lysed MAS tachyzoites on day 7 for 7 days, and parasite viability for each strain was determined by a plaque assay in which 100 tachyzoites were plated in HFF monolayers grown in a 24-well plate; 5 to 7 days later plaques were enumerated by bioluminescence imaging (4× objective). Viability ranged from 20 to 50%. For in vivo bioluminescence imaging, mice were injected i.p. with 300 μg of v-luciferin (Gold Biotechnology) and 5 min later anesthetized with iso-flurane (Abbott); 5 min later, photon emission from individual mice was detected with an IVIS Spectrum bioluminescent and fluorescent imaging system (Xenogen). Images were captured with integration times from 10 s to 5 min, depending on the intensity of the bioluminescent signal. Image analysis was performed with Living Image software (Xenogen).

 Genetic linkage analysis. For QTL analysis, 176 informative genetic markers for each of the F1 I × III progeny were obtained from the website http://toxomap.wustl.edu/IxIII_Typing_Table.html, and mouse survival (as a percentage of total mice) at 26 days after secondary infection in type III chronically infected C57BL/6 mice was analyzed with the program R/QTl (Bowman). LOD scores for each marker were calculated. For all LOD scores of >2, 1,000 permutations were performed to obtain the LOD threshold at a P value of ≤0.05, which was considered statistically significant; only the SAG3 marker returned an LOD score of >2 and was significant for this experiment.

 Brain superinfection assays. Brains were dissected from chronically infected mice that survived secondary challenge, rinsed in PBS, placed in 5 ml PBS, and extruded through a 2-inch 21-gauge needle several times (10-ml syringe). The suspension was spun at 572 × g for 7 min and resuspended in 1 ml of PBS. For rederivation, 100 to 200 μl of the brain homogenate was used to inoculate HFF monolayers in a T-25 flask with Toxo medium (described above). One week after inoculation, the T-25 flask was scraped and syringe lysed through a 25-gauge needle, spun for 5 min at 32 × g to pellet the large debris; the supernatant was collected, pelleted with a faster spin of 572 × g for 7 min, and resuspended in Toxo medium, and the entire suspension was used to inoculate a new HFF monolayer in a T-25 flask. Parasite growth was typically observed between 2 and 3 weeks post-inoculation. To determine whether the challenging strain was present in the ensuing parasite culture, several approaches were used: parasite expression of GFP or lack thereof was directly observed in the culture by fluorescence microscopy; parasites were passed in selection medium containing MPA-xanthine (described above) to test for a functional copy of HXGPRT; parasite genomic DNA was isolated using DNazol (Invitrogen); RFLP analysis of the GRA6 locus was performed using the primers GRA6FW (5′-ATTGTTGTTCCAGGACCAGT) and GRA6RV (3′-TCGCCGAGAAGTGACATAG), and the restriction enzyme MscI, producing unique fragment lengths that identified all three clonal lineages.
Cell isolation, in vitro recall infections, and FACS analysis. PECs were harvested by injecting 4 ml of PBS plus 3 ml of air into the peritoneal cavity (i.p.) with a 30-gauge needle and shaking and extracting the cells by puncture with a 16-gauge needle. Cells were filtered through 70-μm cell strainer and washed in FACS buffer, 1% FBS–PBS before staining. The spleen or, in the case of the T57 mice, the spleen and lymph nodes were dissected and crushed through a cell strainer, pelleted, and incubated in ACK red blood cell (RBC) lysis buffer (NH4Cl at 0.15 M, KHCO3 at 10 mM, EDTA at 0.1 mM) for 5 min at room temperature, washed in FACS buffer, and filtered again through a cell strainer.

For FACS analysis, all preparations were done on ice, and cells were blocked in FACS buffer supplemented with 10% normal hamster serum (Jackson ImmunoResearch) and FcBlock anti-CD16/32 (BD Pharmingen) prior to staining with fluorophore-labeled monoclonal antibodies (MAbs). The following MAbs (1:100 staining dilutions) were purchased from eBioscience unless otherwise stated: anti-CD62L eFluor 450, anti-CD44 eFluor 450 (IM7), anti-KLRG1–fluorescein isothiocyanate (FITC) (2F1), anti-CD127–phycoerythrin (PE) (A7R34), anti-CD19–PE-Cy5 (1D3), anti-CD8α–allophycocyanin (APC) or anti-CD8α-PE-Cy7 (53-6.7), and anti-CD3e APC-Cy7 (145-2C11; BD Pharmingen). Cells were washed in FACS buffer prior to analysis on an LSR HTS-2 FACS machine (BD) equipped with BD FACSDIVA software.

For intracellular staining of cells following in vitro recall infections, 6 × 10^6 PECs or splenocytes per well (96-well plate) were plated in T cell medium (10% FBS in RPMI 1640 with GlutaMAX, antibiotics, 10 mM HEPES, 1 mM sodium pyruvate [Invitrogen], and 1.75 μM β-mercaptoethanol per 500 ml [MP Biomedicals]). Cells were infected with parasites (multiplicity of infection [MOI], 0.2) for 18 to 21 h, and cells were then fixed with BD Cytofix/Cytoperm block in FACS buffer supplemented with 10% normal hamster serum (Jackson ImmunoResearch) and FcBlock anti-CD16/32 (BD Pharmingen). Cells were stained with MAbs labeled with APC or PE that recognized IFN-γ (XMG1.2) at room temperature for 1 h or overnight at 4°C. Cells were then washed once in BD Perm/Wash and once in FACS buffer prior to FACS analysis. All data were compensated and processed with FlowJo software (Treestar).

T57 transnuclear CD8 T cell cytokine secretion. BMDMs (B6) cells were plated at 2 × 10^5 cell/well (96-well plate) in BMDM medium (described above) supplemented with 20% L929 conditioned medium. The next day, the medium was removed and cells were infected with parasites in triplicate (MOI, 0.6, 0.2, or 0.08) in T cell medium (see above). Splenocytes and lymph node cells from T57 transnuclear mice were harvested and combined, and RBCs were lysed with ACK lysis buffer. After washing, 5 × 10^5 cells were added to the infected BMDMs (~2 h from time of infection). Forty-eight hours later, supernatant was removed and stored at −80°C for IL-2 and IFN-γ analysis by ELISA (eBioscience). Viability was inferred via a plaque assay, and wells with equivalent numbers of viable parasites were compared.

Ethics statement. All mouse work was performed in accordance with the recommendations in the Guide to the Care and Use of Laboratory Animals (104) of the National Institutes of Health. The MIT Committee on Animal Care (assurance no. A-3125-01) approved all protocols, and all efforts were made to minimize unnecessary distress to the animals.

SUPPLEMENTAL MATERIAL
Supplemental material for this article may be found at http://mbio.asm.orglookup/suppl/doi:10.1128/mBio.02280-14/-/DCSupplemental.

Figure S1, TIF file, 2.8 MB.
Figure S2, TIF file, 0.3 MB.
Figure S3, TIF file, 0.4 MB.

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