Glycoinositolphospholipids from Leishmania braziliensis and L. infantum: Modulation of Innate Immune System and Variations in Carbohydrate Structure

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Abstract

The essential role of the lipopolysaccharide (LPS) of Leishmania in innate immune response has been extensively reported. However, information about the role of the LPG-related glycoinositolphospholipids (GIPPs) is limited, especially with respect to the New World species of Leishmania. GIPPs are low molecular weight molecules covering the parasite surface and are similar to LPG in sharing a common lipid backbone and a glycan motif containing up to 7 sugars. Critical aspects of their structure and functions are still obscure in the interaction with the vertebrate host. In this study, we evaluated the role of those molecules in two medically important South American species Leishmania infantum and L. braziliensis, causative agents of visceral (VL) and cutaneous Leishmaniasis (CL), respectively. GIPPs derived from both species did not induce NO or TNF-α production by non-purified murine macrophages. Additionally, primed macrophages from mice (BALB/c, C57BL/6, TLR2−/− and TLR4−/−) exposed to GIPPs from both species, with exception to TNF-α, did not produce any of the cytokines analyzed (IL-1β, IL-2, IL-4, IL-5, IL-10, IL-12, IL-24, IFN-γ) or p38 activation. GIPPs induced the production of TNF-α and NO by C57BL/6 mice, primarily via TLR4. Pre incubation of macrophages with GIPPs reduced significantly the amount of NO and IL-12 in the presence of IFN-γ or lipopolysaccharide (LPS), which was more pronounced with L. braziliensis GIPPs. This inhibition was reversed after PI-specific phosphatase C treatment. A structural analysis of the GIPPs showed that L. infantum has manose rich GIPPs, suggestive of type I and Hybrid GIPPs while L. braziliensis has galactose rich GIPPs, suggestive of Type II GIPPs. In conclusion, there are major differences in the structure and composition of GIPPs from L. braziliensis and L. infantum. Also, GIPPs are important inhibitory molecules during the interaction with macrophages.


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Introduction

In the Americas, Leishmaniasis are widely distributed from the southern United States to northern parts of Argentina [1]. In Latin America, especially in Brazil, Leishmania braziliensis and Leishmania infantum are the causative agents of cutaneous (CL) and visceral leishmaniasis (VL), respectively. The severity of the disease may range from self-healing cutaneous ulcers to potentially lethal visceral form [2].

During the life cycle, Leishmania parasites have to survive to extreme adverse conditions in both vertebrate and invertebrate hosts [3]. In the vertebrate host, inoculation of metacyclic Leishmania promastigotes by the sand fly is followed by neutrophil phagocytosis prior to intracellular differentiation into amastigotes [4]. At the early steps of infection, innate microbial mechanisms may include the production of reactive nitrogen intermediates (RNI), reactive oxygen intermediates (ROI) and cytokines (IL-12, TNF-α and IFN-γ) [5,6]. This is crucial for Th1 polarization and subsequent parasite control in the mouse model. Failure in this process can lead to higher parasite burden and increase severity of disease [7].

To avoid destruction, intracellular parasites must interfere with the cytosolic signaling system of the host. In vivo and in vitro studies have demonstrated the importance of nitric oxide (NO) production in response to several stimuli such as bacterial lipopolysaccharide (LPS), IFN-γ and TNF-α [8]. It is known that Leishmania-infected macrophages fail to activate MAPKs, become less responsive to cytokine stimulation (IL-12 and IFN-γ) [9,10,11] and express lower amounts of NO and IL-12 [12,15], impairing Th1 differentiation to a Th2 phenotype.

The molecular mechanisms involved in the immune system modulation by Leishmania have been the focus of many studies. GPI-anchored molecules are closely associated with cell signaling and can act as agonists and second messengers in response to cytokines and other stimuli [9,14,15,16]. The most studied Leishmania glycoconjugate is lipopolysaccharide (LPS), whose functions include attachment and entry into macrophages [17], modulation of NO production [18], inhibition of protein kinase C.
Author Summary

Leishmania infantum (syn. L. chagasi) and L. braziliensis are the causative agents of VL and CL, respectively, in the New World. A vital part of the parasite’s life cycle involves the circumvention of the host immune system and the infection of macrophages. This work focused on an important class of surface glycoinconjugates, the glycino-stilphospholipids (GPIs), and their role in the interaction with murine macrophages. GPIs are expressed on every stage of the parasite life cycle and are the most abundant molecules on its surface. Here we show that these molecules modulate many macrophage functions such as cytokine production, release of nitric oxide and differentially activate MAPK. Although the GPIs of both New World species are capable of modulating the same mechanisms, they do so to different degrees requiring an examination of their glycan composition. We show that L. infantum synthesizes mannose rich GPIs whereas L. braziliensis expresses galactose rich GPIs.

[PKC]-dependent cell activation [19,20], retardation of phagosome maturation [21], disruption of NADPH oxidase assembly at the phagosome membrane [22], induction of neutrophil extracellular traps (NETs) [23], induction of protein kinase R (PKR) [24], and attachment to the sand fly vector midgut [25]. In Leishmania, Toll-like receptor 2 (TLR2) is the main receptor for both LPG and glycoinositolphospholipids (GPIs), the latter as a less potent agonist [26,27]. Besides TLR2, in vitro studies have also demonstrated the importance of TLR4 and TLR9 during Leishmania infection [28,29,30].

Little is known about the functions of GPIs in Leishmania biology, although they are present as the major component of the parasite surface in numbers greater than LPG [31]. The basic GPI structure is a Manα1–6Glc linked to an acylglycerol through a phosphatidylinositol (PI) residue. Polymorphism in this family of molecules relies on the variety of fatty acid substitutions in the lipid anchor and monosaccharide substitutions in the glycan core moiety, leading to their classification into three groups (Figure 1): Type I GPIs are characterized by having an α1,6-mannose residue linked to the Manα1–6Glc motif. This group is represented by M2 and M3 GPIs which structures are Manα1–6Manα1–6Glc-N-PI and Manα1–2Manα1–6Manα1–6Glc-N-PI. Type II GPIs are closely related to GPI anchors of parasites with a very homogenous lipid composition, predominantly C6:0 fatty acids, and are found in Old World species such as L. donovani, L. tropica and L. aethiopica promastigotes [32]. Type II GPIs have a more heterogeneous lipid composition with C8:0, C10:0, C12:0, C14:0, C16:0 and C18:0 fatty acids. They can be found in Old World L. major [33,34] and New World L. mexicana [35,36] and L. panamensis [37]. Type II GPIs are characterized by having an α1,3-mannose residue linked to the Manα1–3Glc motif, similarly to the glycan core of LPG. Structurally, they can range from small IMI GPIs, Manα1–3Manα1–3Glc-N-PI, to longer structures like GPI-L, Gaββ1–3Galββ1–3Galββ1–3Manα1–3Manα1–3Glc-N-PI and GPI-L3, Gaββ1–3Gaββ1–3Gaββ1–3Gaββ1–3Manα1–3Manα1–3Glc-N-PI. The third group is the Hybrid-type GPIs, sharing common features to both Type I and II with mannose residues located on both C-3 and C-6 positions of the Manα1–6Glc motif (isoM3 and isoM4). There may also be other substitutions like phosphate sugars and ethanolamine residues [35,37]. Early studies have shown that GPIs from L. major were highly antigenic, being recognized by sera from chronic CL patients [38]. Recent findings have demonstrated that L. braziliensis GPIs are components of complex membrane microdomains and that these structures were crucial for parasite infectivity and survival [39]. However, little is known about the role of GPIs in the innate immune compartment, especially in L. braziliensis and L. infantum.

This work is part of a wider study on the glycobiology of New World species of Leishmania. In previous studies, we reported on the LPGs of L. braziliensis and L. infantum [40,41] and showed that the differences in LPG structures were relevant in the parasite biology. In this study, we expanded those findings and show the GPI structures of the two New World Leishmanias also differentially modulate the innate immune system in mouse peritoneal macrophages.

Materials and Methods

All animals were handled in strict accordance with good animal practice as defined by the Internal Ethics Committee in Animal Experimentation (CEUA) of Fundação Oswaldo Cruz (FIOCRUZ), Belo Horizonte (BH), Minas Gerais (MG), Brazil (Protocol 40297-06). Knock-out mice handling protocol was approved by the National Commission of Biosafety (CTNBio) (protocol #01200.006193/2001-16).

Parasites

World Health Reference strains of L. braziliensis (MHOM/BR/1975/M1903), L. infantum (MHOM/BR/1974/P775) and L. donovani (MHOM/SD/80/182D) were used. Promastigotes were cultured in M199 medium supplemented with 10% heat-inactivated fetal bovine serum (FBS), penicillin 100 units/ml, streptomycin 50 μg/ml, 12.5 mM glutamine, 0.1 M adenosine, 0.0005% hemin, and 40 mM Heps, pH 7.4 at 26°C [40].

Extraction and purification of GPIs

Cells were harvested and washed in PBS twice prior to GPIs extraction with methanol:chloroform:water (10:9:3). This material was dried under nitrogen stream, resuspended on 0.1 M ammonium acetate buffer containing 5% 1-propanol and loaded onto an octyl-sephrose column (80 ml) equilibrated in the same buffer. The column was subjected to a gradient of 1-propanol in 0.1 M ammonium acetate buffer (5–60%). Three ml fractions were collected and the presence of GPIs in the fractions was detected by staining aliquots of the fractions on a TLC plate with orcinol-sulfuric acid (100°C, 5 min) [39]. GPIs containing fractions were pooled, dried and resuspended in endotoxin-free water (Sanobiol, São Paulo, Brazil). GPIs concentrations determined as described elsewhere [12]. Prior to use in in vivo macrophage cultures, GPIs were diluted in fresh RPMI.

Purification of murine peritoneal macrophages and cell culture

Thiglycollate-elicited peritoneal macrophages were removed from BALB/c, C3H/HeJ and respective TLR2–/– and TLR4–/– knockout mice by peritoneal washing with RPMI and enriched by plastic adherence for 10 h. Cells (5×10⁶ cells/ml) were cultured in RPMI, 2 mM glutamine, 50 U/ml of penicillin and 50 μg/ml streptomycin in 96-well culture plates (37°C/5% CO2). They were incubated with gamma interferon (100 IU/ml) [43], live stationary Leishmania parasites (10¹), GPIs (1, 5, 10 and 25 μg/ml) and lipopolysaccharide (LPS) (100 ng/ml).

Cytokine and nitrite measurements

For CBA, multiplex cytokine detection, cells were plated as described above for 1 h before washing with RPMI without
serum. RPMI supplemented with 10% FBS was added with (for primed macrophages) or without (for non-primed macrophages) the addition of IFN-γ (3 IU/ml) [44] and incubated for 18 h (37°C, 5% CO2). GIPLs (25 μg/ml) and LPS (100 μg/ml) were added and incubated for 48 h. Supernatants were collected and stored at −70°C and cytokines (IL-1β, IL-2, IL-4, IL-5, IL-10, IL-12p40, IFN-γ and TNF-α) were determined using the BD CBA Mouse Cytokine assay kits according to the manufacturer’s specifications (BD Biosciences, CA, USA). Flow cytometric measurements were performed on a FACs Calibur flow cytometer (Becton Dickinson, Mountain View, CA). Cell-Quest™ software package provided by the manufacturer was used for data acquisition and the FlowJo software 7.6.4 (Tree Star Inc., Ashland, OR, USA) was used for data analysis. A total of 1,800 events were acquired for each preparation. Results are representative of two experiments in duplicate.

For inhibition studies, cell suspensions were washed with RPMI and enriched by plastic adherence for 18 h as described above without the addition of IFN-γ. Cells were pre-incubated with GIPLs (15 min) prior to stimulation with LPS or IFN-γ. Supernatants were collected after 24 h for NO, TNF-α and IL-12 measurements. When used, LPS or IFN-γ were added 15 min after the addition of GIPLs. Culture supernatants were collected and nitrate concentrations determined by Griess reaction [45] and TNF-α and IL-12 concentrations were determined using ELISA (BD). Results are representative of two experiments in triplicate.

Phospholipase C treatment (PI-PLC)

To evaluate whether intact GIPL structure is required for activity. Purified GIPLs were resuspended in 150 μl CHAPS buffer (290 mg HEPES, 17 mg EDTA and 50 mg CHAPS in 50 ml endotoxin-free water) and 2 U of PI-PLC (Sigma) (37°C, 16 h). Peritoneal macrophages were plated and stimulated with intact and PI-PLC treated GIPLs as described above. Nitric oxide content was measured on the supernatants by Griess reaction [45].
Preparation of cell lysates and immunoblotting

Stimulated cells (3×10⁶/sample) were washed with ice-cold PBS, lysed in lysis buffer (20 mM Tris-HCl pH 7.5, 1% Triton X-100, 1 mM sodium orthovanadate, 1 mM phenylmethylsulfonyl fluoride (PMSF), 50 mM sodium fluoride, 150 mM NaCl, 5 mM ethylene-diamine-tetraacetic acid (EDTA), 10% Glycerol (v/v), 0.5 mM diithothreitol (DTT) and protease inhibitor cocktail from Sigma). Cells were harvested with a plastic scraper and centrifuged at 13,000× g (4°C, 10 min). Supernatants were transferred to fresh tubes and stored at −20°C until used. Cell lysates were resolved by SDS-PAGE, transferred to a nitrocellulose membrane and blocked (5% milk in TBS-0.1% Tween 20) for 1 h. Primary Abs (anti-dually phosphorylated ERK, dually phosphorylated p38 and Total ERK, 1:1,000) were incubated for 16 h at 4°C. Membranes were washed (3×10 min) with TBS-0.1% Tween 20 and incubated 1 h with anti-mouse IgG conjugated with peroxidase (1:10,000). The reaction was visualized using luminal.

Nitrous acid deamination

Purified GPIPLs were delipidated by nitrous acid deamination (300 μl of 0.5 M sodium acetate and 300 μl of 0.5 M NaNO₂ for 16 h at 37°C [40]). Samples were dried, reconstituted in 0.1N HAc/0.1M HCl and applied to a phenyl-sepharose column (1 ml). The sugar head groups were eluted using 0.1N HAc/0.1M HCl. After washing column with 2 volumes of water, unreacted GPIPLs were eluted using Solvent E [H₂O/ethanol/diethyl ether/pyridine/NH₄OH, 15:15:5:1:0.017] [46].

Gel filtration

To desalt, deamidated GPIPLs were applied to Sephadex G-25 (1.5×5 cm) equilibrated with 10 ml of water. Eluted deamidated glycans were collected in 0.5 ml fractions, checked for the presence of salt using silver nitrate and dried in Speed-Vac [46].

Strong acid hydrolysis

To obtain depolymerized neutral monosaccharides, deamidated glycans were subjected to strong acid hydrolysis (2N trifluoroacetic acid, 3 h, 100°C) and dried in Speed-Vac. To remove acid, 500 μl of water were added to samples, homogenized using vortex and evaporated twice under N₂. Samples were reconstituted in 500 μl of water and desalted by ion exchange chromatography.

Ion exchange chromatography

To remove salt from neutral monosaccharides, dried depolymerized neutral monosaccharides were diluted in 500 μl of H₂O and applied onto a column containing AG1-X8 acetate form over AG50WX12 resin. Samples were eluted with 5 ml of water and dried in a Speed-Vac instrument [47].

Thin layer chromatography (TLC)

Intact and deamidated GPIPLs were chromatographed on TLC Silica Gel 60 plates (Merck). To compare rough GPIPL content of L. braziliensis, L. infantum and as reference, L. donovani. Intact GPIPLs were chromatographed in 1-butanol/10% glacial acetic acid/10% H₂O (3:1:1, v/v/v) for 20 h. To access Deamination by nitrous acid sensitivity, GPIPLs were subjected to nitrous acid deamination as described above and resolved in chloroform/methanol/1M ammonium hydroxide/1M ammonium acetate water (100:1:95:9:25 v/v/v/v) for 20 h. Bands were visualized as described above [46,48].

Fluorophore-assisted carbohydrate electrophoresis (FACE)

To access the oligosaccharide composition, deamidated GPIPLs headgroups were fluorescently labeled with 0.05 N ANTS (8-amino-1-naphthalene-3,6-disulfonic acid) and 1 M cyanoborohydride (37°C, 16 h). To determine the monosaccharide composition of the GPIPLs, depolymerized and desalted monosaccharides were fluorescently labeled with 0.1 M AMAC (2-aminomercapto) in 5% acetic acid and 1 M cyanoborohydride. Labeled sugars were subjected to FACE and the gel was visualized under UV light. Oligoglucose ladders (G₁–G₅) and monosaccharides (D-galactose, D-glucose and D-mannose Sigma were used as standards for oligosaccharides and monosaccharide gels, respectively [47,49].

HPLC

Desalted monosaccharides were separated using a DX-500 HPLC Dionex Corp.) with ESI+ electrochemical detection. Samples were run on a CarboPac PA10 column (4×250 mm) in the presence of 18 mM NaOH (flow rate 1 ml/min, 2000 psi). D-galactose, D-glucose and D-mannose (100 μg/ml) were used as standards.

Statistical analyses

For nitrite and cytokine measurements, the Shapiro-Wilk test was conducted to test the null hypothesis that data were sampled from a Gaussian distribution [50]. The P-value (P<0.05) showed that data did not deviate from Gaussian distribution. For this reason, student’s “t” test and ANOVA were performed to test equality of population means among groups and independent samples. Data were analysed using GraphPad Prism 5.0 software (Graph Prism Inc., San Diego, CA, USA) and P<0.05 was considered significant.

Results

Nitrite and cytokine production

To determine whether GPIPLs from both L. braziliensis and L. infantum are able to induce the production of nitrite, peritoneal macrophages were incubated with live promastigotes (10⁴) or treated with different concentrations of GPIPLs (1 to 25 μg/ml) with IFN-γ serving as positive control (100 U/mL). Neither of the purified GPIPLs could induce any detectable increase in the production of nitric oxide (NO) in primed BALB/c macrophages (Figure 2) nor the production of the cytokines tested (IL-1β, IL-2, IL-4, IL-5, IL-10, IFN-γ and TNF-α) in non-primed macrophages in all other mice lines (data not shown). NO production was detected in non-primed macrophages of BALB/c, C57BL/6, and TR2 mice (data not shown) and in BALB/c primed macrophages (Figure 3A). A higher NO production was detected in primed C57BL/6 IFN-γ-primed macrophages stimulated with GPIPLs and live promastigotes when compared to BALB/c mice (P<0.001). There was a significant NO production in primed C57BL/6 and TR2 mice (+/−) macrophages stimulated with GPIPLs in comparison to BALB/c (P<0.01) (Figure 3A) suggesting the involvement of TR2 in this activation. Also, a slight reduction of NO production was noticed in macrophages from TR2 mice stimulated with live promastigotes when compared to C57BL/6 (P<0.04). This reduction may indicate the participation of other parasite molecules that are recognized by TR2 such as the LPG. The LPG is known to be a potent agonist of TR2 and is capable of inducing the production of cytokines (IL-12, IFN-γ and TNF-α) in macrophages and NK cells [25,27]. Differently from NO, TNF-α production was higher in BALB/c.
Figure 2. Nitrite production by BALB/c primed macrophages after stimulation with different concentrations of GIPLs. C, negative control; IFN-γ, gamma-interferon; LPS, lipopolysaccharide; Gb, L. braziliensis GIPLs; Gi, L. infantum GIPLs. Cells were primed with IFN-γ (5 IU/ml) for 18 h prior to the addition of the GIPLs or LPS (positive control). Non primed cells and primed cells without the addition of a new stimulus were also used as controls. ANOVA test was performed and P<0.05 was considered significant. Results are the representation of three experiments in triplicate.

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Figure 3. Nitrite and TNF-α production by primed macrophages after stimulation with GIPLs and parasites. C, negative controls; Gb, L. braziliensis GIPLs; Gi, L. infantum GIPLs; Lb, L. braziliensis live promastigotes and Li, L. infantum live promastigotes. Cells were pre-incubated with IFN-γ (5 IU/ml) for 18 h then 25 μg/ml of GIPLs or 100 ng/ml of LPS was added. Supernatants were collected 48 hours later, in (A) NO concentrations were measured by Griess reaction and in (B) TNF-α concentrations determined by flow cytometry. ANOVA test was performed and P<0.05 was considered significant.

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Inhibition of nitrite and IL-12 production in BALB/c macrophages pre-exposed to GIPLs

In mice and in C57BL/6 (P<0.05) in response to the stimulation of GIPLs from both species. Similarly this production was higher in TLR2 (−/−) than TLR4 (−/−) (P<0.02). This data also indicate a slight TLR1 involvement in TNF-α production. In both WT macrophages, the TNF-α production was higher after stimulation with GIPLs in comparison to live promastigotes (Figure 3B) (P<0.01). A lower TNF-α production was noticed in TLR2 (−/−) suggesting the involvement of TLR2 in this process.

GIPLs did not induce the production of any of the cytokines tested (IL-1β, IL-2, IL-4, IL-5, IL-10, IL-12(p70) and IFN-γ) in BALB/c, C57BL/6, TLR2 (−/−) and TLR4 (−/−) mice (data not shown). In all experiments, live parasities from both species induced cytokine production close to background levels (Figure 3B and data not shown). These results suggest that GIPLs are able to activate NO in C57BL/6 mice and TNF-α in either BALB/c or C57BL/6 during the early steps of infection, and were not able to stimulate most of the cytokines assayed.

Inhibition of nitrite and IL-12 production in BALB/c macrophages pre-exposed to GIPLs

Compared to LPS, GIPLs had a less potent agonistic activity to stimulate nitrite and cytokine production in previous studies [27]. To test if this pattern was due to inhibition and/or lack of activation, thio-glucoside elicited peritoneal macrophages were pre-incubated with GIPLs prior to stimulation with IFN-γ or LPS. A strong inhibition (approx. 42%) of NO production stimulated by IFN-γ was observed for L. infantum GIPLs and was almost completely abolished for L. braziliensis (P<0.01) (Figure 4A). A similar response was observed for LPS and this inhibition was more pronounced in L. braziliensis (P<0.001) (Figure 4B). Pre-incubation with GIPLs was also able to inhibit approximately 63% of IL-12, but not TNF-α production (Figures 4C and D). These results indicate an inhibitory role of GIPLs.
Figure 4. Modulation of nitrite, TNF-α and IL-12 production by Leishmania GIPs in BALB/c macrophages. Cells were incubated with GIPs (25 μg/ml) from *L. braziliensis* (Gb) and *L. infantum* (Gi) for 15 min prior to stimulation with IFN-γ (100 IU/ml) (A) or LPS (100 ng/ml) (B). Nitrite content was measured by Griess reaction; TNF-α and IL-12 concentrations were measured by ELISA. *P* > 0.05 was considered significant. Results are the representation of three experiments.

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Figure 5. Modulation of nitrite production by macrophages stimulated with intact and PI-PLC treated GIPs. Mouse peritoneal macrophages were incubated with GIPs (25 μg/ml) from *L. braziliensis* (Gb), *L. infantum* (Gi), PI-PLC treated *L. braziliensis* GIPs (Gb PI-PLC) and *L. infantum* PI-PLC treated GIPs (Gi PI-PLC) for 15 min prior to stimulation with IFN-γ (100 IU/ml). Nitrite content was measured by Griess reaction on the supernatants after 24 h. Student "t" test was performed and *P* < 0.05 was considered significant. Results are the mean of two experiments.

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Also, to test whether the intact structure of GIPs is required for its inhibitory activity, macrophages were incubated with intact and PI-PLC treated GIPs. As shown on Figure 5, PI-PLC treated GIPs failed to inhibit NO production by IFN-γ stimulated cells.

**Activation of MAPKs**

Since GIPs were strong inhibitors of cytokine production, we investigated whether those molecules could modulate MAPKs activation. Mouse peritoneal macrophages were previously incubated with GIPs and MAPK activation was detected using western blot. No significant activation of p38 and only a minimal induction of ERK were observed. Also when cells were preincubated with GIPs prior to stimulation with LPS, there was a reduction on the phosphorylation of both ERK and p38 (Figure 6). densitometry analysis normalized by total-ERK expression detected an 11% and 17.5% decrease on ERK activation for *L. braziliensis* and *L. infantum*, respectively. For p38 this inhibition was 16.5% and 33%, respectively.

**Preliminary characterization of L. braziliensis and L. infantum GIPs**

Due to the interspecific differences in the intensity of NO and IL-12 production inhibition (Figures 4 and 5), and MAPKs activation (Figure 6), we examined whether those variations could be due to polymorphisms in GIPs structure and composition. Intact GIPs were resolved on TLC plates and the GIP profile differed between the two species (Figure 7A). *Leishmania braziliensis* exhibited slower migrating GIPs compared to *L. infantum*, whose...
Figure 6. Activation of MAPKs (ERK and p38) by *Leishmania* GIPs in BALB/c peritoneal macrophages. Macrophages were stimulated with 30 min with 25 μg/mL of GIPs. Dually phosphorylated MAPKs were detected by western blot. C. negative control; Gb, L. braziliensis GIPs; and Gi, L. infantum GIPs. Also, cells were incubated with GIPs prior to stimulation with LPS; total ERK content as a normalizing protein.

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profile was very similar to *L. donovani* [32] with three main bands co-migrating with isoM2, isoM3 and isoM4. In *L. braziliensis*, the three faster bands co-migrated with bands isoM2, isoM3 and isoM4 of *L. donovani*. All bands were susceptible to nitrile acid degradation, and this is consistent with the presence of the GIPLs of a non-N-substituted glucosamine residue (Figure 7B), a hallmark of *Leishmania* GIPLs anchors [51].

To better determine sizes of the glycan portions, purified GIPLs were deaminated and desalted. The carbohydrate portions were reductively labeled with a fluorophore and then subjected to FACE. Consistent with the TLC data (Figure 7), the carbohydrate portions of the GIPLs from *L. braziliensis* were larger exhibiting up to 6–9 sugars while those from *L. infantum* and *L. donovani* consisted of up to 4–5 sugars (Figure 8).

To access sugar composition, GIPLs were subjected to strong acid hydrolysis and the resulting monosaccharides were analysed by FACE and HPLC (Figure 9A and B). Consistent with the TLC data (Figure 7A), the monosaccharide composition of the GIPLs from *L. donovani* (Figure 9A). The relative amounts of galactose, glucose and mannose (calculated by the relative peak areas on HPLC) were determined (Figure 9B). Supporting our earlier findings and GIPL assignments, the GIPLs from *L. infantum* had higher concentrations of mannose (36%), followed by galactose (12%) and glucose (5%). This indicates that these are mostly Type I or hybrid GIPLs, whose structure bears a terminal mannose, but a small proportion of Type II GIPLs (terminated in galactose) is probably present. On the other hand, *L. braziliensis* GIPLs had higher galactose content (42%), followed by, mannose (30%) and glucose (28%), thus suggesting a Type II GIPL structure.

**Discussion**

Infection with protozoan parasites remains a prominent problem in different parts of the world having a major impact on public health in the developing countries. Leishmaniasis are considered by World Health Organization [52] as one of the major six important infectious diseases worldwide. This class of parasitic diseases currently affects over 12 million people all around the world, up to 1.5 million new individuals developing the visceral and tegumentary disease respectively each year. In Brazil, most of these cases are caused by *L. infantum* and *L. braziliensis*, respectively.

The question of how parasites interact with host cells to promote infection and survival has been the focus of interest for a long time. In order to survive in the macrophage cells, *Leishmania* has to prevent or inhibit a variety of intracellular mechanisms of parasite killing, one of which is dependent on ROS and RNI [53,54]. However, RNI alone is effective for controlling visceral Leishmaniasis [55].

Parasite surface molecules, especially the LPG, have long been known to play an important role in the host-parasite interactions [17,27,28]. In this work, we focused on another class of glycoconjugates, the GIPLs, in two New World species of *Leishmania* with different known immunopathologies. These molecules are abundantly present on the parasite surface in...
numbers great that $10^5$. Recently, they have been found associated to lipid rafts, essential for parasite infectivity and selective modulation of the host cell response [39]. In fact, there are several indications that GPIls and other GPI-anchored molecules participate in cell signaling and are involved in the assembly of the NADPH oxidase complex. NO production [16,57,58,59] and inhibition of LPS and TNF-z induction of the NO gene expression by macrophages [61]. Also, synthetic LPg, whose GPI anchor is structurally similar to GPIls, can stimulate ERK activation and therefore inhibit IL-12 synthesis by macrophages [9].

Previous studies have demonstrated GPIls antigenicity in chronic patients infected with L. major [31,62]. However, information concerning the biological relevance of GPIls at early steps of infection in the innate immune compartment was still limited. Here, we demonstrated that GPIls from both New World species were not able to activate the production of NO in non-prrimed macrophages, which was similar to published data from Old World species [59,60]. In primed macrophages an initial NO and TNF-z production was detected. Further, GPIls differentially inhibited NO production even in the presence of IFN-z and LPS, two major NO inducers. Previous studies indicated that LPg was a more potent agonist than GPIls for the induction of proinflammatory cytokines [20,27]. In general, in comparison to LPS, GPIls induced a lower production of NO and TNF-z. Also, they exhibited a strong inhibitor pattern during NO and cytokine induction, especially IL-12.

Similar strategy was demonstrated using crude extracts of the rat tapeworm Hymenolepis diminuta, although using different pathways. As shown by Johnston et al. [2010] [63], crude extracts of this tapeworm could inhibit the production of TNF-z and IL-6 by mouse and human macrophages stimulates with TLR agonists poly(I:C) and flagellin. These extracts also protected mice from experimental colitis accompanied by enhanced IL-10 and IL-4 production.

In vivo studies using Old World species of Leishmania have demonstrated the importance of TLRs and other components of the innate immune system during infection. Mx1D80 is the most common adaptor molecule for the activation of NF-kB in most TLRs [28]. Also many studies using gene knockout of Mx1D80 is the most common adaptor molecule for cytokine production [29]. IL-10 production [64], IFN-z and IL-12 production [65].

NF-kB activation through TLR2 [26], cAMP-dependent protein kinase of L. major promastigotes [66], and ultimately parasite control and lesion healing [27,65,67].

Indeed, in primed macrophages, GPIls from both New World species were able to stimulate the production of NO, and this induction was mostly via TLR4 and to a lesser extent TLR2 (Figure 3A). However, no difference was observed while stimulating with live parasites.

Interestingly, in the L. braziliensis model, the TLR2 receptor plays a much more regulatory role in dendritic cells, repressing IL-12p40 and promoting IL-10 expression. This observation is correlated with sustained IFN-z production and enhanced parasite control in TLR2 (-/-) mice [68]. However, in macrophages exposed to GPIls, this difference in NO expression between TLR2 (-/-) and TLR4 (-/-) strains was not due to IL-12, IFN-z or IL-10 production [Figure 3B and 4]. Also this induction was more pronounced in C57BL/6 than in BALB/c this was expected since C57BL/6 derived macrophages tend to be more responsive to stimuli than BALB/c macrophages [69]. These data are in accord with previous studies showing that related GPIls from Trypanosoma cruzi are able to activate TLR4 [70] and studies with

![Figure 8. Fluorophore-assisted carbohydrate electrophoresis (FACE) of Leishmania GPIls.](image)

![Figure 9. Monosaccharide profile of Leishmania glycoinositol-phospholipids (GPIls).](image)
Old World species of *Leishmania* being able to activate TLR2, TLR3, TLR4 and TLR9 [28]. With exception to TNF-α, GPIs and live parasites from *L. braziliensis* and *L. infantum* were not able to induce the other cytokines studied (IL-1β, IL-2, IL-4, IL-5, IL-10, IL-1β/10 and IFN-γ) in primed and non-primed macrophages (data not shown). Thus, we conclude that the GPIs from these two *Leishmania* species are less potent agonists or strong inducers for macrophages and the data presented here supports that the later might be true.

When pre-incubated with GPIs, a strong inhibition of both NO and IL-12 production was observed (Figures 4C and D). This inhibitory effect seems to be in specific pathways since no significant inhibition was detected for TNF-α (Figure 4C). This inhibition is dependent on the intact structure of GPIs since PIPLCs digested GPIs that have its glycan core detached from its lipid anchor, failed to inhibit NO production by IFN-γ stimulated macrophages (Figure 5). Also, regarding TNF-α, only WT mice were able to trigger the production of this cytokine and this production was very low for TLR2 (−/−) and completely absent in TLR1 (−/−) (Figure 3B). These data support the premise that NF-κB translocation is not affected by GPI exposure [71]. It is noteworthy that the inhibition of IL-12 is not due to production of IL-10, because we observed no IL-10 production either in unprimed (data not shown) or in primed macrophages incubated with GPIs (Data not shown). Simultaneously, the most common adaptor molecule is MyD88 but other adaptor molecules may be involved in NF-κB translocation such as mitogen-activated protein kinases [72] or p38 [73]. Early studies showed that the *Leishmania* LPG can inhibit IL-12 without affecting NF-κB translocation to the nucleus [9].

For maximal downstream activation and GPI-induced gene expression, a full activation and cooperation Protein Tyrosine Kinase (PTK) and Protein Kinase C (PKC) are required. Although MyD88 is able to stimulate rapid PTK phosphorylation it failed in activating PKC [10]. In fact the unusual glycolipid composition (mostly alkyl-acrlyglycerol) of *Leishmania* GPIs inhibits the activations of PKC [58,73]. This is in accordance with our observations that GPIs not only fail on inducing a pro-inflammatory response in non-macrophages but also that the GPIs inhibit the production of IL-12 and NO.

Also we tested whether GPIs from both New World species were able mediate the phosphorylation of MAPKs. We observed that the GPIs activate only ERK, whereas LPS activated both ERK and p38 (Figure 6). Also we observed that the GPIs can prevent the phosphorylation of both ERK and p38 MAPKs stimulated by LPS. However, ERK activation was too low to provide evidence for any further effect on IL-12 production. It is likely that *L. braziliensis* and *L. infantum* GPIs have a profound effect on macrophage cell signaling affecting PTKs, PKCs and MAPKs, and that GPIs from both species use similar pathways but differ in the intensity in which they modulate NO and IL-12 production.

In this work, GPIs interacted with primed macrophages resulting only in the production of NO and TNF-α. GPIs are abundant in the amastigote stage of *Leishmania* and are associated to highly specialized microdomains [39] and the participation of each kind of GPI on the process is still under debate [74,75,76]. Also it is possible that the dependency on a particular glycolipid may vary throughout species and life cycle stage. The data presented here clearly supports the hypothesis that *Leishmania* GPIs, differently from other trepanosomatids, may contribute to build a safer environment to promote infection by manipulating macrophage function and by disrupting the polarization of TH1/TH2 response, through inhibiting IL-12 production during the initial stages of infection and manipulate macrophage for parasite survival.

In general, LPGs and GPIs share similar lipid anchor moieties among the various species of *Leishmania* and the integrity of this portion is important for TLR2 activation [27]. To ascertain if the differences in the inhibition of NO and IL-12 production could be related to polymorphisms in GPI structure, we analyzed the carbohydrate core of *L. braziliensis* and *L. infantum* GPIs. Previous studies from our group showed that the phosphoglycan domains of LPGs from *L. braziliensis* and *L. infantum* differ in structure and composition [10,41] and differences in glycan portions of GPIs were also observed in this study. The iM2 species of GPIs possess the structure Manz1-3Manz1-4GlcN-P, similar to LPG core region, and isoM3 has a hybrid glycan in GPIs substitutions on both the third and sixth carbons of the distal mannos) with the structure of Manz1-6Manz1-3Manz1-4GlcN-P. Our structural observations indicated that the GPIs from *L. infantum* are similar to the known structures and are substituted mainly of mannosic residues. This data suggests that the majority of these GPIs may be Type I GPIs and Hybrid GPIs. On the other hand, *L. braziliensis* GPIs shows a different profile of sugar composition and different bands distinguishable on TLC (Figure 7A). We determined that there was a stoichiometric ratio of galactose and mannosic in the glycan portion of these GPIs. This data suggest that these GPIs are similar to the closely related species *L. braziliensis* [36], which have a common Galβ1-3Manβ1-3Manβ1-4GlcN-acyloxytocular glycan headgroup and a structurally related to LPG lipid anchor, suggestive of Type II GPI. Type II GPIs can be very diverse and substitutions on the 3rd carbon of the Gal residue by Galβ1-3Galβ1-3galβ1, and even longer suchanides like Manβ1-3PO2Glα worried can be detected in other species like *L. major* [31]. These substitutions can lead to large GPIs containing up to 7, 8 or even more hexoses [34,36], which we observed from the *L. braziliensis* GPIs as seen on Figure 8.

In conclusion, GPIs from both New World species *L. infantum* and *L. braziliensis* have a strong inhibitory potential during intracellular *Leishmania* infection of the mammalian host. Only an initial production of NO and TNF-α was detected after stimulation by GPIs. Due to their importance in modulating NO and cytokine production, these molecules could be possible targets to alternative immunological and chemotherapeutic control methods. The preliminary qualitative analysis of GPIs from these two species showed that they differ in composition and structures thus, suggesting that the structural distinctions could be responsible for differential NO and IL-12 inhibition in macrophages. Also, GPIs were also capable of affecting macrophage ability to produce NO in the presence of IFN-γ and LPS. These data, together with already published data from other groups, suggest that GPIs may be involved in the interaction with the macrophage triggering a minimal pro-inflammatory response in the host and to the benefit of the parasite. Phylogenetic interspecies polymorphisms, not only in the GIps, but also in LPGs and other GPI-anchored molecules could be important for differential establishment of infection. These polymorphisms could result in different clinical outcomes, such as those shown by *L. infantum* and *L. braziliensis*, causative agents of visceral and tegumentary forms, respectively [77].

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