



A comparative study of the effects of venoms from five rear-fanged snake species on the growth of *Leishmania major*: Identification of a protein with inhibitory activity against the parasite

María E. Peichoto^{a,b,*}, Flávio L. Tavares^b, Gregory DeKrey^b, Stephen P. Mackessy^b

^a Cátedra de Farmacología, Facultad de Ciencias Veterinarias, Universidad Nacional del Nordeste, Sargento Cabral 2139, 3400 Corrientes, Argentina

^b School of Biological Sciences, University of Northern Colorado, 501 20th St., CB 92, Greeley, CO 80639-0017, USA

ARTICLE INFO

Article history:

Received 25 November 2010

Received in revised form 24 April 2011

Accepted 27 April 2011

Available online 12 May 2011

Keywords:

Antileishmanial activity

Hypsiglena torquata texana

Philodryas baroni

Philodryas olfersii olfersii

Philodryas patagoniensis

Phospholipase A₂

Trimorphodon biscutatus lambda

ABSTRACT

Leishmania parasites of several species cause cutaneous and visceral disease to millions of people worldwide, and treatment for this vector-borne protozoan parasite typically involves administration of highly toxic antimonial drugs. Snake venoms are one of the most concentrated enzyme sources in nature, displaying a broad range of biological effects, and several drugs now used in humans were derived from venoms. In this study, we compared the effects of the venoms of the South American rear-fanged snakes *Philodryas baroni* (PbV), *Philodryas olfersii olfersii* (PooV) and *Philodryas patagoniensis* (PpV), and the North American rear-fanged snakes *Hypsiglena torquata texana* (HttV) and *Trimorphodon biscutatus lambda* (TbIV), on the growth of *Leishmania major*, a causative agent of cutaneous leishmaniasis. Different concentrations of each venom were incubated with the log-phase promastigote stage of *L. major*. TbIV showed significant anti-leishmanial activity (IC₅₀ of 108.6 µg/mL) at its highest concentrations; however, it induced parasite proliferation at intermediate concentrations. PpV was not very active in decreasing the parasitic growth, and a high final concentration (1.7 mg/mL) was necessary to inhibit proliferation by only 51.5% ± 3.6%. PbV, PooV and HttV, at final concentrations of 562, 524 and 438 µg/mL respectively, had no significant effect on *L. major* growth. The phospholipase A₂ of TbIV (trimorphin) was isolated and assayed as for crude venom, and it also exhibited dose-dependent biphasic effects on the parasite culture, with potent cytotoxicity at higher concentrations (IC₅₀ of 0.25 µM; 3.6 µg/mL) and stimulation of proliferation at very low concentrations. Anti-leishmanial activity of TbIV appears to be solely due to the action of trimorphin. This is the first report of anti-leishmanial activity of rear-fanged snake venoms, and these results suggest novel possibilities for discovering new protein-based drugs that might be used as possible agents against leishmaniasis as well as tools to study the biology of *Leishmania* parasites.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Leishmaniasis is an anthroponosis caused by cutaneous infection with protozoan parasites of the genus

Leishmania following the bite of an infected sandfly (commonly *Phlebotomus* sp.). It is a severe disease affecting millions of people in Africa, America, Europe and Asia (Desjeux, 1992). Because of its prevalence and morbidity, this disease has been considered a serious health problem by the World Health Organization (WHO) and is statistically the second most important parasitic disease worldwide (Rath et al., 2003).

Currently, the main drugs used for the treatment of patients are pentavalent antimonials, whereas the antifungal

* Corresponding author. Universidad Nacional del Nordeste, Facultad de Ciencias Veterinarias, Cátedra de Farmacología, Sargento Cabral 2139, 3400 Corrientes, Argentina. Tel./fax: +54 3783 425753.

E-mail addresses: mepeichoto@yahoo.com.ar, mepeichoto@conicet.gov.ar (M.E. Peichoto).

drug amphotericin B (a polyene macrolide antibiotic) is considered an efficient treatment option for many antimonial-resistant strains of *Leishmania* (Rosenthal et al., 2009). Other drugs, such as allopurinol, miltefosine and pentamidine also represent important options for leishmaniasis treatment (Loiseau and Bories, 2006). However, effective new anti-leishmanial compounds are needed due to the high costs, development of parasite resistance and side effects related to those drugs currently in use. Importantly, no licensed human vaccine for leishmaniasis is available.

A productive, more recent approach to the search for more efficient and less toxic chemotherapeutic agents has been the screening of natural compounds able to inhibit protistan growth. Snake venoms, one of the most concentrated enzyme sources in nature, are complex mixtures of proteins, peptides and small organic molecules whose composition varies phylogenetically and as a function of other factors, overall displaying a broad range of biological effects (Mackessy, 2010). Previous studies have shown that the venom of the front-fanged snakes *Bothrops marajoensis* (Costa Torres et al., 2010), *Bothrops moojeni* (Tempone et al., 2001), *Bothrops jararaca* (Gonçalves et al., 2002), *Crotalus durissus terrificus*, *Crotalus durissus cascavella*, *Crotalus durissus collilineatus* (Passero et al., 2007), *Cerastes cerastes* and *Naja haje* (Fernandez-Gomez et al., 1994) can inhibit the growth of different *Leishmania* species. However, at present no venoms from rear-fanged snakes, most species of which do not represent a risk to humans, have been evaluated for anti-protist activity.

There is tremendous potential for discovering novel bioactive compounds in rear-fanged snake venoms, because this is the most speciose group of advanced snakes and relatively few studies have investigated their composition and biological activities (Mackessy, 2002). The current study evaluates new sources of potential anti-leishmanial compounds from rear-fanged snake venoms. In this study, we compared the effects of the venoms of the South American rear-fanged snakes *Philodryas baroni* (PbV), *Philodryas olfersii olfersii* (PooV) and *Philodryas patagoniensis* (PpV), and the North American rear-fanged snakes *Hypsiglena torquata texana* (HttV) and *Trimorphodon biscutatus lambda* (TbIV), as well as a purified PLA₂ from *T. b. lambda* venom, on the growth of the promastigote stage of *Leishmania major*, a causative agent of cutaneous leishmaniasis, as an initial screen of their potential anti-leishmanial activity.

2. Materials and methods

2.1. Rear-fanged snake venoms

Pools of *P. patagoniensis* and *P. o. olfersii* venoms were obtained from wild specimens captured in northeastern Argentina and then maintained at the serpentarium of the local Zoo, Corrientes, Argentina. Specimens were extracted by introducing a 100- μ L micropipette under each fang, according to a procedure described previously (Ferlan et al., 1983).

Hypsiglena torquata and *T. biscutatus* venoms were obtained from wild specimens captured in Colorado and Arizona, USA (scientific collecting permits MCKSY000221

and 0456), and maintained in the UNC Animal Facility. Four captive-born specimens of *P. baroni* were obtained from the Dallas Zoological Park and were also maintained in the UNC Animal Facility. All housing and handling procedures were approved by the UNC-IACUC (protocols #9204.1 & 9401). Extraction of snakes utilized a previously published method (Hill and Mackessy, 1997; Rosenberg, 1992).

After extraction, all venoms were centrifuged, lyophilized and kept frozen at -20°C . When required, venoms were dissolved in 0.01 M phosphate buffer saline (PBS), pH 7.4, and filtered through a 0.22 μm Millipore filter to remove insoluble material and to sterilize.

2.2. Protein concentration determination

Protein concentration was assayed in triplicate according to Bradford (1976) as modified by BioRad Inc. (Hercules, CA, USA), using bovine gamma globulin as a standard.

2.3. Purification of phospholipase A₂ (PLA₂) from TbIV

TbIV was dissolved in 25 mM HEPES buffer containing 100 mM NaCl (pH 6.8). Two hundred microliters (4 mg) of the venom was injected onto a TSKgel G2000 SWXL size exclusion column (7.8 mm i.d., 30 cm, 5 μm) (TOSOH Bioscience LLC, Tokyo, Japan) at a flow rate of 0.15 mL/min using the same buffer (Waters HPLC), and chromatograms were recorded using Empower software. Fractions were collected and assayed for PLA₂ activity (see below). Selected fractions were electrophoresed on NuPAGE[®] Novex[®] 12% Bis-Tris gels (Invitrogen, Inc., Carlsbad, CA, USA). Active fractions were pooled and applied to a Protein and Peptide C₁₈ column (5 μm , 4.6 mm i.d. \times 250 mm) (VYDAC, Hesperia, CA, USA) equilibrated with solvent A [0.1% (v/v) trifluoroacetic acid (TFA) in Milli-Q water], using a Waters HPLC system. Bound proteins were eluted with 0–100% increasing linear gradient of solvent B [0.1% TFA/80% acetonitrile (ACN)] at a flow rate of 1 mL/min for 90 min. The elution profile was monitored at 220 and 280 nm.

2.4. PLA₂ activity assay

PLA₂ enzyme activity was determined by the method of Holzer and Mackessy (1996), using 4-nitro-3-(octanoyloxy) benzoic acid as substrate. The assay buffer was 10 mM Tris-HCl (pH 8.0) containing 10 mM CaCl₂ and 100 mM NaCl.

2.5. SDS-PAGE

Crude venoms and purified PLA₂ fractions were subjected to SDS-PAGE using NuPage Bis-Tris gels (Invitrogen, Inc., Carlsbad, CA, USA), MES/SDS running buffer and 24 μg venom/lane as described previously (Weldon and Mackessy, 2010). Following staining with Coomassie brilliant blue R-250 and destaining, the gel was imaged using an Alphamager (Cell Biosciences, Inc., Santa Clara, CA, USA).

2.6. Mass spectrometry

In order to determine the molecular mass of the purified PLA₂, approximately 1 μg protein in 50% ACN containing

0.1% TFA was spotted onto a MALDI sample holder, mixed with an equal volume of 10 mg/mL sinapinic acid in 50% ACN containing 0.1% TFA, and allowed to dry. Mass spectrum was obtained using a Bruker Ultraflex II MALDI-TOF/TOF mass spectrometer.

For unequivocal identification of the purified PLA₂, gel bands of interest were excised, destained and subjected to reduction with DTT, alkylation with iodoacetamide, and then in-gel digestion with mass spectrometry grade Trypsin Gold (Promega, Madison, WI, USA), following the manufacturer's instructions. The tryptic peptide mixtures were purified and concentrated using ZipTip® C18 pipette tips (Millipore Corporation, Billerica, MA, USA). The peptides eluted from the ZipTip® tips were dried in a Speed-Vac and redissolved in 5 µL of 50% ACN containing 0.1% TFA. Digests (1 µL) were spotted onto a MALDI sample holder, mixed with an equal volume of 10 mg/mL α-cyano-4-hydroxycinnamic acid in 50% ACN containing 0.1% TFA, dried, and analyzed with a Bruker Ultraflex II MALDI-TOF/TOF mass spectrometer. Singly-charged ions of selected peptides from the MALDI-TOF mass fingerprint spectra were sequenced by collision-induced dissociation tandem mass spectrometry. Spectra were interpreted using the on-line form of the MASCOT program at <http://www.matrixscience.com>.

2.7. Parasite viability assays

L. major parasites (LV39, RHO/SU/59/P, Neal, or P strain) were obtained as a generous gift from R. Titus (Colorado State University, Ft. Collins, CO, USA). The parasites were isolated from infected foot pads of C57BL/6 mice 7–10 days after infection and maintained *in vitro* as previously described (Sacks and Perkins, 1984) in Schneider's *Drosophila* medium (Sigma, St. Louis, MO, USA) containing 10% fetal bovine serum (FBS), hemin (0.005%), penicillin (100 U/mL), streptomycin (100 µg/mL), gentamicin (50 µg/mL), CaCl₂ (0.6 mg/mL), and NaHCO₃ (0.4 mg/mL). Promastigotes in logarithmic phase of growth (1 × 10⁶ parasites/mL, 100 µL/well) were used for parasite viability assays which were performed in 96-well microplates, according to a previous method (Mukherjee et al., 2009) with some modifications. Briefly, venom samples were added to cultured cells at various final concentrations; amphotericin B was utilized as positive control at a final concentration of 100 µg/mL. Controls containing only parasites were also included. Plates were incubated at 26 °C for 72 h, and parasite viability was determined colorimetrically by the MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assay (e.g., Passero et al., 2007; Costa Torres et al., 2010) according to the manufacturer's instructions (ATCC, Manassas, VA, USA). The IC₅₀ values were calculated from the dose-response curves of each experiment using Microsoft-Excel software. Experimental samples were evaluated in triplicate and experiments were repeated at least twice.

2.8. Statistical analysis

The data are presented as mean ± standard deviation (SD). Results were analyzed using one-way analysis of

variance (ANOVA) with the Holm-Sidak method for multiple comparisons versus control group. Statistical analyses were performed using the software SigmaStat for Windows, version 3.5. A value of $p < 0.05$ indicated statistical significance.

3. Results and discussion

The effect of the whole venom from front-fanged snakes on *Leishmania* promastigotes has been well documented (Costa Torres et al., 2010; Fernandez-Gomez et al., 1994; Gonçalves et al., 2002; Passero et al., 2007; Tempone et al., 2001). Nonetheless, no reports in the literature describe the effects of the venom of rear-fanged snakes on *Leishmania* parasites, or even on any other kind of microorganism. Venoms from *P. baroni*, *P. o. olfersii*, *P. patagoniensis*, *H. t. texana* and *T. b. lambda* contain a diversity of protein/peptide components (Fig. 1) and the activity of these "colubrid" venoms toward *L. major* promastigote proliferation was assessed.

Trimorphodon venom showed significant anti-leishmanial activity (Fig. 2), exhibiting an IC₅₀ value of 108.6 µg/mL against the promastigote stage. An intriguing stimulant effect on parasite growth was observed at intermediate concentrations of the venom (48 µg/mL). *P. patagoniensis* venom showed low activity toward parasitic

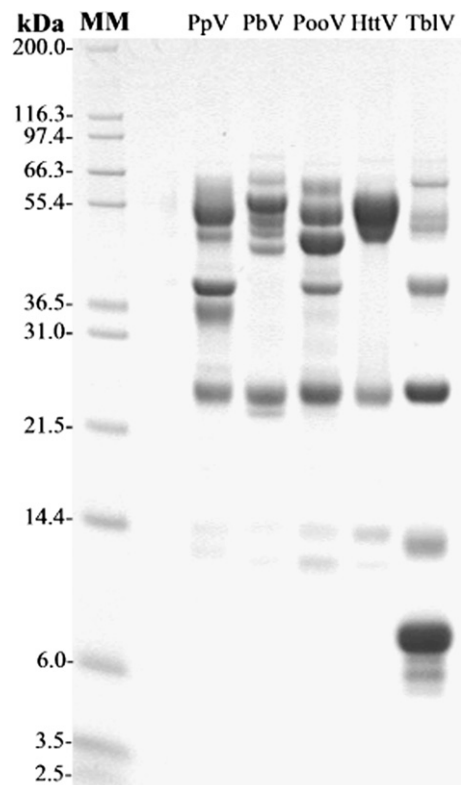


Fig. 1. SDS-PAGE of venoms from five rear-fanged snake species (24 µg) under reducing conditions on NuPAGE Novex 12% Bis-Tris gel; stained with Coomassie Brilliant Blue. Novex Mark 12 molecular mass standards (MM) are on the left lane of the gel.

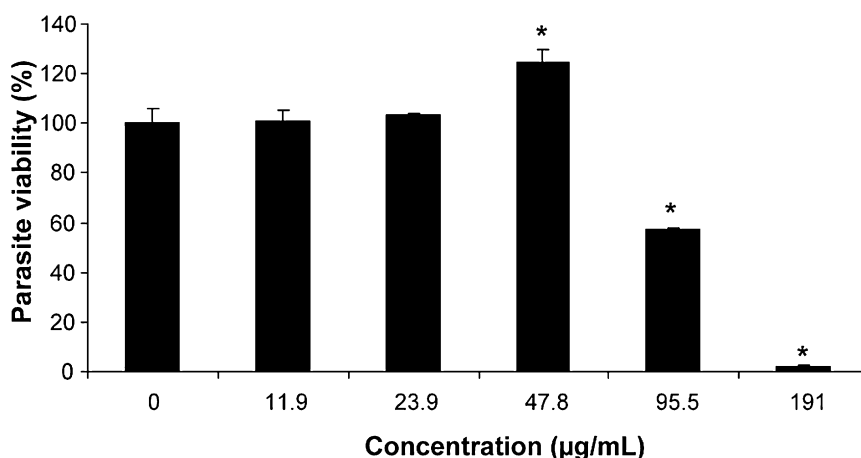


Fig. 2. Effects of different concentrations of TbV on the log-phase promastigote stage of *L. major*. The initial parasite density was 1×10^6 cells/mL. Parasite viability was determined by MTT assay after 72 h of incubation. The graph presents means \pm SD ($n = 3$). * $p < 0.05$ compared to the control group.

growth (Fig. 3), and a very high final concentration of 1.7 mg/mL was necessary to inhibit parasite proliferation by only $51.5 \pm 3.6\%$. This venom represents an example of non-specific effects against parasite growth and results provide rationale for *not* considering it further for possible drug screening. Venoms from the other three species (PbV, PooV and HttV), at final concentrations of 562, 524 and 438 $\mu\text{g/mL}$ respectively, had no significant effect on *L. major* growth (data not shown).

We recently observed that one of the most significant differences among the five rear-fanged snake venoms tested is the presence of PLA₂ activity in TblV only (Peichoto et al., 2010). In addition, a comparison of size exclusion HPLC chromatograms revealed the presence of three differential protein peaks in TblV (Peichoto, unpublished data). Only one of these contained anti-leishmanial activity (Fig. 4a), and it corresponded to the PLA₂ active fraction of the venom. This enzyme was further purified by C₁₈ reversed-phase HPLC (Fig. 4b), and SDS-PAGE demonstrated a high degree of

purity (Fig. 4c). Mass spectroscopic analysis revealed a single peak with a molecular mass of 13,962 Da (Fig. 4d). This enzyme was previously named trimorphin, the PLA₂ isolated in native form from the venom of the Sonoran Lyre Snake *T. b. lambda* by Huang and Mackessy (2004). SDS-PAGE-separated protein bands were excised, in-gel digested with trypsin and the resulting peptides were analyzed by MALDI-TOF peptide mass fingerprinting (Fig. 4e) followed by MALDI-TOF/TOF. The MS/MS spectrum of the fragmented singly-charged peptide ion ($m/z = 2419.692$) was matched by MASCOT to an internal sequence, NVNCEGDNDECGAFVCECDR, from a PLA₂ (trimorphin) also sequenced from the venom gland transcriptome of *T. biscutatus* (Fry et al., 2008). When assayed for anti-leishmanial activity under similar conditions used for assessing crude venom effects, trimorphin was very active against *L. major* (Fig. 5), exhibiting an IC₅₀ value of 0.25 μM (3.6 $\mu\text{g/mL}$). This value is comparable to that exhibited by gyroxin, the fraction from the venom of *C. d. cascavella* most active against

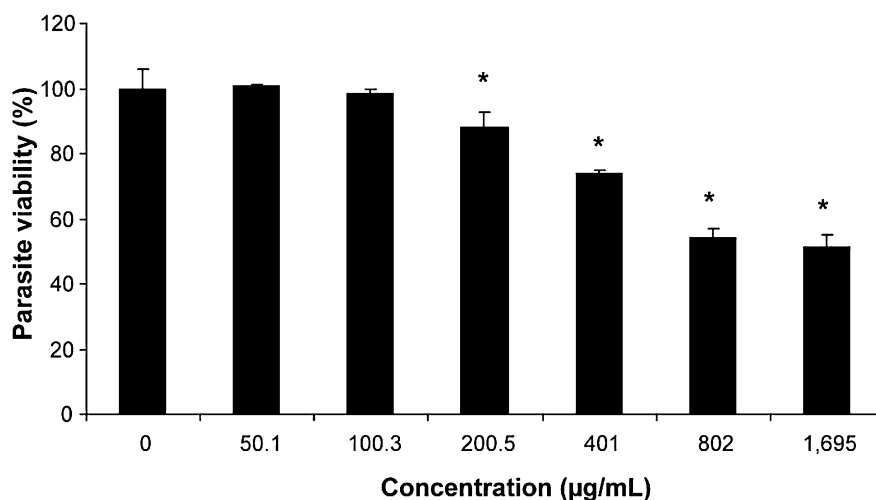


Fig. 3. Effects of different concentrations of PpV on the log-phase promastigote stage of *L. major*. The initial parasite density was 1×10^6 cells/mL. Parasite viability was determined by MTT assay after 72 h of incubation. The graph presents means \pm SD ($n = 3$); note that exceptionally high concentrations of this venom were required to obtain statistically significant effects on parasites. * $p < 0.05$ compared to the control group.

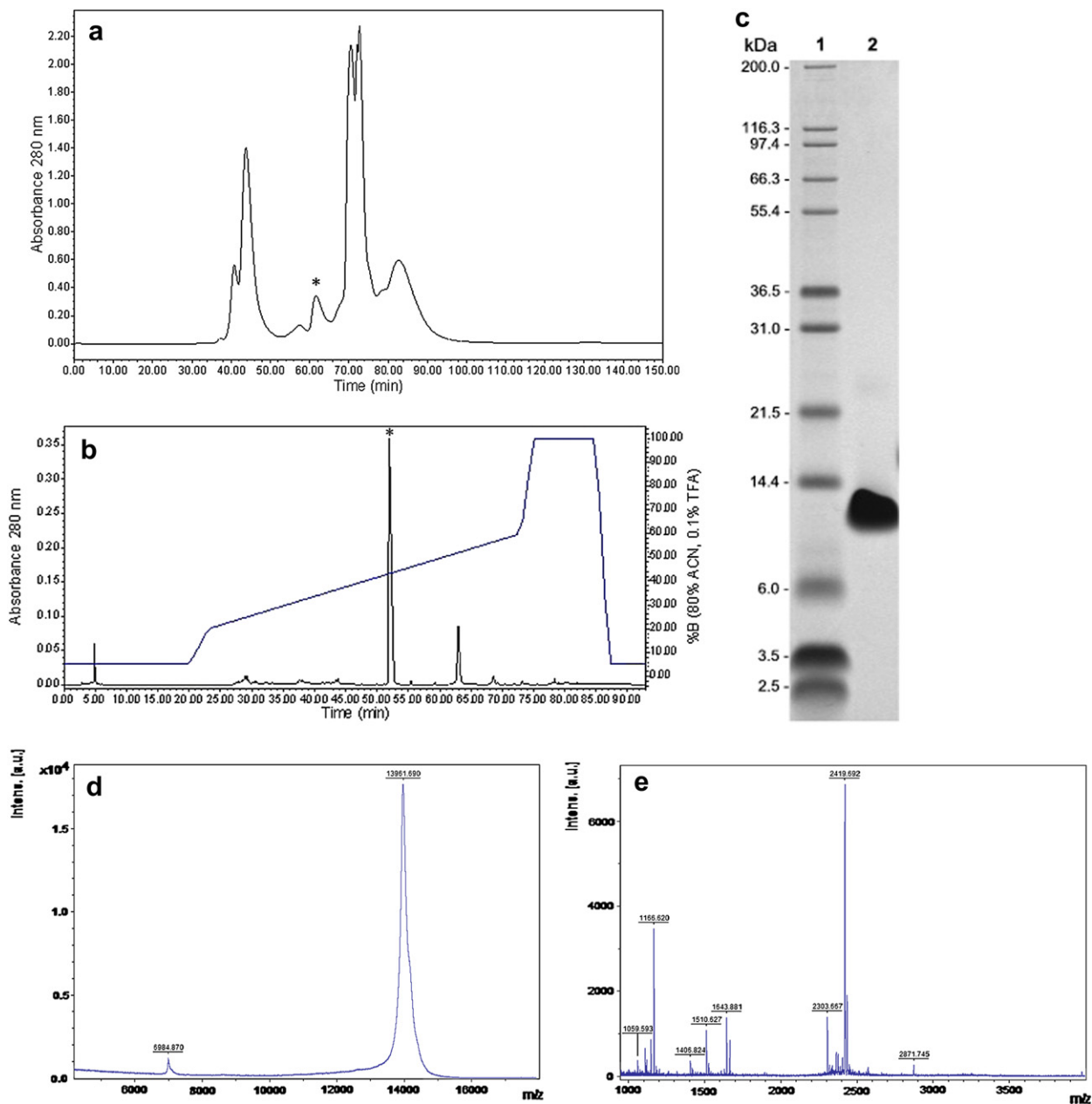


Fig. 4. (a) Size exclusion HPLC separation of crude TbIV (4 mg). Proteins eluting between 60 and 65 min (*) showed anti-leishmanial and PLA₂ activities. (b) Second step for purification of PLA₂ on analytical reversed-phase HPLC. The PLA₂ peak from SE-HPLC was applied to a C₁₈ column, and the resulting highly purified PLA₂ (*) was eluted with a 20–60% linear gradient of solvent B. (c) SDS-PAGE of PLA₂ from TbIV under non-reducing conditions. Lane 1: Novex Mark 12 protein standards. Lane 2: RP-HPLC purified PLA₂ (trimorphin), approximately 10 µg protein; note lack of contaminant bands. (d) MALDI-TOF mass spectrum of the intact enzyme. A single peak with a molecular mass of 13,962 Da is seen, and the 6.98 kDa peak is the doubly charged ion of the enzyme. This data also shows that the isolation method produces a highly purified product. (e) MALDI-TOF mass spectrum of trimorphin in-gel digested with trypsin. MS/MS CID sequence of peptide 2419.692 matched internal sequence of PLA₂ of *Trimorphodon biscutatus*.

Leishmania amazonensis promastigotes (Passero et al., 2007). However, it is less potent than amphotericin B, a standard anti-leishmanial drug, which showed an IC₅₀ of 0.2 µg/mL against *L. major* (Sabina et al., 2005), though on a molar basis it shows comparable potency. The amount of purified trimorphin required to eliminate parasite viability is approximately 3.3% of the amount of crude venom required to accomplish the same decrease in viability;

significantly, PLA₂ represents about 3.2% of the total protein of the venom. Thus, it is likely that the anti-leishmanial activity of TbIV can be accounted for solely by the mass of trimorphin present in this venom.

Snake venom PLA₂s are multifunctional proteins that induce important biological effects, such as inflammation, myotoxicity and other deleterious effects following snake envenomation (Doley et al., 2010). However, these enzymes

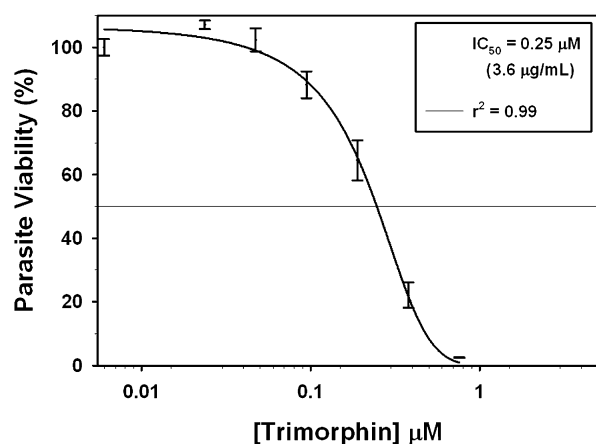


Fig. 5. Effects of different concentrations of trimorphin (PLA₂ isolated from TblV) on the log-phase promastigote stage of *L. major*. The initial parasite density was 1×10^6 cells/mL. Parasite viability was determined by MTT assay after 72 h of incubation. The graph presents means \pm SD ($n = 3$). Trimorphin molar concentrations are based on a mass of 13.962 kDa.

have been extensively studied and used in some applied areas of biomedicine: detection of severe pre-eclampsia, general anesthetic action, treatment of rheumatoid arthritis, as bactericidal agents in lachrymal glands and other tissues, as a new class of HIV inhibitors by blocking host cell invasion, and as potential antimalarial agents (Costa et al., 2008; Soares et al., 2004; Stabeli et al., 2006). In addition, some snake venom PLA₂s show antitumoral activities (Chen et al., 2008; Kessentini-Zouari et al., 2010).

Purified snake venom PLA₂s also show a diversity of effects on parasites, such as *Leishmania* protozoans. MjTX-II, a myotoxic PLA₂ from *B. moojeni* venom that is catalytically inactive, proved to be an effective parasitocidal agent against several *Leishmania* species (*L. amazonensis*, *Leishmania braziliensis*, *Leishmania donovani* and *L. major*) (Stabeli et al., 2006). Moreover, Costa et al. (2008) reported that two myotoxic PLA₂s from *Bothrops brazili* venom (MTX-I, catalytically active, and MTX-II, catalytically inactive) displayed effective parasitocidal activity against *Leishmania* species (*L. amazonensis* and *L. braziliensis*). On the other hand, a PLA₂ from *B. marajoensis* venom exhibited neither significant enzymatic activity nor inhibitory activity against the growth of the parasites *L. amazonensis* and *Leishmania chagasi* (Costa Torres et al., 2010). Furthermore, a PLA₂ isolated from *C. d. collilineatus* was not deleterious toward *L. amazonensis* until after 24 h incubation, but it increased the infectiveness of this parasite in experimental mice (Passero et al., 2008). Thus, not all snake venom PLA₂s are able to inhibit the growth of *Leishmania* parasites.

PLA₂s present in eukaryotic cells mediate important phenomena such as cell migration, growth, differentiation and apoptosis (Farooqui and Horrocks, 2005; Schaeffer et al., 2009). This class of enzymes has been obtained from snake venoms and then used as models to explain a great number of pathophysiological phenomena occurring in human beings, since its structure is similar to human PLA₂s (Rufini et al., 1999). Some snake venom PLA₂s, such as the PLA₂ isolated from *Agkistrodon blomhoffii siniticus*, induce the proliferation of human hepatoma HEP3B

cells (Ma et al., 2006). Mora et al. (2005) also observed a similar effect of PLA₂ isolated from *Bothrops asper* venom on lymphoblastoid CRL-8062 cells, and Rufini et al. (1999) reported an increase in multiplication of smooth muscle cells in culture by PLA₂ isolated from *Vipera ammodytes*. Furthermore, Passero et al. (2007) suggested that the presence of PLA₂ (the basic sub-unit of crotoxin) in the venom of *C. d. collilineatus* is involved in the increase of the number of promastigotes when treated with this venom. Probably for this reason, the crude venom from *C. d. collilineatus* increased parasite numbers by approximately 50% at 44.3 µg/mL, while at higher concentrations the venom showed anti-leishmanial activity (IC₅₀ = 281 µg/mL). A similar effect was observed in the present study using TblV. However, the IC₅₀ for this "colubrid" venom is less than one half the IC₅₀ value for *C. d. collilineatus* venom (Passero et al., 2007).

In the present work, we demonstrate that PLA₂ from TblV also induces opposing dose-related effects, similar to investigations that have shown these biphasic dose-response relationships in other pharmacological and toxicological phenomena (Conolly and Lutz, 2004). A possible explanation for this kind of biphasic response is the hormesis hypothesis, which is related to the adaptive responses of cells and organisms to a moderate stress (Calabrese and Baldwin, 2001; Mattson, 2008). As PLA₂s are important mediators of complex intracellular signaling pathways, lower concentrations of these enzymes could trigger favorable stimuli for cell growth and proliferation. However, under higher concentrations, the toxicity of their enzymatic activity could result in direct damage of the cell membrane, or even in the triggering or exacerbation of unfavorable intracellular changes. Further investigations should clarify not only the actions of PLA₂s on *Leishmania* but also their mechanisms of interferences with various biological phenomena of prokaryotic or eukaryotic cells.

In conclusion, this is the first report of rear-fanged snake venoms with activity against a pathogenic parasite which is able to infect not only humans but also domestic and wild mammals worldwide. Thus, these results open new possibilities to finding protein-based drugs that might be used as possible agents against leishmaniasis. Furthermore, because of the dose-dependent biphasic action of this toxin, PLA₂ from TblV may be a useful molecular tool to investigate the biology of *Leishmania* sp. Snake venom PLA₂s are multifunctional proteins with promising biotechnological applications, and we are continuing to investigate the action of this protein in leishmaniasis as well as identifying specific protein regions with anti-leishmanial activity.

Conflict of interest

The authors declare that there are no conflicts of interest.

Acknowledgments

A postdoctoral fellowship for MEP by the Fulbright Commission and the National Scientific and Technical Research Council (CONICET) is gratefully acknowledged. Additional financial support was provided by CONICET

from Argentina (PIP 114-200801-00088, to MEP), by a Bioscience Discovery Evaluation Grant from the Colorado Office of Economic Development and International Trade (to SPM), and by the University of Northern Colorado (FRPB grant #PRR44). The donation of *P. baronii* by the Dallas Zoological Park (D. Hartigan) to SPM is also greatly appreciated.

References

- Bradford, M.M., 1976. A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. *Anal. Biochem.* 72, 248–254.
- Calabrese, E.J., Baldwin, L.A., 2001. Hormesis: a generalizable and unifying hypothesis. *Crit. Rev. Toxicol.* 31, 353–424.
- Chen, K.C., Kao, P.H., Lin, S.R., Chang, L.S., 2008. p38 MAPK activation and mitochondrial depolarization mediate the cytotoxicity of Taiwan cobra phospholipase A₂ on human neuroblastoma SK-N-SH cells. *Toxicol. Lett.* 180, 53–58.
- Conolly, R.B., Lutz, W.K., 2004. Nonmonotonic dose-response relationships: mechanistic basis, kinetic modeling, and implications for risk assessment. *Toxicol. Sci.* 77, 151–157.
- Costa, T.R., Menaldo, D.L., Oliveira, C.Z., Santos-Filho, N.A., Teixeira, S.S., Nomizo, A., Fuly, A.L., Monteiro, M.C., de Souza, B.M., Palma, M.S., Stabeli, R.G., Sampaio, S.V., Soares, A.M., 2008. Myotoxic phospholipases A₂ isolated from *Bothrops brazili* snake venom and synthetic peptides derived from their C-terminal region: cytotoxic effect on microorganism and tumor cells. *Peptides* 29, 1645–1656.
- Desjeux, P., 1992. Human leishmaniasis: epidemiology and public health aspects. *World Health Stat. Q.* 45, 267–275.
- Doley, R., Zhou, X., Kini, R.M., 2010. Snake venom phospholipase A₂ enzymes. In: Mackessy, S.P. (Ed.), *Handbook of Venoms and Toxins of Reptiles*. CRC Press/Taylor & Francis Group, Boca Raton, pp. 173–205.
- Farooqui, A.A., Horrocks, L.A., 2005. Signaling and interplay mediated by phospholipases A₂, C, and D in LA-N-1 cell nuclei. *Reprod. Nutr. Dev.* 45, 613–631.
- Ferlan, I., Ferlan, A., King, T., Russell, F.E., 1983. Preliminary studies on the venom of the colubrid snake *Rhabdophis subminatus* (red-necked keelback). *Toxicon* 21, 570–574.
- Fernandez-Gomez, R., Zerrouk, H., Sebti, F., Loyens, M., Benslimane, A., Ouaisi, M.A., 1994. Growth inhibition of *Trypanosoma cruzi* and *Leishmania donovani* infantum by different snake venoms: preliminary identification of proteins from *Cerastes cerastes* venom which interact with the parasites. *Toxicon* 32, 875–882.
- Fry, B.G., Scheib, H., van der Weerd, L., Young, B., McNaughtan, J., Ramjan, S. F., Vidal, N., Poelmann, R.E., Norman, J.A., 2008. Evolution of an arsenal: structural and functional diversification of the venom system in the advanced snakes (Caenophidia). *Mol. Cell. Proteomics* 7, 215–246.
- Gonçalves, A.R., Soares, M.J., Souza, W.d., DaMatta, R.A., Alves, E.W., 2002. Ultrastructural alterations and growth inhibition of *Trypanosoma cruzi* and *Leishmania major* induced by *Bothrops jararaca* venom. *Parasitol. Res.* 88, 598–602.
- Hill, R.E., Mackessy, S.P., 1997. Venom yields from several species of colubrid snakes and differential effects of ketamine. *Toxicon* 35, 671–678.
- Holzer, M., Mackessy, S.P., 1996. An aqueous endpoint assay of snake venom phospholipase A₂. *Toxicon* 34, 1149–1155.
- Huang, P., Mackessy, S.P., 2004. Biochemical characterization of phospholipase A₂ (trimorphin) from the venom of the Sonoran Lyre Snake *Trimorphodon bescutatus lambda* (family Colubridae). *Toxicon* 44, 27–36.
- Kessentini-Zouari, R., Jebali, J., Taboubi, S., Srairi-Abid, N., Morjen, M., Kallech-Ziri, O., Bezzine, S., Marvaldi, J., El Ayeb, M., Marrakchi, N., Luis, J., 2010. CC-PLA₂-1 and CC-PLA₂-2, two *Cerastes cerastes* venom-derived phospholipases A₂ inhibit angiogenesis both *in vitro* and *in vivo*. *Lab. Invest.* 90, 510–519.
- Loiseau, P.M., Bories, C., 2006. Mechanisms of drug action and drug resistance in *Leishmania* as basis for therapeutic target identification and design of anti-leishmanial modulators. *Curr. Top. Med. Chem.* 6, 539–550.
- Ma, A.D., Wu, S.Y., Zhang, J.J., Li, Z.Q., Xu, W., Wen, X.Y., Yu, L., Wu, S.G., 2006. Purification of a new phospholipase A₂ homologue from *Agkistrodon blomhoffii siniticus* and its effects on gene expression profile of Hep3B cells. *Nan Fang Yi Ke Da Xue Xue Bao* 26, 75–79.
- Mackessy, S.P., 2002. Biochemistry and pharmacology of colubrid snake venoms. *J. Toxicol. Toxin Rev.* 21, 43–83.
- Mackessy, S.P., 2010. The field of reptile toxicology. Snakes, lizards, and their venoms. In: Mackessy, S.P. (Ed.), *Handbook of Venoms and Toxins of Reptiles*. CRC Press/Taylor & Francis Group, Boca Raton, pp. 1–21.
- Mattson, M.P., 2008. Hormesis defined. *Ageing Res. Rev.* 7, 1–7.
- Mora, R., Valverde, B., Diaz, C., Lomonte, B., Gutierrez, J.M., 2005. A Lys49 phospholipase A₂ homologue from *Bothrops asper* snake venom induces proliferation, apoptosis and necrosis in a lymphoblastoid cell line. *Toxicon* 45, 651–660.
- Mukherjee, P., Majee, S.B., Ghosh, S., Hazra, B., 2009. Apoptosis-like death in *Leishmania donovani* promastigotes induced by diospyrin and its ethanolamine derivative. *Int. J. Antimicrob. Agents* 34, 596–601.
- Passero, L.F.D., Tomokane, T.Y., Corbett, C.E.P., Laurenti, M.D., Toyama, M.H., 2007. Comparative studies of the anti-leishmanial activity of three *Crotalus durissus* ssp. venoms. *Parasitol. Res.* 101, 1365–1371.
- Passero, L.F., Laurenti, M.D., Tomokane, T.Y., Corbett, C.E., Toyama, M.H., 2008. The effect of phospholipase A₂ from *Crotalus durissus collilineatus* on *Leishmania amazonensis* infection. *Parasitol. Res.* 102, 1025–1033.
- Peichoto, M.E., Tavares, F.L., Dekrey, G., Mackessy, S.P., 2010. Enzymatic and antileishmanial activities of five rear-fanged snake venoms. *Toxicol. Lett.* 196S, S347.
- Rath, S., Trivelin, L.A., Imbrunito, T.R., Tomazela, D.M., Jesús, M.N.d., Marzal, P.C., Junior, H.F.d.A., Tempone, A.G., 2003. Antimoniasis empregados no tratamento da leishmaniose: estado da arte. *Quim. Nova* 26, 550–555.
- Rosenberg, H.I., 1992. An improved method for collecting secretion from Duvernoy's gland of colubrid snakes. *Copeia* 1992, 244–246.
- Rosenthal, E., Delaunay, P., Jeandel, P.Y., Haas, H., Pomares-Estran, C., Marty, P., 2009. Liposomal amphotericin B as treatment for visceral leishmaniasis in Europe. *Med. Mal. Infect.* 39, 741–744.
- Rufini, S., de Vito, P., Balestro, N., Pescatori, M., Luly, P., Incerpi, S., 1999. PLA₂ stimulation of Na⁺/H⁺ antiport and proliferation in rat aortic smooth muscle cells. *Am. J. Physiol.* 277, C814–C822.
- Sabina, H., Tasneem, S., Samreen, Y., Kausar Choudhary, M.I., Aliya, R., 2005. Antileishmanial activity in the crude extract of various seaweed from the coast of Karachi, Pakistan. *Pak J. Bot.* 37, 163–168.
- Sacks, D.L., Perkins, P.V., 1984. Identification of an infective stage of *Leishmania* promastigotes. *Science* 223, 1417–1419.
- Schaeffer, E.L., Forlenza, O.V., Gattaz, W.F., 2009. Phospholipase A₂ activation as a therapeutic approach for cognitive enhancement in early-stage Alzheimer disease. *Psychopharmacology (Berl)* 202, 37–51.
- Soares, A.M., Fontes, M.R.M., Giglio, J.R., 2004. Phospholipases A₂ myotoxins from *Bothrops* snake venoms: structure-function relationship. *Curr. Org. Chem.* 8, 1677–1690.
- Stabeli, R.G., Amui, S.F., Sant'Ana, C.D., Pires, M.G., Nomizo, A., Monteiro, M.C., Romão, P.R., Guerra-Sa, R., Vieira, C.A., Giglio, J.R., Fontes, M.R., Soares, A.M., 2006. *Bothrops moojeni* myotoxin-II, a Lys49-phospholipase A₂ homologue: an example of function versatility of snake venom proteins. *Comp. Biochem. Physiol. C. Toxicol. Pharmacol.* 142, 371–381.
- Tempone, A.G., Andrade Jr., H.F., Spencer, P.J., Lourenco, C.O., Rogero, J.R., Nascimento, N., 2001. *Bothrops moojeni* venom kills *Leishmania* spp. with hydrogen peroxide generated by its L-amino acid oxidase. *Biochem. Biophys. Res. Commun.* 280, 620–624.
- Costa Torres, A.F., Dantas, R.T., Toyama, M.H., Diz Filho, E., Zara, F.J., Rodrigues de Queiroz, M.G., Pinto Nogueira, N.A., Rosa de Oliveira, M., de Oliveira Toyama, D., Monteiro, H.S., Martins, A.M., 2010. Antibacterial and antiparasitic effects of *Bothrops marajoensis* venom and its fractions: phospholipase A₂ and L-amino acid oxidase. *Toxicon* 55, 795–804.
- Weldon, C.L., Mackessy, S.P., 2010. Biological and proteomic analysis of venom from the Puerto Rican Racer (*Alsophis portoricensis*: Dipsadidae). *Toxicon* 55, 558–569.