



From drug screening to target deconvolution: A target-based drug discovery pipeline using Leishmania casein kinase 1 isoform 2 to identify compounds with anti-leishmanial activity

Emilie Durieu, Eric Prina, Olivier Leclercq, Nassima Oumata, Nicolas Gaboriaud-Kolar, Konstantina Vougianniopoulou, Nathalie Aulner, Audrey Defontaine, Joo Hwan No, Sandrine Ruchaud, et al.

► To cite this version:

Emilie Durieu, Eric Prina, Olivier Leclercq, Nassima Oumata, Nicolas Gaboriaud-Kolar, et al.. From drug screening to target deconvolution: A target-based drug discovery pipeline using Leishmania casein kinase 1 isoform 2 to identify compounds with anti-leishmanial activity. *Antimicrobial Agents and Chemotherapy*, 2016, 10.1128/AAC.00021-16 . hal-01299756

HAL Id: hal-01299756

<https://hal.sorbonne-universite.fr/hal-01299756>

Submitted on 8 Apr 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

From drug screening to target deconvolution: A target-based drug discovery pipeline using *Leishmania casein kinase 1 isoform 2* to identify compounds with anti-leishmanial activity.

Emilie DURIEU^{2,§&}, Eric PRINA^{4,#&}, Olivier LECLERCQ¹, Nassima OUMATA⁶, Nicolas GABORIAUD-KOLAR⁵, Konstantina VOUGOGIANNOPOULOU⁵, Nathalie AULNER³, Audrey DEFONTAINE², Joo Hwan NO⁸, Sandrine RUCHAUD², Alexios-Leandros SKALTSOUNIS⁵, Hervé GALONS⁷, Gerald F. SPÄTH¹, Laurent MEIJER^{2,§} and Najma RACHIDI^{2,##},

¹ Institut Pasteur and INSERM U1201, Unité de Parasitologie moléculaire et Signalisation, Paris, France; ² Sorbonne Universités, UPMC Univ Paris 06, CNRS USR3151, "Protein Phosphorylation & Human Diseases", Station Biologique, Place Georges Teissier, 29688 Roscoff, France; ³ Institut Pasteur, Imagopole®, Paris, France; ⁴ Institut Pasteur, Laboratoire d'Immunophysiologie et Parasitisme, Paris, France; ⁵ Department of Pharmacognosy and Natural Products Chemistry, School of Pharmacy, University of Athens, Greece; ⁶ ManRos Therapeutics, Centre de Perharidy, Roscoff, France; ⁷ Université Paris-Descartes, Laboratoire de Chimie Organique 2, INSERM U 648, Paris, France; ⁸ Institut Pasteur Korea, Leishmania Research Laboratory, Seongnam-si, Republic of Korea.

Running Title: *Leishmania* CK1.2 drug screening

*To whom correspondence should be addressed: Najma Rachidi. Institut Pasteur and INSERM U1201, Unité de Parasitologie Moléculaire et Signalisation, Paris, France. Tel: +33144389231; Fax: +330145688332; E-mail: najma.rachidi@pasteur.fr

Keyword: Casein kinase I, Leishmaniasis, Therapeutic target, drug screening

Present address: Institut Pasteur and INSERM U1201, Unité de Parasitologie moléculaire et Signalisation, Paris, France.

§ Present address: ManRos Therapeutics, Centre de Perharidy, Roscoff, France.

& These two authors contributed equally to the work.

ABSTRACT

Existing therapies for leishmaniasis present significant limitations, such as toxic side effects, and are rendered inefficient by parasite resistance. It is of utmost importance to develop novel drugs targeting *Leishmania* that take these two limitations into consideration. We thus chose a target-based approach using an exo-protein kinase, *Leishmania* casein kinase 1.2 (LmCK1.2) that was recently shown to be essential for intracellular parasite survival and infectivity. We developed a four-step pipeline to identify novel selective anti-leishmanial compounds. In step 1, we screened 5018 compounds from kinase-biased libraries with *Leishmania* and mammalian casein kinase 1 in order to identify hit compounds and assess their specificity. For step 2, we selected 88 compounds among those with the lowest IC₅₀ to test their biological activity on host-free parasites using a resazurin reduction assay and on intramacrophagic amastigotes using a high content phenotypic assay. Only seventy-five compounds showed anti-leishmanial

activity and were retained for step 3 to evaluate their toxicity against mouse macrophages and human cell lines. The four compounds that displayed a selectivity index above 10 were then assessed for their affinity to LmCK1.2 using a target deconvolution strategy in step 4. Finally, we retained two compounds, PP2 and compound 42, for which LmCK1.2 seems to be the primary target. Using this four-step pipeline, we identify from several thousand molecules, two lead compounds with a selective anti-leishmanial activity.

INTRODUCTION

The protozoan parasite *Leishmania* is the causative agent of leishmaniasis, a potentially fatal disease with worldwide distribution. Depending on the species, three clinical forms of the disease can be distinguished, cutaneous (CL, e.g. *L. major*), mucocutaneous (MCL, e.g. *L. braziliensis*) and fatal visceral leishmaniasis (VL, e.g. *L. donovani*) (1). Several treatment options are available, which either show important side effects or are unaffordable. In all endemic regions, the first line of treatment is pentavalent antimonials, despite their important side effects and the appearance of parasite resistance. Although their target has not been identified, one member, sodium stibogluconate was shown to inhibit the energy metabolism and macromolecule biosynthesis (2) (3). The second line of treatment is Amphotericin B, a very potent but highly toxic antifungal drug. This compound creates pores targeting ergosterol only present in the plasma membrane of parasites but not in that of mammalian cells. Its less toxic lipid formulation is extremely expensive and thus incompatible with treatment in developing countries (3, 4). Among the other drugs that have been recently developed, miltefosine was a major breakthrough in leishmaniasis therapy as this anticancer drug is the first oral treatment against VL.

69 Unfortunately, its teratogenicity excludes the treatment of pregnant women and its slow
70 turnover could promote the emergence of clinical parasite resistance (4). Miltefosine
71 plays a role in the perturbation of the lipid metabolism, the induction of apoptosis-like
72 cell death and has immuno-stimulatory effects; however its mode of action has not been
73 precisely identified (5). The activity of miltefosine is due to its accumulation inside the
74 parasite (6), which is prevented in resistant lines generated *in vitro* by the overexpression
75 of members of the ABC (ATP-binding cassette) transporter family and/or mutation of the
76 flippase LdMT (6) (7). Three more drugs complete the list of available treatments for
77 Leishmaniasis: (i) pentamidine, which has been used for VL, CL and MCL treatment,
78 induces the inhibition of polyamine biosynthesis and a decrease of the mitochondrial
79 inner membrane potential, (ii) the aminoglycosidic antibiotic paromomycin, which is
80 restricted to endemic areas, cures both VL and CL efficiently by targeting mitochondria,
81 and (iii) sitamaquine, an 8-aminoquinoline, which intercalates within biological
82 membranes to accumulate in *Leishmania* cytosolic acidic compartments (4).

83 Despite the various drugs available, none of these treatments are ideal because of two
84 main aspects: (i) their side effects, due mainly to off-target effects that cannot be
85 eliminated by drug optimization as the target responsible for the anti-leishmanial effect is
86 unknown, and (ii) the emergence of parasite resistance, due to the plasticity of the
87 parasite. Therefore there is an urgent need to discover new molecules and to develop new
88 drug discovery pipelines that take these two aspects into consideration. First, the use of
89 known validated targets for drug screening represents a major advantage as the
90 compound could be optimized to fit exclusively the target, avoiding off-target effects
91 mainly responsible for side effects. Protein kinases are among the best candidates as drug

targets for leishmaniasis because: (i) kinase inhibitors are one of the most important group of FDA-approved drugs for the treatment of diseases such as cancer or Alzheimer disease, (ii) they are considered as valid targets for diseases caused by unicellular parasites, such as malaria, and (iii) kinases regulate many key processes, such as cell cycle or signal transduction and thus the inhibition of their activity decreases cell viability (8) (9-14). Second, targeting proteins secreted by the parasite could delay the emergence of drug resistance. Indeed it has been recently shown that parasitic proteins could be exported, via exosomes, into the host cell to modify its biology or its innate immune response (15) (16). To perform their function in the host, these proteins need to interact with host proteins and thus any mutations could abrogate their functions in the host cell, which could be detrimental for the intracellular parasite survival.

Among the proteins identified in the recent proteomic analysis of *Leishmania* exosomes, 13 could qualify as good drug targets as defined above because they are excreted kinases. Most of these kinases are involved in purine or glucose metabolism, and only one is involved in signal transduction, casein kinase 1. Member of a highly conserved Ser/Thr protein kinase family (17), casein kinase I contains six isoforms in *Leishmania* (15, 18-20). LmjF35.1010 (LmCK1.2), the major isoform, has been validated pharmacologically as a drug target based on the findings that the inhibition of CK1 activity by the specific inhibitor D4476 strongly compromises axenic amastigote viability and decreases the percentage of infected macrophages (21). We hypothesize that the capacity of LmCK1.2 to recognize and phosphorylate host proteins could allow the parasite to regulate essential host cell processes (22) and therefore to survive. This hypothesis is based on our previous

findings showing that (i) the protein sequence of LmCK1.2 kinase domain is 100% identical in all sequenced *Leishmania* species (except the lizard-isolated *L. tarentolae* and unclassified *L. sp. MAR LEM2494*), suggesting that there is a selection pressure to maintain the integrity of the protein sequence, and (ii) LmCK1.2 is the most closely related kinase to its human orthologs in *Leishmania*. These two elements suggest that LmCK1.2 cannot be mutated without compromising the survival of the intracellular parasite, which would render the emergence of drug resistant parasites expressing mutated LmCK1.2 unlikely (21).

Here we present a four-step pipeline that allows the discovery of novel lead compounds. First, we generated an active recombinant LmCK1.2 and purified mammalian CK1 from porcine brain (SsCK1, (23)). We developed an enzymatic assay to screen 4030 compounds from kinase-biased and focused libraries as well as 988 analogs with both *Leishmania* and mammalian kinases in order to identify hit compounds and assess their specificity. We selected 88 compounds with an IC_{50} below 10 μ M. Second, we tested the anti-leishmanial effect of these compounds on cultured parasites using a rezasurin-based assay as well as on intracellular parasites using a high content phenotypic screen. We retained seventy-five compounds with an anti-leishmanial activity. Third, after evaluation of the toxicity of the selected anti-leishmanial compounds against mouse macrophages and human cell lines, only four compounds had a selectivity index (SI) above 10. Fourth, the affinity for LmCK1.2 for these compounds was tested using a target deconvolution approach. Two compounds for which LmCK1.2 seems to be the primary target were eventually selected. The identification of these two lead compounds validates our

pipeline, which will be used to screen diversified libraries to identify more lead compounds.

MATERIAL AND METHODS

***L. donovani* culture and axenic amastigote differentiation.**

L. donovani 1S2D (MHOM/SD/62/1S-CL2D), clone LdB, was obtained from Steve Beverley, Washington University School of Medicine, St. Louis, USA and cultured as described (24-26).

Parasite growth inhibition assay.

L. donovani promastigotes and axenic amastigotes (2×10^6 cells/ml) in their respective media were distributed in 96 well plates (125 μ l/well). An equal volume of medium containing inhibitor at the indicated concentrations (in 1% of dimethyl sulfoxide final concentration, DMSO) was added. After 24h incubation in the dark at 26°C (promastigotes) or 37°C (amastigotes), 25 μ l of resazurin solution at 0.001% was added and the plates were incubated for an additional 24h in the dark at appropriate temperatures. The plates were read (λ_{ex} : 544 nm; λ_{em} : 590 nm) using a fluorescent microplate reader (Safas xenius XML) (27).

Human cell lines MTT.

HFF1, SH-SY5Y and U-2 OS cells were cultured in Dulbecco's modified Eagle's medium (DMEM), hTERT RPE-1 were cultured in DMEM:F12 medium. All media were supplemented with 10% fetal calf serum, 2 mM L-glutamine, 50 IU penicillin and

streptomycin. Cell viability was assayed using the ‘CellTiter96 AQueous non-radioactive cell proliferation assay’ test (MTS) from PROMEGA according to manufacturer’s instructions.

Macrophage infection and assessment of intracellular parasite survival.

A high content, biologically relevant cell-based assay was used to determine the anti-leishmanial activity of D4476 as previously described (21, 28). Briefly, the assay combines (1) the use of primary bone marrow-derived mouse macrophages as natural host cells and DsRed2-expressing amastigotes of *L. amazonensis* (MPRO/BR/1972/M1841), the clinically relevant parasite stage of *Leishmania* with (2) the detection of fluorescent markers as reporter molecules. 10,000 macrophages were counted per well depending on the number of replicates per tested compound.

Ethics statement.

All animals were housed in our A3 animal facilities in compliance with the guidelines of the A3 animal facilities at the Institut Pasteur, which is a member of Committee 1 of the “Comité d’Ethique pour l’Expérimentation Animale” (CEEAA) - Ile de France - Animal housing conditions and the protocols used in the work described herein were approved by the “Direction des Transports et de la Protection du Public, Sous-Direction de la Protection Sanitaire et de l’Environnement, Police Sanitaire des Animaux under number B75-15-27 and B75-15-28 in accordance with the Ethics Charter of animal experimentation that includes appropriate procedures to minimize pain and animal suffering. GS and EP are authorized to perform experiment on vertebrate animals (licence

B75-1159 and 75-1265, respectively) issued by the “Direction Départementale de la Protection des Populations de Paris” and is responsible for all the experiments conducted personally or under his supervision as governed by the laws and regulations relating to the protection of animals.

Automated microtiter plate CK-S kinase assay.

A mixture of native CK1 isoforms (essentially CK1 δ and CK1 ϵ) was extracted from porcine brain (SsCK1) and purified by affinity chromatography on immobilised axin (23). LmCK1.2 was produced and purified as previously described (21). Both SsCK1 and recombinant LmCK1.2 were assayed, with 27 μ M CK-specific peptide substrate CK-S (RRKHAAIGpSAYSITA) synthesized by Proteogenix (Oberhausbergen, France), in buffer C pH 7 (60 mM β -glycerophosphate, 30 mM p-nitrophenyl phosphate, 25 mM MOPS, 5 mM EGTA, 15 mM MgCl₂, 1 mM dithiothreitol, 0.1 mM sodium vanadate), with 15 μ M [γ -³³P] ATP in a final volume of 30 μ l. After 30 min incubation at 30°C, 30 μ L aliquots were filtered onto whatman P81 phosphocellulose paper. The filters were washed with a solution of 1% phosphoric acid then counted in the presence of 20 μ l scintillation fluid per well. Blank values were subtracted and activities calculated as pmoles of phosphate incorporated during the 30 min incubation. The activities were expressed in percent of maximal activity, i.e. in the absence of inhibitors. Controls were performed with appropriate dilutions of DMSO.

ATP depletion and competition

Seven mg of axenic amastigote total protein extract were dialyzed overnight at 4°C in dialysis solution (1X PBS, 1 mM EDTA, 1 mM DTT) using a Slide-A-Lyzer 10kD dialysis cassette (Pierce) to eliminate free ATP. One mg of dialyzed extract per condition was mixed with the binding solution (1X Binding solution, 1mM DTT, 1X Protease inhibitor) of the ATP affinity test kit (Jena Bioscience) and 500 µM of inhibitor. The samples were incubated 30 min at 4°C and added to a mixture of 12.5 µl of each ATP agarose (ATP affinity test kit from Jena Bioscience). ATP binding proteins from the assay and the competition samples were enriched according to the manufacturer's instructions. Finally, eluted samples were concentrated using Amicon Ultra 10K centrifugal filters (Millipore) to a final volume of approximately 100 µl.

12.5 µl of the flow through and 30 µl of the eluate were separated on Novex NuPAGE 4-12% bis tris gel (Life technologies) from both the assay and the competition. The gel was stained with SYPRO Ruby (Life technologies) according to the manufacturer's instructions and revealed using a Typhoon scanner. Alternatively, proteins separated by SDS-PAGE were transferred onto a PVDF membrane and probed with SY3535 antibody (21). Signals were revealed by Super Signal ECL (Pierce).

Compound libraries

We screened 5018 compounds from the Roscoff library including 588 purine derivatives (29) and 400 indirubin derivatives (30) (31) (32).

Homology modeling and structural alignment

The amino acid sequence of *L. major* CK1.2 was retrieved from NCBI database (Accession number: XP_003722496) in FASTA format. The homology modeling of the sequence was performed by SWISS-MODEL program (33) and the protein with PDB code 3SV0 was selected as a template. PyMOL program (34) was used for the structural alignment of *Schizosaccharomyces pombe* casein kinase 1 in complex with the specific CK1 inhibitor, IC261 (PDB code: 1EH4) and *Homo sapiens* casein kinase 1 δ (PDB code: 4KB8) to the generated *L. major* CK1.2 homology model. The figures were also prepared using PyMOL (34).

RESULTS

We present below, a comprehensive drug discovery pipeline encompassing four steps.

STEP 1: Identification of specific LmCK1.2 inhibitors.

Primary screening comparing SsCK1 and LmCK1.2

We purified recombinant LmCK1.2-V5-His₆ from *E. coli* and a mixture of *Sus scrofa* CK1 δ and CK1 ϵ (SsCK1) from porcine brain (21) (23). The conditions used previously for the manual kinase assay were adapted to an automated 96-well plate format (23) (21). We used CK-S as substrate for both kinases, and 15 μ M [γ -³³P] ATP (23) (21). We screened 4030 compounds at 10 μ M from a kinase-biased library that has been previously tested on mammalian kinases, such as Cyclin-Dependent Kinases (CDK) (29). For each compound, the percentage of inhibition of LmCK1.2 versus that of SsCK1 is presented in Figure 1A. We classified as hit compounds those that decreased the kinase activity by more than 40% (Figure 1A a and b). We obtained twice as much hit compounds for the mammalian CK1 than for LmCK1.2 (Figure 1B). Indeed, we identified 245 hit

250 compounds against SsCK1 (6.1% Hit rate) and 128 against LmCK1.2 (3.2% Hit rate)
251 with only 37 compounds with a similar potency against both kinases. This finding, which
252 is surprising considering the high similarity between the protein sequences of LmCK1.2
253 and the mammalian CK1s (about 70% (21)), suggests that the ATP binding pocket of the
254 two kinases is sufficiently divergent to accommodate different inhibitors. We next
255 classified the compounds according to their potency and specificity (Class 1 corresponds
256 to compounds that inhibit the kinase activity between 80-100%, Class 2 between 60-80%,
257 and Class 3 between 40-60%, Figure 1C). We obtained a similar number and distribution
258 of hit compounds active on SsCK1 (30 compounds) and on LmCK1.2 (31 compounds) in
259 Class 1. In contrast, we observed an increased number of compounds inhibiting
260 specifically SsCK1 in Class 2 and 3 (Figure 1C). This could suggest that the ATP binding
261 pocket of SsCK1 could be more permissive than that of LmCK1.2. We selected 45
262 compounds either belonging to Class 1 that inhibited LmCK1.2 activity by more than
263 90% or that belong to Class 2 and were specific to LmCK1.2 to determine their IC_{50} . As
264 shown in Figure 2, all the compounds with an IC_{50} below 1.3 μ M (most potent) were not
265 specific, whereas all the specific compounds had an IC_{50} above 1.3 μ M.

266 Among the 45 compounds that were potent against LmCK1.2, we identified several
267 inhibitors described to have anti-leishmanial activity, including known CK1 inhibitors,
268 such as anthraquinone (35-37), or compounds for which we revealed CK1 as a new
269 target, such as Gossypol, purpurogallin and some flavonoids (38-41) (42) (43). These
270 compounds, identified from several libraries, were found at least twice with similar IC_{50} ,
271 indicating that our assay is reproducible (data not shown). Altogether, these data
272 demonstrate the efficiency of using CK1 as a target to identify compounds with anti-

leishmanial activities and confirm LmCK1.2 as a valid drug target. However we did not retain these compounds for subsequent characterization as they have been already extensively studied.

Secondary screening of purine and indirubin libraries

Out of the 45 compounds for which we determined the IC_{50} , we selected 2 compounds with low IC_{50} but only moderate specificity towards LmCK1.2, purvalanol B and indirubin-3'-monoxime, and tested analog libraries to perform SAR analysis in order to identify more specific compounds. We chose purvalanol B because we showed previously that *Leishmania* CK1.2 binds to purvalanol B better than its mammalian counterpart, suggesting that the sensitivity to purvalanol B could be higher for LmCK1.2 than for SsCK1 (44). Confirming this finding, the IC_{50} of purvalanol B towards LmCK1.2 (2 +/- 0.3 μ M) is slightly lower than that towards SsCK1 (2.9 +/- 1.2 μ M). We tested the potency of 588 purine analogs (Figure 3A) at 10 μ M against LmCK1.2 and SsCK1 to identify compounds with better potency and/or specificity. As shown in Figure 3B and 3C, most compounds were more potent against mammalian CK1 than against LmCK1.2 (below the black line, Figure 3B and dark grey in Figure 3C). Next, we determined the IC_{50} of the 21 most potent purine derivatives against LmCK1.2 (Figure 3D). For all the compounds, except one, the IC_{50} was systematically higher against LmCK1.2 (0.44 to 2.4 μ M) than against mammalian CK1 (0.081 to 1.6 μ M). Only compound **26** had a lower IC_{50} against LmCK1.2 (1 +/- 0.4 μ M) than against SsCK1 (3.7 +/- 1.2 μ M), which could be due to the presence of a long carbon chain, a unique feature compared to the other derivatives. Thus although the purines were very potent towards LmCK1.2, they present a higher affinity for SsCK1.

The second family of compounds we screened are the indirubins (Figure 4A). We showed that the IC₅₀ of indirubin-3'-monoxime is lower against LmCK1.2 (0.13 +/- 0.03; Table S1) than against mammalian CK1 (0.39 +/- 0.08 μM; Table S1). To identify better compounds with higher selectivity, we tested 400 indirubin derivatives (Figure 4B). Contrary to the purine analogs, the indirubins were globally more potent against LmCK1.2 than SsCK1 (Figure 4B). For instance, in Class 1, forty-six compounds were more specific toward LmCK1.2 than SsCK1 versus only 9 were more specific towards SsCK1 than LmCK1.2 (Figure 4C). Indeed, the most active compounds were the most selective toward LmCK1.2, whereas compounds with lower potency (Class 3) were more specific toward SsCK1 (Figure 4C). We selected the 55 most potent compounds to measure their IC₅₀. They were comprised between 0.08 and 10 μM, and for almost all the compounds, the IC₅₀ against LmCK1.2 was systematically lower than that against mammalian CK1 (Figure 4D), suggesting that the indirubin compounds have more affinity towards LmCK1.2 than SsCK1.

The differences in specificity observed with the purine and indirubin compound families confirm that important differences exist between the ATP binding pocket of both kinases (21). It also suggests that due to the strong affinity of the purine for the mammalian CK1, it is likely that these compounds will be toxic for the host cell.

Among all the compounds identified in the primary and secondary screenings, we eliminated all the compounds for which the chemical optimization was unfeasible and selected 12 compounds from the main library, 21 compounds from the purine library and 55 compounds from the indirubin library to assess their anti-leishmanial activity.

STEP 2: Evaluation of the anti-leishmanial activity of selected compounds.

We evaluated the anti-leishmanial activity of the 88 compounds selected in STEP 1 on cultured *L. donovani* promastigotes and axenic amastigotes by measuring the percentage of metabolically active parasites in liquid culture using the rezasurin-based assay (27) (Table S1). As a positive control, we treated the parasites with 1 μ M of the anti-leishmanial reference drug, AMB and obtained a growth inhibition of 90.4 ± 1.5 % and 79.9 ± 1.3 % for promastigotes and amastigotes, respectively, with excellent reproducibility as reported by the small standard deviation values.

We then tested the compounds against intracellular *L. amazonensis* using a visual high content phenotypic assay (21, 28). We measured three parameters: (i) the percentage of cells remaining after treatment compared to the vehicle control (DMSO) to evaluate cell detachment (Total Macrophages, TM), (ii) the percentage of healthy cells compared to the total number of cells remaining after treatment to evaluate cell mortality (Viability Index, VI), and (iii) the percentage of parasitophorous vacuoles per healthy cell to evaluate the parasite burden (PB). We used AMB at 0.5 μ M and cycloheximide (CHX) at 150 μ M as anti-leishmanial and cytotoxic control compounds, respectively. Figure S1 presents the data of all the controls performed during the screening campaign. As expected, AMB is reducing parasite burden without affecting the number of macrophages or their viability, whereas CHX does not affect significantly the number of macrophages but decreases dramatically the viability, as it is extremely toxic to macrophages. The data were reproducible as judged by the small standard deviation values, (Figure S1).

For each of the 88 compounds, we plotted the percentage of metabolically active promastigotes or amastigotes at 10 μ M versus the percentage of parasite burden at 10 μ M

(Figure 5). We considered as efficient, those compounds that decreased the percentage of metabolically active parasites or the percentage of parasite burden by 40%. We eliminated compounds that had no effect on the percentage of intracellular parasites; remarkably those compounds were also mainly inefficient on cultured parasites (Figure 5, b and d). Among the 65 compounds that were potent towards the intracellular parasites, we identified two categories: compounds equally efficient on cultured and intracellular parasites (Figure 5, c) and compounds that were only efficient on intracellular parasites, which represent the majority of the compounds (43 out of 65 for promastigotes and 57 out of 65 for amastigotes, Figure 5, a). This finding suggests that the exclusion of compounds based on their lack of efficacy on cultured parasites could lead to the elimination of compounds very efficient on intracellular parasites, among which, inhibitors that kill indirectly parasites by targeting host cell proteins.

Main library

We selected seven out of twelve compounds from the main library including i) Rottlerin, NSC 146771, gefitinib and sunitinib, all potent against intracellular parasites at 10 μ M, and ii) 5'ITu, PP2 (1-tert-butyl-3-(4-chlorophenyl)-1h-pyrazolo[3,4-d]pyrimidin-4-amine,(45)) and NSC 699479 that were efficient against intracellular parasites at 10 and 1 μ M as well as against cultured parasites (Table S1). 5'ITu, which is described as a general kinase inhibitor (46), is potent against promastigotes and axenic amastigotes, with an EC₅₀ of 0.4 ± 0.1 and 5.4 ± 1.8 μ M respectively (Table S1). It has also a strong effect at 10 and 1 μ M on intracellular parasites with only $10 \pm 1\%$ and $13 \pm 4.5\%$ remaining PB, respectively, which is similar to 0.5 μ M AMB. PP2 is potent against intracellular

amastigotes at 1 μ M ($54 \pm 3\%$ PB; Table S1). NSC 699479 (4-[(E)-[2-(4-chlorophenyl)-1-methylpyrazolo[1,5-a]indol-1-ium-4-ylidene]methyl]-N,N-dimethylaniline; tri-fluoromethane-sulfonate) is known for anti-cancer activity and has been shown to target a wide range of proteins including the DNA polymerase ϵ (47). It is extremely potent against promastigotes and axenic amastigotes, with an EC_{50} below 1 μ M as well as intracellular parasites at 10 μ M ($3.6 \pm 1.9\%$ PB), and 1 μ M ($11 \pm 1.4\%$ PB; Table S1), activity which is comparable to AMB.

Purine library

We selected 13 out of 21 purine compounds that were able to kill efficiently intracellular parasites at either 1 μ M or 10 μ M (compound 21 and 30, Table S1). Consistent with their high potency against recombinant LmCK1.2, most compounds were active against intracellular parasites. Surprisingly the purine derivatives were not very potent against promastigotes and axenic amastigotes. With the exception of compound **22** and **30**, which present an EC_{50} of 0.72 ± 0.03 μ M and 6.2 ± 0.8 μ M against promastigotes respectively, most of the compounds were weakly active against promastigotes and inactive against axenic amastigotes at 50 μ M (Table S1). This lack of potency against cultured parasites cannot be explained by cell permeability as these compounds efficiently decrease the parasite burden of infected macrophages.

Indirubin library

Fifty-five indirubins were tested against promastigotes and axenic amastigote. Twenty-one compounds showed an EC_{50} below 10 μ M against promastigotes (ranging from 0.4 to

2 μ M) whereas only 6 showed an EC₅₀ below 10 μ M against amastigotes (ranging from 3.5 to 8 μ M). These compounds were all members of a subfamily of indirubins, containing a diethanolamine substitution in position-3', suggesting that the presence of this substitution could be important for their anti-leishmanial activity against cultured parasites. It is remarkable that the EC₅₀ against promastigotes was systematically lower than that against axenic amastigotes (21). We next tested all the indirubin derivatives against intracellular parasites. In contrast to purine derivatives, all indirubin compounds were efficient against intracellular parasites at 10 μ M, with 9 also efficient at 1 μ M (Table S1). The most efficient indirubin is compound **42** with a remaining $22 \pm 5\%$ PB, corresponding to a decrease of 78% compared to the DMSO-treated controls. Altogether, these data confirm what we observed with recombinant LmCK1.2 (Figure 4C and D) that the indirubin compound family, which has a stronger affinity for LmCK1.2 is also showing a higher anti-leishmanial activity.

STEP 3: Evaluation of the toxicity of the compounds.

Cytotoxicity against mouse Bone Marrow Derived Macrophages

We first assessed the toxicity towards mouse bone marrow-derived macrophages of the 75 compounds that displayed anti-leishmanial activity against intracellular parasites (Table S1, column VI%). We plotted the percentage of parasite burden versus the percentage of viable macrophages for each of the three libraries (Figure 6). As shown in Figure 6A, 3 compounds out of the 7 selected from the main library were toxic towards macrophages at 10 μ M (Figure 6A, c, black dots) but none were toxic at 1 μ M (Figure 6A, b and d, grey dots). However, decreasing their concentration from 10 μ M to 1 μ M to

prevent cytotoxicity led, in some cases such as with sunitinib, to a decrease in potency against intracellular parasites. Nevertheless, we identified compounds that were not toxic and able to efficiently decrease PB (Figure 6A d). We obtained a similar result with the indirubin derivatives (Figure 6B, b and d) as we identified compounds with anti-leishmanial activity and no toxicity against macrophages: 35 compounds at 10 μ M and 9 compounds at 1 μ M (Figure 6B d). These results are in contrast to the results obtained for the purine library, as most of the 21 purine derivatives that we tested led to cell death, preventing proper analysis of their effect on intracellular parasites. Indeed, we did not identify any compound that decreased the percentage of parasite burden without cytotoxicity (Figure 6C, d). To investigate whether these derivatives could be efficient toward intracellular parasites at lower concentration, we tested compound **16**, **22** and **30** at 0.01 μ M and 0.1 μ M (data not shown). These compounds were no longer toxic to host cells at 0.1 μ M, 0.1 μ M and 0.01 μ M respectively, and no longer active against intracellular parasites. It seems that the efficient concentration to kill intracellular parasites could be similar to the cytotoxic concentration. This finding could be explained by the higher affinity of this compound family for the mammalian CK1 compared to *Leishmania* CK1.2 (Figure 3B and C).

Based on these results, we eliminated the sunitinib from the main library, all the remaining compounds from the purine library and 11 compounds from the indirubin library because of their toxicity against macrophages. We thus retained 6 compounds from the main library and 7 indirubins from those with anti-leishmanial activity at 1 μ M and without cytotoxicity against BMDM.

Cytotoxicity against human cell lines

434 To establish the selectivity index (SI, this unit corresponds to the ratio between the EC₅₀
435 against intracellular parasites and the EC₅₀ against mammalian cells), we determined the
436 EC₅₀ against intracellular parasites, macrophages as well as human cell lines (RPE-1,
437 SHSY-5Y, HFF-1 and U2OS, Table S1) for the remaining 13 compounds (Table S1). The
438 SI ranged from 0.15 to 50, which is consistent with small molecules being able to
439 discriminate between *Leishmania* CK1.2 and mammalian CK1, as we identified
440 compounds that show leishmanicidal activity without cytotoxicity (Table S1). We
441 eliminated all the compounds with a SI below 10, as they were likely to lead to side
442 effects, retaining only five compounds: 5'ITu, PP2, NSC 699479 from the main library
443 and compound **38** and **42** from the indirubin library. The EC₅₀ of 5'ITu against
444 intracellular parasites is in the nanomolar range ($0.06 \pm 0.01 \mu\text{M}$) while that against
445 mouse macrophages is in the micromolar range ($3.5 \mu\text{M} \pm 0$), which represents a 60-fold
446 difference between the cytotoxic and the anti-leishmanial concentrations (Table S1). The
447 toxicity of this compound towards the human cell lines seems to be cell-dependent;
448 indeed the EC₅₀ against RPE-1 and U2OS is $1.2 \mu\text{M}$, whereas it is above $25 \mu\text{M}$ against
449 SHSY-5Y and HFF-1 (Table S1). Taking in account both cell lines and macrophages the
450 minimum SI is thus 20, indicating that the leishmanicidal concentration is 20 fold lower
451 than the toxic concentration. NSC699479 has also an EC₅₀ against intracellular parasites
452 in the nanomolar range ($0.33 \pm 0.05 \mu\text{M}$) but a SI of only 10, due to the low EC₅₀ towards
453 macrophages and U2OS, respectively at $3.5 \pm 0.24 \mu\text{M}$ and $3 \pm 0.5 \mu\text{M}$. Indirubin **38** has
454 an EC₅₀ of 0.6 ± 0.1 with a SI above 17, whereas compound **42**, more potent, has an EC₅₀
455 of $0.06 \pm 0.005 \mu\text{M}$, with a high SI of 50 (Table S1). For PP2, it was impossible to
456 determine the exact EC₅₀, because the parasite burden at $10 \mu\text{M}$ of PP2 was $98 \pm 8.5\%$,

whereas it was only $54 \pm 3\%$ at $1 \mu\text{M}$. This result could be explained by the detachment of non-infected macrophages. Indeed, we showed that treatment of infected BMDM with $10 \mu\text{M}$ of PP2 led to cell detachment as judged by the percentage of total remaining cells in the well ($60 \pm 1\%$, Table S1). We cannot completely exclude that cell detachment could be the consequence of cell mortality, but it seems unlikely, as the cells that remained attached were viable in the presence of the drug (VI of $83 \pm 4\%$). This is consistent with what has been previously observed for other cell types, as PP2 is known to directly interfere with cell attachment (48). We estimated the EC_{50} of PP2 around $1 \mu\text{M}$ as the PB is $54.3 \pm 3.2\%$ at $1 \mu\text{M}$ (Table S1), with a SI above 10. For STEP4, we only selected 5'ITu, NSC699479, PP2 and compound **42** (Table 1).

STEP 4: Target deconvolution.

To confirm that 5'ITu, NSC699479, PP2 and compound **42** (Table 1) target *Leishmania* CK1.2 in the parasite and to estimate their affinity for this kinase, we investigated whether they could prevent the binding of CK1.2 to ATP-agarose (21). We treated amastigote lysates with PP2, 5'ITu, compound **42**, NSC699479 or D4476 (positive control) before performing an affinity chromatography; we used an untreated sample as negative control. The proteins eluted from the ATP-agarose were separated by SDS-PAGE and either stained with SYPRO-Ruby or analyzed by Western blotting using an anti-LmCK1.2 antibody (21). By comparing the protein elution profiles obtained with the untreated sample (Ama) to that obtained with the treated samples (D4476, PP2, Iodo, **73** and **42**) we were able to assess compound selectivity (Figure 7A). Most of the treated samples showed a profile similar to that of the untreated sample, except for the 5'ITu

(Figure 7A). As judged by the disappearance of several bands, 5'ITu could be targeting many ATP-binding proteins aside CK1.2. Because this absence of selectivity prevents any possibility for compound optimization, which could in turn lead to side effects, we eliminated 5'ITu. Based on the Western blot analysis, we also discarded NSC699479, as LmCK1.2 could still bind to the ATP beads in presence of this compound, suggesting that this kinase is not the primary target of NSC699479 (Figure 7B). This is consistent with the fact that the IC₅₀ of NSC699479 against LmCK1.2 is 8 μ M, which is higher than that of the other compounds (Table S1). However because of its strong anti-leishmanial activity, it would be interesting to identify the primary target of NSC699479. As shown in Figure 7B, similarly to D4476, only PP2 and compound **42** prevent the binding of LmCK1.2 to the ATP beads without affecting the elution profile. This result suggests that LmCK1.2 could be one of the primary targets of these two compounds.

DISCUSSION

The anti-leishmanial drugs currently available are compromised mostly because they lead to parasite resistance and have important side effects. Considering these parameters early in the process of drug development is therefore crucial to discover more efficient drugs. We established a pipeline consisting of 4 steps from target-based screening to target deconvolution. In order to integrate these parameters, we used LmCK1.2 (a *Leishmania* exo-kinase) as a target to address parasite resistance, and excluded compounds based on their absence of anti-leishmanial activity, on their lack of specificity or on their poor affinity for LmCK1.2 to address side effects. Our pipeline introduces two improvements compared to previous screening campaigns. First, as *Leishmania* and mammalian CK1s

are closely related and to limit the possibility of cell toxicity, which leads to side effects, we screened, in parallel, the leishmanial and mammalian CK1 to assess specificity. Using this approach we could discriminate between compounds with low and high specificity. For instance, we showed that the purine derivatives displayed a better potency against mammalian CK1 than against LmCK1.2, which led to toxicity against mammalian host cells. Reversely, compounds of the indirubin family displayed a better potency against LmCK1.2 than mammalian CK1, which was subsequently confirmed by their absence of toxicity toward the mammalian host cell at 1 μ M. This finding suggests that a strong correlation between the specificity toward the target and the subsequent effect on intracellular parasite survival. Moreover, our results also confirm that LmCK1.2 has an ATP binding pocket sufficiently divergent from that of mammalian CK1 to identify discriminating compounds (21). Indeed, more than 70% of the small molecules that we tested showed a differential potency against both kinases. We modelled the structure of *Leishmania* CK1.2 based on existing crystal structures of CK1s found in Protein Data Bank and noticed a few differences between the LmCK1.2 model (green, Figure S2) and the crystal structure of human CK1 δ or of *Schizosaccharomyces pombe* CK1 (magenta or cyan (SpCK1) respectively, Figure S2) that could account for the specificity of LmCK1.2 towards certain compounds. Indeed, residues in the active site of LmCK1.2 such as F22 and K40 could be positioned differently, which could overall change the shape of the active site. Moreover, the structural alignment of LmCK1.2, human CK1 δ and SpCK1 (49), which is in complex with IC261 (specific CK1 inhibitor) shows that the position of K40 in the active site of LmCK1.2 compared to that of K41 or K38 in the active site of CK1 δ and SpCK1 respectively, may account for the differential response to compound

inhibition. Indeed, contrary to K38 and K41, K40 could lead to conformational clash with IC261. This finding supports our previous results showing that the IC₅₀ of IC261 towards LmCK1.2 is above 10 μ M whereas it is 0.47 μ M towards mammalian CK1 (21). Our results demonstrate that *Leishmania* CK1.2, which would have been rejected based on the strong identity to its mammalian orthologs, is a good drug target.

A second improvement was to assess whether compounds have multiple targets or low affinity for LmCK1.2. To address this issue, we performed target deconvolution. This strategy, which depends on affinity purification and competition, allowed the elimination of compounds based on their lack of specificity or their lack of affinity towards LmCK1.2. Indeed, we excluded 5'ITu that could be targeting many proteins as revealed by their depletion following competition assay and ATP-affinity chromatography. This finding is consistent with recent publications showing that 5'ITu is a general kinase inhibitor due to its broad inhibitory activity (46). Although this compound could be a good lead compound purely based on its SI, its optimisation could be difficult as the target responsible for the leishmanicidal activity is unknown. We also excluded NSC699479 because of its weak affinity towards LmCK1.2, suggesting that this kinase might not be its primary target. Based on previous results in mammalian cells, the primary target of NSC699479 could be topoisomerases in *Leishmania*, enzymes already known as good drug targets (50) (51) (52).

Using this pipeline, we screened 5018 compounds in total and identified two lead compounds, PP2 and compound **42**. PP2 is an inhibitor for which no anti-leishmanial activity against intracellular parasites in THP-1 cells *in vitro* has been previously

described but appears to be efficient in animal model (53). It has an EC₅₀ on intracellular parasites around 1 µM, but a selectivity index above 10 for murine macrophages and above 25 for human cell lines. The known targets of PP2 are tyrosine kinases, Src, Lck, Csk, Rip2 and Gak, for which there are no orthologs identified in *Leishmania* (54, 55). The two other kinases that are targeted by PP2 are p38 (52% of inhibition at 1 µM (54)) and CK1δ (93% of inhibition at 1 µM (54)), suggesting that the anti-leishmanial activity of PP2 is more likely mediated by the inhibition of CK1.2 in *Leishmania*. This finding is consistent with our experimental data showing that *Leishmania* CK1.2 is one of the primary targets of PP2. However, treatment with high concentrations of PP2 leads to macrophage detachment (40% at 10 µM) similarly to what has been shown previously for other cell types (48). Our results seem to indicate that most of the macrophages that detach from the slides are those non-infected by *Leishmania*. This hypothesis is supported by Tejle *et al*, which showed that the presence of *L. donovani* affect the detachment of monocyte-derived dendritic cells, suggesting that the presence of the parasite could promote cell adhesion (56).

Indirubins are particularly potent against cultured as well as intracellular parasites and among the 55 indirubin derivatives showing leishmanicidal activity at 10 µM, only 37% were cytotoxic against macrophages. Compound **42** is our best lead compound, with an EC₅₀ on intracellular parasites of 60 ± 5 nM and a SI of 50. Although several authors have already described the anti-leishmanial effect of indirubins (57-59), this particular derivative has not been previously tested on intracellular parasites. From previous published work, we already know some of the targets of the indirubins, such as *Leishmania* CRK3 or GSK3 (57, 58). In our study, we reveal for the first time CK1.2 as a

novel target for this family of compounds. This is particularly striking as in higher eukaryotes GSK3 and CK1 are often involved in similar signalling pathways such as the Wnt/ β -catenin or the Hedgehog pathways, where they act as priming kinases for one another (60, 61) (62) (63). Using affinity purification, we found that GSK-3 is also a target of compound **42** (data not shown). We will determine precisely, using biochemical approaches, whether this compound targets other kinases and which one causes the anti-leishmanial effect.

In conclusion, we have established a comprehensive pipeline that identify and select LmCK1.2 inhibitors based on their specificity, anti-leishmanial activity, absence of cytotoxicity and selectivity. As a proof of principle, we identified two lead compounds, PP2 and compound **42** that will be studied further to understand their mode of action and could also be used as pharmacological tools to study parasite-specific signal transduction. We will use this pipeline to screen diversified libraries that have not yet been screened against *Leishmania* kinases, in order to identify lead compounds.

FUNDING INFORMATION

This work was supported by the 7th Framework Program of the European Commission through grants to the LEISHDRUG project (223414), by the ANR-11-RPIB-0016 TRANSLEISH, the French Government's Investissements d'Avenir program Laboratoire d'Excellence Integrative Biology of Emerging Infectious Diseases (grant no. ANR-10-LABX-62-IBEID). The Imagopole-CiTech is part of the FranceBioImaging infrastructure supported by the French National Research Agency (ANR-10-INSB-04-01, "Investments

for the future”) and is grateful to be supported by Conseil de la Region Ile-de-France (program Sesame 2007, project Imagopole, S. Shorte) and by the Fondation Française pour la Recherche Médicale (FRM, Programme Grands Equipements) to N. Aulner.

ACKNOWLEDGMENTS

We thank all members of the FP7 LEISHDRUG consortium for fruitful discussions, in particular Geneviève Milon. Additional thanks go to Olivier Helynck and Hélène Munier-Lehmann for providing access to the TECAN Freedom EVOware platform for automatic distribution of cells, parasites, and chemicals in a biosafety level 2 facility.

REFERENCES

1. **Pace D.** 2014. Leishmaniasis. *J Infect* **69 Suppl 1**:S10-18.
2. **Hussain H, Al-Harrasi A, Al-Rawahi A, Green IR, Gibbons S.** 2014. Fruitful decade for antileishmanial compounds from 2002 to late 2011. *Chem Rev* **114**:10369-10428.
3. **Croft SL, Sundar S, Fairlamb AH.** 2006. Drug resistance in leishmaniasis. *Clin Microbiol Rev* **19**:111-126.
4. **Singh N, Kumar M, Singh RK.** 2012. Leishmaniasis: current status of available drugs and new potential drug targets. *Asian Pac J Trop Med* **5**:485-497.
5. **Dorlo TP, Balasegaram M, Beijnen JH, de Vries PJ.** 2012. Miltefosine: a review of its pharmacology and therapeutic efficacy in the treatment of leishmaniasis. *J Antimicrob Chemother* **67**:2576-2597.
6. **Perez-Victoria FJ, Sanchez-Canete MP, Castanys S, Gamarro F.** 2006. Phospholipid translocation and miltefosine potency require both *L. donovani* miltefosine transporter and the new protein LdRos3 in *Leishmania* parasites. *J Biol Chem* **281**:23766-23775.
7. **Perez-Victoria JM, Baychvarov BI, Torrecillas IR, Martinez-Garcia M, Lopez-Martin C, Campillo M, Castanys S, Gamarro F.** 2011. Sitamaquine overcomes ABC-mediated resistance to miltefosine and antimony in *Leishmania*. *Antimicrob Agents Chemother* **55**:3838-3844.
8. **Cohen P.** 2002. Protein kinases--the major drug targets of the twenty-first century? *Nat Rev Drug Discov* **1**:309-315.
9. **Doerig C.** 2004. Protein kinases as targets for anti-parasitic chemotherapy. *Biochimica et Biophysica Acta (BBA) - Proteins and Proteomics* **1697**:155-168.
10. **Weinmann H, Metternich R.** 2005. Drug discovery process for kinase inhibitors. *Chembiochem* **6**:455-459.
11. **Eglen RM, Reisine T.** 2009. The current status of drug discovery against the human kinome. *Assay Drug Dev Technol* **7**:22-43.
12. **Eglen R, Reisine T.** 2011. Drug discovery and the human kinome: recent trends. *Pharmacol Ther* **130**:144-156.

- 633 13. **Carvalho TG, Doerig C, Reininger L.** Nima- and Aurora-related kinases of malaria
634 parasites. *Biochim Biophys Acta* **1834**:1336-1345.
- 635 14. **Yang SH, Sharrocks AD, Whitmarsh AJ.** MAP kinase signalling cascades and
636 transcriptional regulation. *Gene* **513**:1-13.
- 637 15. **Silverman JM, Clos J, de'Oliveira CC, Shirvani O, Fang Y, Wang C, Foster LJ,**
638 **Reiner NE.** 2010. An exosome-based secretion pathway is responsible for protein export
639 from *Leishmania* and communication with macrophages. *J Cell Sci* **123**:842-852.
- 640 16. **Silverman JM, Clos J, Horakova E, Wang AY, Wiesgigl M, Kelly I, Lynn MA,**
641 **McMaster WR, Foster LJ, Levings MK, Reiner NE.** 2011. *Leishmania* exosomes
642 modulate innate and adaptive immune responses through effects on monocytes and
643 dendritic cells. *J Immunol* **185**:5011-5022.
- 644 17. **Knippschild U, Gocht A, Wolff S, Huber N, Lohler J, Stoter M.** 2005. The casein
645 kinase 1 family: participation in multiple cellular processes in eukaryotes. *Cell Signal*
646 **17**:675-689.
- 647 18. **Allocco JJ, Donald R, Zhong T, Lee A, Tang YS, Hendrickson RC, Liberator P,**
648 **Nare B.** 2006. Inhibitors of casein kinase 1 block the growth of *Leishmania* major
649 promastigotes in vitro. *Int J Parasitol* **36**:1249-1259.
- 650 19. **Silverman JM, Chan SK, Robinson DP, Dwyer DM, Nandan D, Foster LJ, Reiner**
651 **NE.** 2008. Proteomic analysis of the secretome of *Leishmania donovani*. *Genome Biol*
652 **9**:R35.
- 653 20. **Paape D, Barrios-Llerena ME, Le Bihan T, Mackay L, Aebischer T.** 2010. Gel free
654 analysis of the proteome of intracellular *Leishmania mexicana*. *Mol Biochem Parasitol*
655 **169**:108-114.
- 656 21. **Rachidi N, Taly JF, Durieu E, Leclercq O, Aulner N, Prina E, Pescher P, Notredame**
657 **C, Meijer L, Spath GF.** 2014. Pharmacological assessment defines the *Leishmania*
658 *donovani* casein kinase 1 as a drug target and reveals important functions in parasite
659 viability and intracellular infection. *Antimicrob Agents Chemother*
660 doi:10.1128/AAC.02022-13.
- 661 22. **Liu J, Carvalho LP, Bhattachariya S, Carbone CJ, Kumar KG, Leu NA, Yau PM,**
662 **Donald RG, Weiss MJ, Baker DP, McLaughlin KJ, Scott P, Fuchs SY.** 2009.
663 Mammalian casein kinase 1alpha and its leishmanial ortholog regulate stability of
664 IFNAR1 and Type I interferon signaling. *Mol Cell Biol* **29**:6401-6412.
- 665 23. **Reinhardt J, Ferandin Y, Meijer L.** 2007. Purification of CK1 by affinity
666 chromatography on immobilised axin. *Protein Expr Purif* **54**:101-109.
- 667 24. **Saar Y, Ransford A, Waldman E, Mazareb S, Amin-Spector S, Plumblee J, Turco**
668 **SJ, Zilberstein D.** 1998. Characterization of developmentally-regulated activities in
669 axenic amastigotes of *Leishmania donovani*. *Mol Biochem Parasitol* **95**: 9-20.
- 670 25. **Goyard S, Segawa H, Gordon J, Showalter M, Duncan R, Turco SJ, Beverley SM.**
671 2003. An in vitro system for developmental and genetic studies of *Leishmania donovani*
672 phosphoglycans. *Mol Biochem Parasitol* **130**: 31-42.
- 673 26. **Morales MA, Watanabe R, Laurent C, Lenormand P, Rousselle J-C, Namane A,**
674 **Spath GF.** 2008. Phosphoproteomic analysis of *Leishmania donovani* pro- and
675 amastigote stages. *Proteomics* **8**:350-363.
- 676 27. **Shimony O, Jaffe CL.** 2008. Rapid fluorescent assay for screening drugs on *Leishmania*
677 amastigotes. *J Microbiol Methods* **75**:196-200.
- 678 28. **Aulner N, Danckaert A, Rouault-Hardoin E, Desrivot J, Helynck O, Commere PH,**
679 **Munier-Lehmann H, Spath GF, Shorte SL, Milon G, Prina E.** 2013. High content
680 analysis of primary macrophages hosting proliferating *Leishmania* amastigotes:
681 application to anti-leishmanial drug discovery. *PLoS Negl Trop Dis* **7**:e2154.
- 682 29. **Oumata N, Bettayeb K, Ferandin Y, Demange L, Lopez-Giral A, Goddard ML,**
683 **Myrianthopoulos V, Mikros E, Flajolet M, Greengard P, Meijer L, Galons H.** 2008.

- 684 Roscovitine-derived, dual-specificity inhibitors of cyclin-dependent kinases and casein
685 kinases 1. *J Med Chem* **51**:5229-5242.
- 686 30. **Polychronopoulos P, Magiatis P, Skaltsounis A-L, Myrianthopoulos V, Mikros E,**
687 **Tarricone A, Musacchio A, Roe SM, Pearl L, Leost M, Greengard P, Meijer L.**
688 2004. Structural Basis for the Synthesis of Indirubins as Potent and Selective Inhibitors of
689 Glycogen Synthase Kinase-3 and Cyclin-Dependent Kinases. *Journal of Medicinal*
690 *Chemistry* **47**:935-946.
- 691 31. **Vougogiannopoulou K, Ferandin Y, Bettayeb K, Myrianthopoulos V, Lozach O,**
692 **Fan Y, Johnson CH, Magiatis P, Skaltsounis A-L, Mikros E, Meijer L.** 2008. Soluble
693 3',6-Substituted Indirubins with Enhanced Selectivity toward Glycogen Synthase Kinase -
694 3 Alter Circadian Period. *Journal of Medicinal Chemistry* **51**:6421-6431.
- 695 32. **Ferandin Y, Bettayeb K, Kritsanida M, Lozach O, Polychronopoulos P, Magiatis P,**
696 **Skaltsounis A-L, Meijer L.** 2006. 3'-Substituted 7-Halogenoindirubins, a New Class of
697 Cell Death Inducing Agents. *Journal of Medicinal Chemistry* **49**:4638-4649.
- 698 33. **Schwede T, Kopp J, Guex N, Peitsch MC.** 2003. SWISS-MODEL: An automated
699 protein homology-modeling server. *Nucleic Acids Res* **31**:3381-3385.
- 700 34. **Delano W.** 2009. The PyMOL Molecular Graphics System 1.01,
701 <http://www.pymol.sourceforge.net>.
- 702 35. **Schnur L, Bachrach U, Bar-Ad G, Haran M, Tashma Z, Talmi M, Katzhendler J.**
703 1983. The effect of diaminoalkyl-anthraquinone derivatives on the growth of the
704 promastigotes of *Leishmania tropica* minor, *L. t. major*, *L. donovani* and *L. aethiopica*.
705 *Biochem Pharmacol* **32**:1729-1732.
- 706 36. **Sittie AA, Lemmich E, Olsen CE, Hviid L, Kharazmi A, Nkrumah FK, Christensen**
707 **SB.** 1999. Structure-activity studies: in vitro antileishmanial and antimalarial activities of
708 anthraquinones from *Morinda lucida*. *Planta Med* **65**:259-261.
- 709 37. **Bolognesi ML, Lizzi F, Perozzo R, Brun R, Cavalli A.** 2008. Synthesis of a small
710 library of 2-phenoxy-1,4-naphthoquinone and 2-phenoxy-1,4-anthraquinone derivatives
711 bearing anti-trypanosomal and anti-leishmanial activity. *Bioorg Med Chem Lett* **18**:2272-
712 2276.
- 713 38. **Connors R, Schambach F, Read J, Cameron A, Sessions RB, Vivas L, Easton A,**
714 **Croft SL, Brady RL.** 2005. Mapping the binding site for gossypol-like inhibitors of
715 *Plasmodium falciparum* lactate dehydrogenase. *Mol Biochem Parasitol* **142**:137-148.
- 716 39. **Montamat EE, Burgos C, Gerez de Burgos NM, Rovai LE, Blanco A, Segura EL.**
717 1982. Inhibitory action of gossypol on enzymes and growth of *Trypanosoma cruzi*.
718 *Science* **218**:288-289.
- 719 40. **Padmanabhan PK, Mukherjee A, Singh S, Chattopadhyaya S, Gowri VS, Myler PJ,**
720 **Srinivasan N, Madhubala R.** 2005. Glyoxalase I from *Leishmania donovani*: a potential
721 target for anti-parasite drug. *Biochem Biophys Res Commun* **337**:1237-1248.
- 722 41. **Tasdemir D, Kaiser M, Brun R, Yardley V, Schmidt TJ, Tosun F, Ruedi P.** 2006.
723 Antitrypanosomal and antileishmanial activities of flavonoids and their analogues: in
724 vitro, in vivo, structure-activity relationship, and quantitative structure-activity
725 relationship studies. *Antimicrob Agents Chemother* **50**:1352-1364.
- 726 42. **Sen G, Mukhopadhyay S, Ray M, Biswas T.** 2008. Quercetin interferes with iron
727 metabolism in *Leishmania donovani* and targets ribonucleotide reductase to exert
728 leishmanicidal activity. *J Antimicrob Chemother* **61**:1066-1075.
- 729 43. **da Silva ER, Maquiaveli Cdo C, Magalhaes PP.** 2012. The leishmanicidal flavonols
730 quercetin and quercitrin target *Leishmania (Leishmania) amazonensis* arginase. *Exp*
731 *Parasitol* **130**:183-188.
- 732 44. **Knockaert M, Gray N, Damiens E, Chang YT, Grellier P, Grant K, Fergusson D,**
733 **Mottram J, Soete M, Dubremetz JF, Le Roch K, Doerig C, Schultz P, Meijer L.**

2000. Intracellular targets of cyclin-dependent kinase inhibitors: identification by affinity chromatography using immobilised inhibitors. *Chem Biol* **7**:411-422.
45. **Hanke JH, Gardner JP, Dow RL, Changelian PS, Brissette WH, Weringer EJ, Pollok BA, Connelly PA.** 1996. Discovery of a novel, potent, and Src family-selective tyrosine kinase inhibitor. Study of Lck- and FynT-dependent T cell activation. *J Biol Chem* **271**:695-701.
 46. **Massillon D, Stalmans W, van de Werve G, Bollen M.** 1994. Identification of the glycogenic compound 5-iodotubercidin as a general protein kinase inhibitor. *Biochem J* **299** (Pt 1):123-128.
 47. **Bento AP, Gaulton A, Hersey A, Bellis LJ, Chambers J, Davies M, Kruger FA, Light Y, Mak L, McGlinchey S, Nowotka M, Papadatos G, Santos R, Overington JP.** 2014. The ChEMBL bioactivity database: an update. *Nucleic Acids Res* **42**:D1083-1090.
 48. **Hishiki T, Saito T, Sato Y, Mitsunaga T, Terui E, Matsuura G, Saito E, Shibata R, Mise N, Yokoyama Y, Yoshida H.** 2011. Src kinase family inhibitor PP2 induces aggregation and detachment of neuroblastoma cells and inhibits cell growth in a PI3 kinase/Akt pathway-independent manner. *Pediatr Surg Int* **27**:225-230.
 49. **Mashhoon N, DeMaggio AJ, Tereshko V, Bergmeier SC, Egli M, Hoekstra MF, Kuret J.** 2000. Crystal structure of a conformation-selective casein kinase-1 inhibitor. *J Biol Chem* **275**:20052-20060.
 50. **Balana-Fouce R, Alvarez-Velilla R, Fernandez-Prada C, Garcia-Estrada C, Reguera RM.** 2014. Trypanosomatids topoisomerase re-visited. New structural findings and role in drug discovery. *Int J Parasitol Drugs Drug Resist* **4**:326-337.
 51. **Katayama H, Kiryu Y, Kaneko K, Ohshima R.** 2000. Anti-cancer activities of pyrazolo[1,5-a]indole derivatives. *Chem Pharm Bull (Tokyo)* **48**:1628-1633.
 52. **Das BB, Ganguly A, Majumder HK.** 2008. DNA topoisomerases of Leishmania: the potential targets for anti-leishmanial therapy. *Adv Exp Med Biol* **625**:103-115.
 53. **Sanderson L, Yardley V, Croft SL.** 2014. Activity of anti-cancer protein kinase inhibitors against Leishmania spp. *J Antimicrob Chemother* **69**:1888-1891.
 54. **Bain J, Plater L, Elliott M, Shpiro N, Hastie CJ, McLauchlan H, Klevernic I, Arthur JS, Alessi DR, Cohen P.** 2007. The selectivity of protein kinase inhibitors: a further update. *Biochem J* **408**:297-315.
 55. **Parsons M, Worthey EA, Ward PN, Mottram JC.** 2005. Comparative analysis of the kinomes of three pathogenic trypanosomatids: Leishmania major, Trypanosoma brucei and Trypanosoma cruzi. *BMC Genomics* **6**:127.
 56. **Tejle K, Lindroth M, Magnusson KE, Rasmusson B.** 2008. Wild-type Leishmania donovani promastigotes block maturation, increase integrin expression and inhibit detachment of human monocyte-derived dendritic cells--the influence of phosphoglycans. *FEMS Microbiol Lett* **279**:92-102.
 57. **Grant KM, Dunion MH, Yardley V, Skaltsounis AL, Marko D, Eisenbrand G, Croft SL, Meijer L, Mottram JC.** 2004. Inhibitors of Leishmania mexicana CRK3 cyclin-dependent kinase: chemical library screen and antileishmanial activity. *Antimicrob Agents Chemother* **48**:3033-3042.
 58. **Xingi E, Smirlis D, Myrianthopoulos V, Magiatis P, Grant KM, Meijer L, Mikros E, Skaltsounis AL, Soteriadou K.** 2009. 6-Br-5methylindirubin-3'-oxime (5-Me-6-BIO) targeting the leishmanial glycogen synthase kinase-3 (GSK-3) short form affects cell-cycle progression and induces apoptosis-like death: exploitation of GSK-3 for treating leishmaniasis. *Int J Parasitol* **39**:1289-1303.
 59. **Efstathiou A, Gaboriaud-Kolar N, Smirlis D, Myrianthopoulos V, Vougianniopoulou K, Alexandratos A, Kritsanida M, Mikros E, Soteriadou K, Skaltsounis AL.** 2014. An inhibitor-driven study for enhancing the selectivity of

- 785 indirubin derivatives towards leishmanial Glycogen Synthase Kinase-3 over leishmanial
786 cdc2-related protein kinase 3. *Parasit Vectors* **7**:234.
- 787 60. **Harwood AJ.** 2002. Signal transduction in development: holding the key. *Dev Cell*
788 **2**:384-385.
- 789 61. **Niehrs C, Shen J.** 2010. Regulation of Lrp6 phosphorylation. *Cell Mol Life Sci* **67**:2551-
790 2562.
- 791 62. **Knippschild U, Kruger M, Richter J, Xu P, Garcia-Reyes B, Peifer C, Halekotte J,**
792 **Bakulev V, Bischof J.** 2014. The CK1 Family: Contribution to Cellular Stress Response
793 and Its Role in Carcinogenesis. *Front Oncol* **4**:96.
- 794 63. **Beurel E, Grieco SF, Jope RS.** 2015. Glycogen synthase kinase-3 (GSK3): Regulation,
795 actions, and diseases. *Pharmacol Ther* **148C**:114-131.

796

797 **FIGURE LEGENDS**

798 **FIGURE 1. Differential target-based screen of 4030 compounds from various**
799 **libraries. A.** Representation of the percentage of inhibition towards LmCK1.2 activity
800 versus the percentage of inhibition toward SsCK1 activity. Compounds in a and b are
801 potent toward LmCK1.2 as they show more than 40% inhibition, whereas compounds in
802 b and d are potent toward SsCK1. **B.** 336 hit compounds were identified in the screen
803 from which 245 inhibit SsCK1 (6.1 % hit rate) and 128 inhibit LmCK1.2 (3.2% hit rate).
804 Only 37 compounds showed equal potency against both CK1s. **C.** Compounds were
805 classified according to their specificity: compounds only potent against SsCK1 (only
806 SsCK1), more potent against SsCK1 than LmCK1.2 ($SsCK1 > LmCK1.2$), equally
807 potent on both kinases ($SsCK1 = LmCK1.2$), more potent against LmCK1.2 than SsCK1
808 ($SsCK1 < LmCK1.2$) and only potent on LmCK1.2 (only LmCK1.2). Compounds were
809 also classified according to their % of inhibition: Class 1 corresponds to compounds that
810 inhibit the kinases activity between 80-100%, Class 2 between 60-80% and class 3
811 between 40-60%. Twenty-three compounds are more potent toward LmCK1.2 than
812 SsCK1 and 68 compounds are specific to LmCK1.2 (the numbers in the histograms
813 indicate the percentage of compounds in each category).

814

815 **FIGURE 2. Determination of the IC₅₀ of the 45 compounds belonging to Class 1 that**
816 **have a percentage of inhibition above 90%.** Each point represents the IC₅₀ of a
817 particular compound towards LmCK1.2. Non-specific compounds have a potency below
818 10 µM towards both kinases, whereas specific compounds have a potency below 10 µM
819 only towards LmCK1.2.

820

821 **FIGURE 3. Screening of the purine derivative library. A.** Structure of the purine
822 backbone. R1, R2 and R3 represent different substitutions of the purines. **B.** We
823 performed a target-based screening of 588 derivatives. Each point represents the
824 percentage of inhibition towards LmCK1.2 activity versus the percentage of inhibition
825 towards SsCK1 activity of each compound. The compounds in the top left are more
826 potent toward LmCK1.2 whereas the compounds in the bottom right are more potent
827 towards SsCK1. **C.** Compounds were classified according to their specificity: only potent
828 on SsCK1, more potent on SsCK1 than LmCK1.2 (SsCK1 > LmCK1.2), equally on both
829 kinases (SsCK1 = LmCK1.2), more potent on LmCK1.2 than SsCK1 (SsCK1 <
830 LmCK1.2) and only potent on LmCK1.2. Compounds were also classified according to
831 their % of inhibition: Class 1 corresponds to compounds that inhibit the kinases between
832 80-100%, Class 2 between 60-80% and class 3 between 40-60%. Only 4 percent of the
833 compounds are more potent toward LmCK1.2 than SsCK1 or specific to LmCK1.2. **D.**
834 We determined the IC₅₀ of the 21 compounds belonging to class 1 that have a percentage
835 of inhibition above 90%. Each point represents the IC₅₀ of a particular compound towards
836 LmCK1.2 versus SsCK1. The IC₅₀ are lower towards SsCK1 than LmCK1.2.

837

838 **FIGURE 4. Screening of the indirubin derivative library.** **A.** Structure of the indirubin
839 backbone. **B.** Target-based screening of 400 derivatives. Each point represents the
840 percentage of inhibition towards LmCK1.2 activity versus the percentage of inhibition
841 toward SsCK1 activity for each compound. The compounds in the top left are more
842 potent towards LmCK1.2 whereas the compounds in the bottom right are more potent
843 towards SsCK1. **C.** Compounds were classified according to their specificity: only potent
844 on SsCK1, more potent on SsCK1 than LmCK1.2 ($SsCK1 > LmCK1.2$), equally on both
845 kinases ($SsCK1 = LmCK1.2$), more potent on LmCK1.2 than SsCK1 ($SsCK1 <$
846 $LmCK1.2$) and only potent on LmCK1.2. Compounds were also classified according to
847 their % of inhibition: Class 1 corresponds to compounds that inhibit the kinases between
848 80-100%, Class 2 between 60-80% and class 3 between 40-60%. Fifty-seven percent of
849 the compounds are more potent towards LmCK1.2 than SsCK1 and 46% are specific to
850 LmCK1.2. **D.** IC_{50} of the 55 compounds that are specific to LmCK1.2 or that belong to
851 class 1 with a percentage of inhibition above 90%. Each point represents the IC_{50} of a
852 particular compound towards LmCK1.2 versus SsCK1. The IC_{50} are lower against
853 LmCK1.2 than SsCK1.

854

855 **FIGURE 5. Comparaison of the anti-leishmanial activity of compounds on cultured**
856 **and intracellular parasites.** We performed a screening of 88 compounds from the main,
857 the purine and the indirubine libraries on cultures promastigotes, axenic amastigotes and
858 intracellular parasites. Each point represents the percentage of metabolically active
859 promastigotes or amastigotes at 10 μ M versus the percentage of parasite burden at 10 μ M

for each compound. Black squares correspond to the percentage of metabolically active promastigotes at 10 μ M versus the percentage of parasite burden at 10 μ M and grey dots correspond to the percentage of metabolically active amastigotes at 10 μ M versus the percentage of parasite burden at 10 μ M. a: compounds that are potent against intracellular parasites but not against cultured parasites, b: compounds that are not potent against intracellular and cultured parasites, c: compounds that are potent against intracellular and cultured parasites and d: compounds that are not potent against intracellular but potent against cultured parasites.

FIGURE 6. Parasite burden versus macrophage viability. Using a visual high content phenotypic assay, we calculated the percentage of viable macrophages and the percentage of infected cells. We analysed the anti-leishmanial effect of the selected compounds from the main library (A), the indirubin library (B) and the purine library (C) versus their toxicity against macrophages. a: compounds that are not potent against intracellular parasites but cytotoxic, b: compounds that are not potent against intracellular parasites and not cytotoxic, c: compounds that are potent against intracellular but cytotoxic and d: compounds that are potent against intracellular and not cytotoxic.

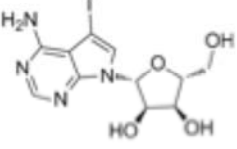
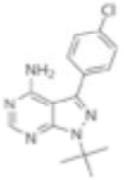
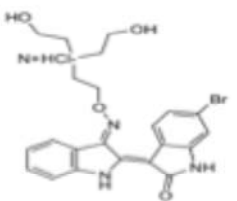
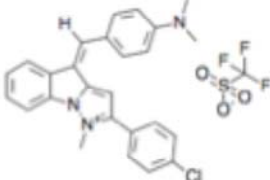
FIGURE 7. PP2 and compound 42 are the most specific compounds towards CK1.2. Competitive ATP affinity chromatography assays were performed on amastigote cell lysates in presence or not of D4476, PP2, 5'ITu (Iodo), NSC699479 (73) and 42. ATP-binding proteins (Elution) were eluted with an excess of ATP, resolved by SDS-PAGE

electrophoresis and stained by SYPRO Ruby (**A**). CK1.2 was revealed by Western blot using an anti-LmCK1.2 antibody (SY3535, **B**).

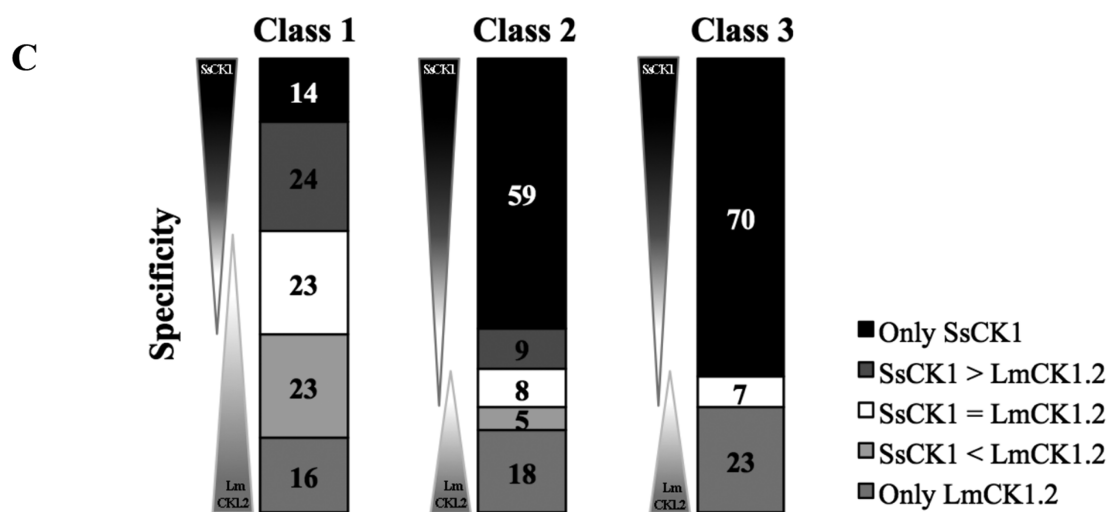
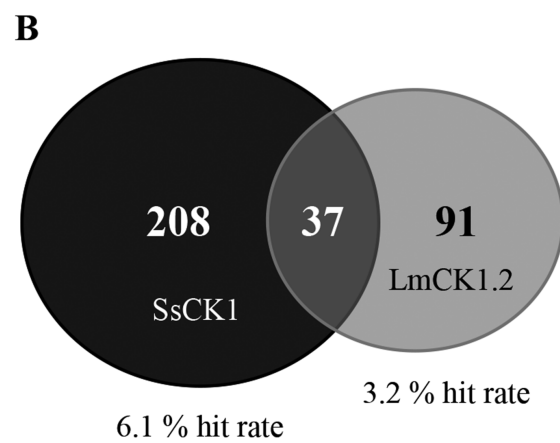
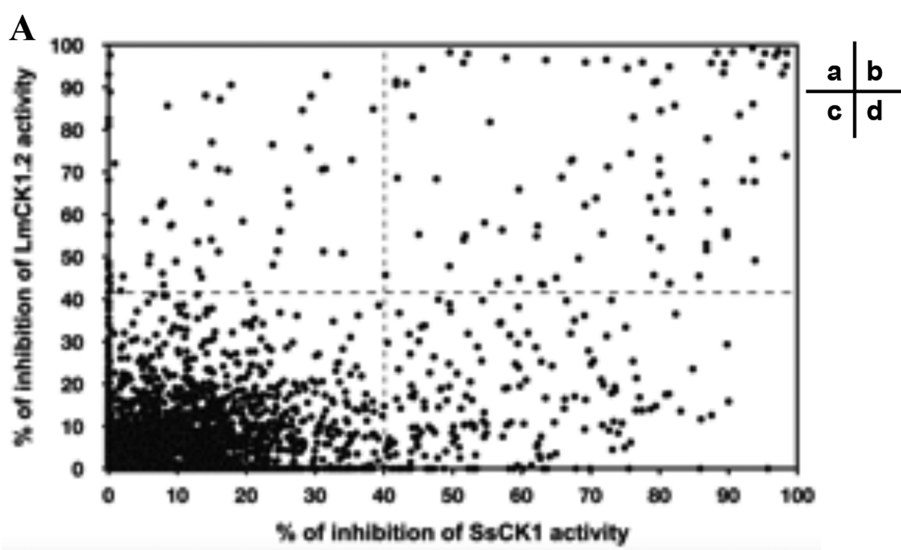
FIGURE S1. Controls for the phenotypic screen. We analysed the effect of DMSO, AMB and CHX on intracellular parasites using a visual high content phenotypic assay. We assessed several parameters including the percentage of total cells compared to control cells with DMSO (TM%), the percentage of viable cells (VI%) and the percentage of viable cells with parasitophorous vacuoles that is considered as an indication of parasite burden (PB%).

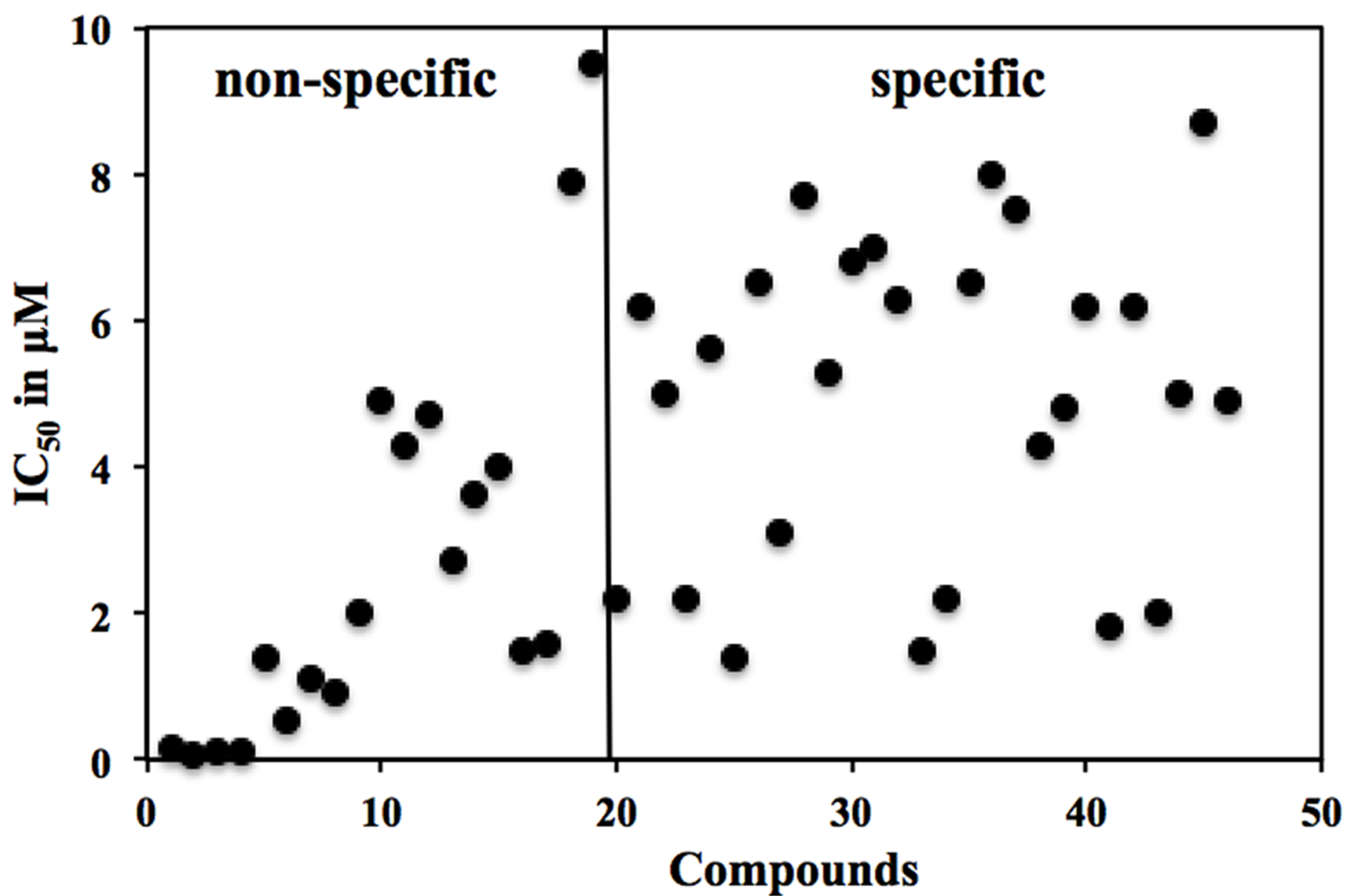
FIGURE S2. Model of the ATP binding pocket of LmCK1.2 compared to that of human and yeast CK1s. Comparison of yeast (cyan) and human (magenta) CK1 crystal structures with a structural model of LmCK1.2 (green). IC261 is represented in the ATP-binding pocket.

Table 1: Selected compounds against intracellular parasites tested for target deconvolution.

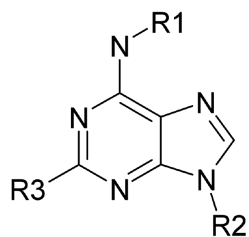
Compound name and structure	LmCK1.2 IC ₅₀ in μ M	EC ₅₀ on cultured Promastigote in μ M	EC ₅₀ on cultured Amastigote in μ M	EC ₅₀ on intracellular parasites in μ M	SI
5' Iodotubercidin 	0.18 $\pm$ 0.04	0.40 $\pm$ 0.10	5.40 $\pm$ 1.80	0.06 $\pm$ 0.01	20
PP2 	1.60 $\pm$ 0.30	> 10	> 50	1*	> 10
42 	0.93 $\pm$ 0.20	2.00 $\pm$ 0.00	> 10	0.06 $\pm$ 0.00	50
NSC699479 	8.00 $\pm$ 0.30	<1	<1	0.33 $\pm$ 0.05	10

898
 *: Estimation of the EC₅₀.

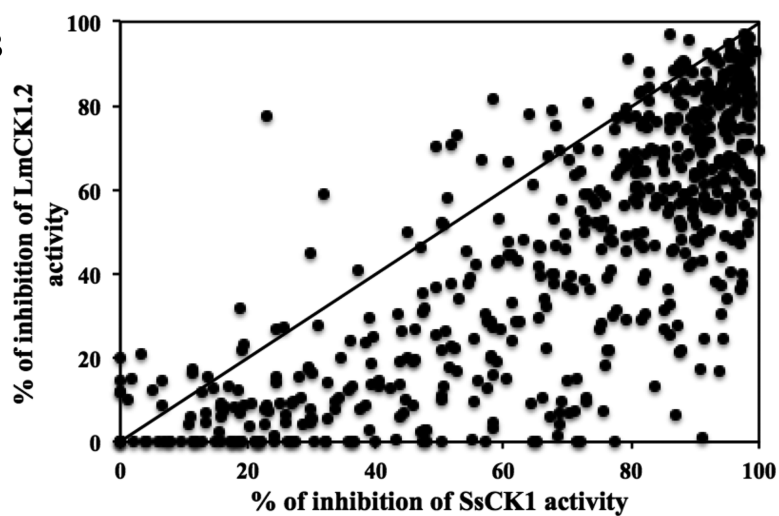




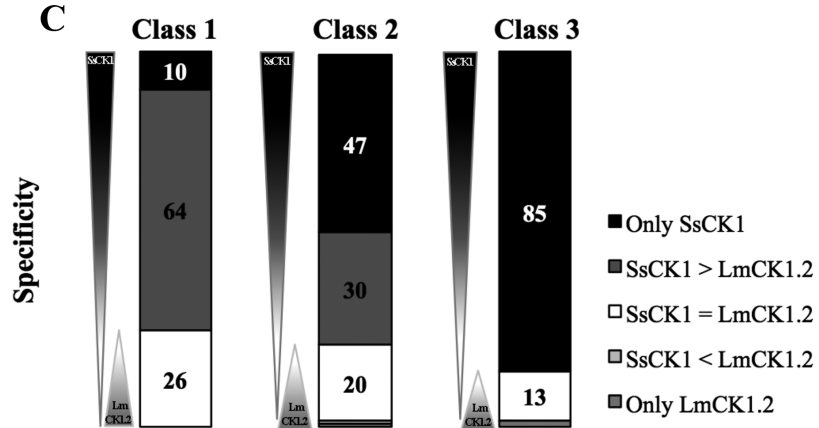
A



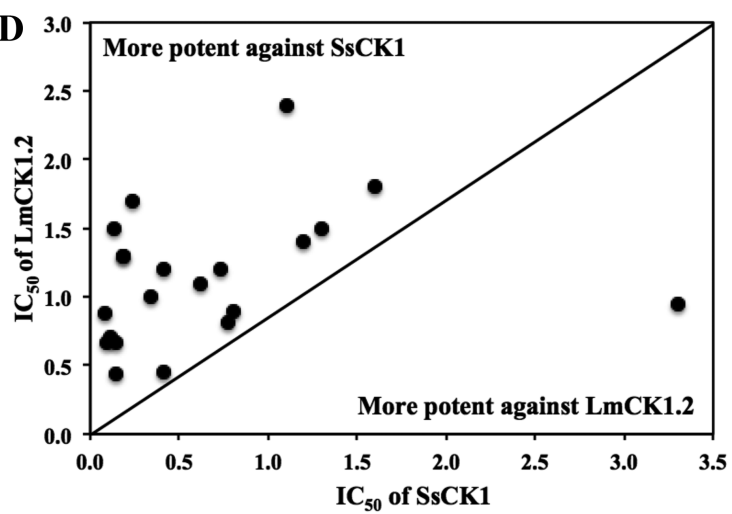
B



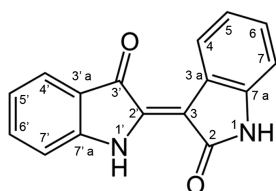
C



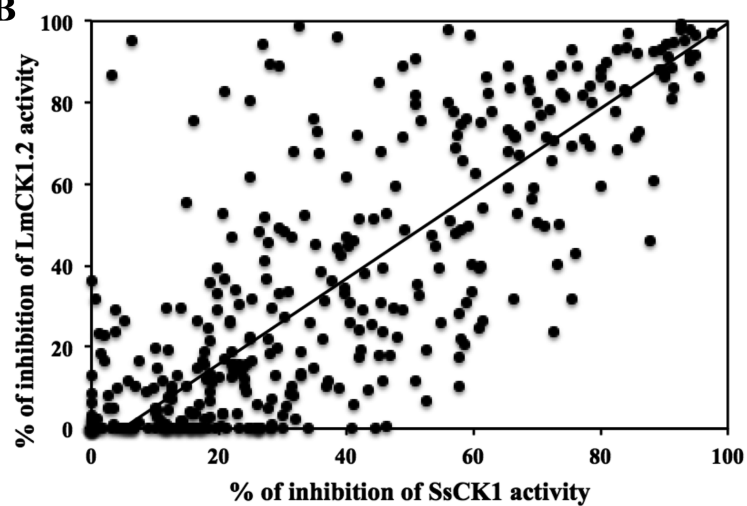
D



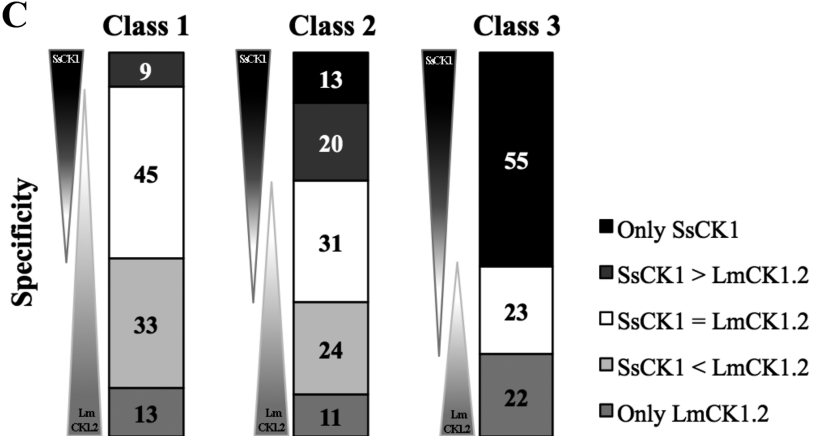
A



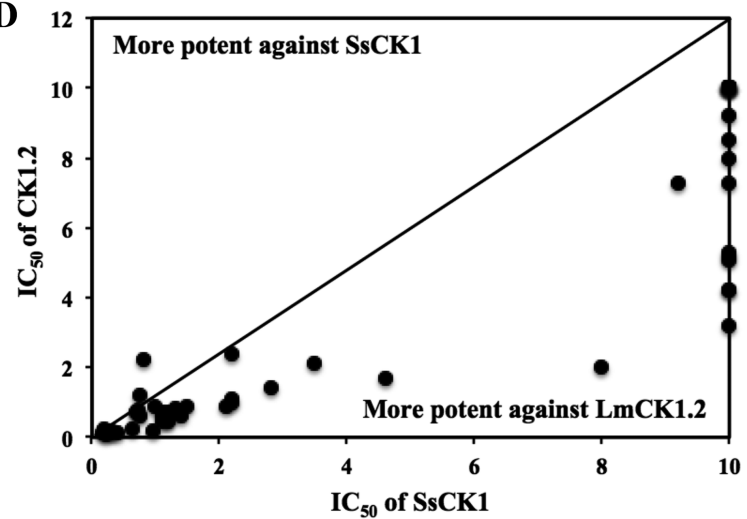
B

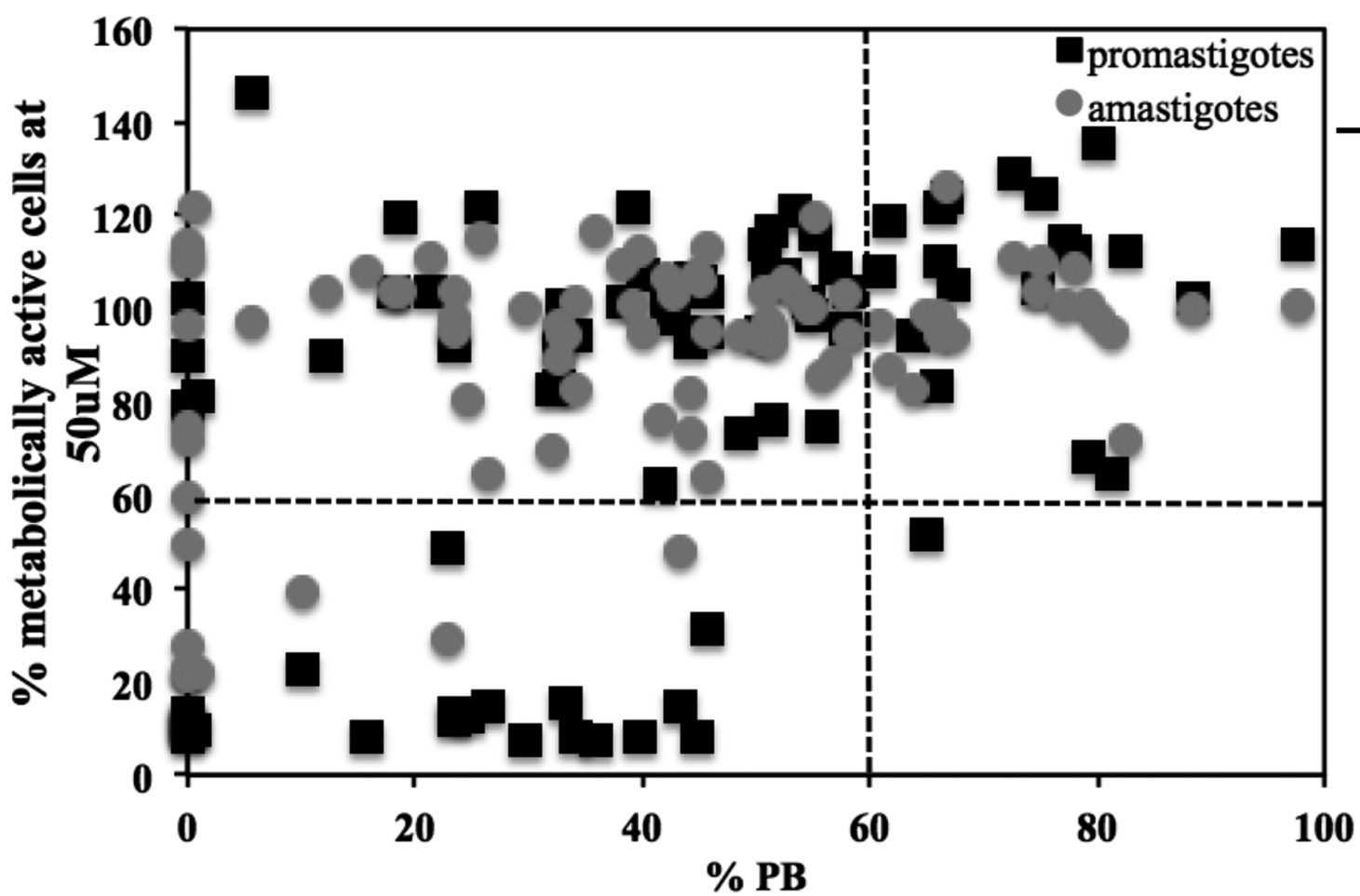


C

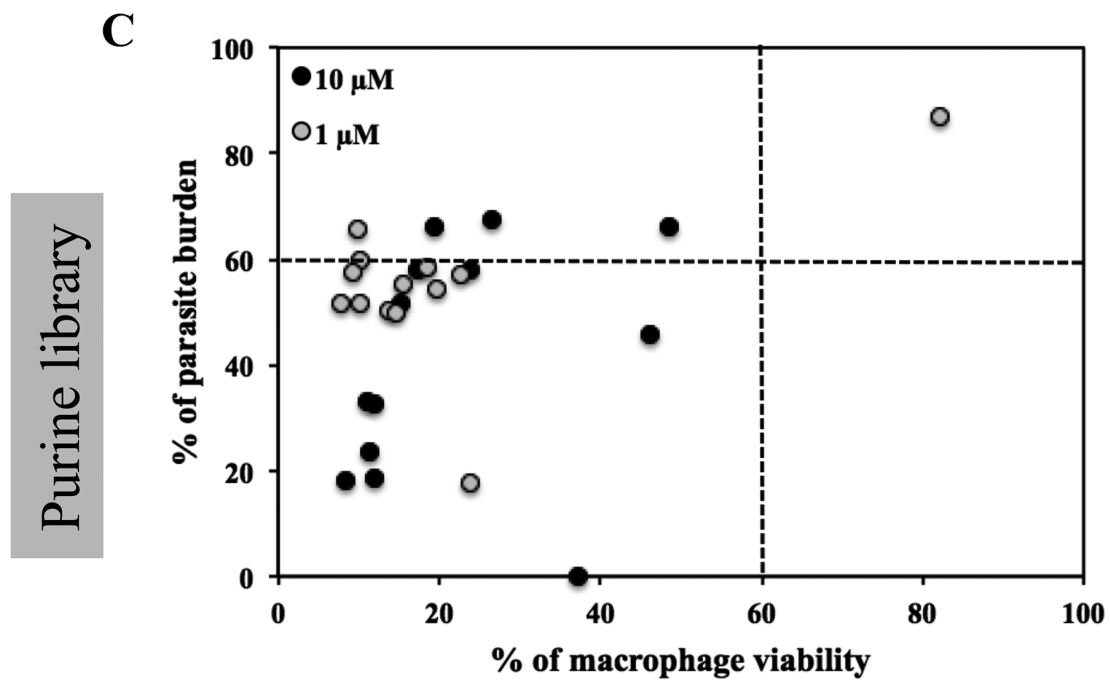
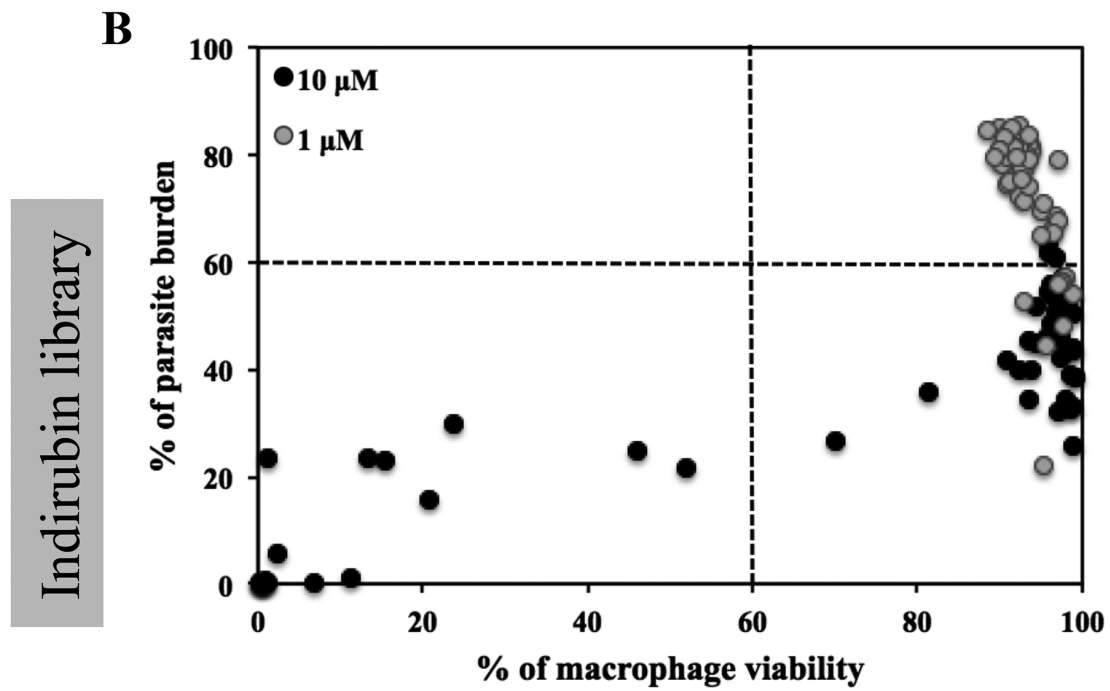
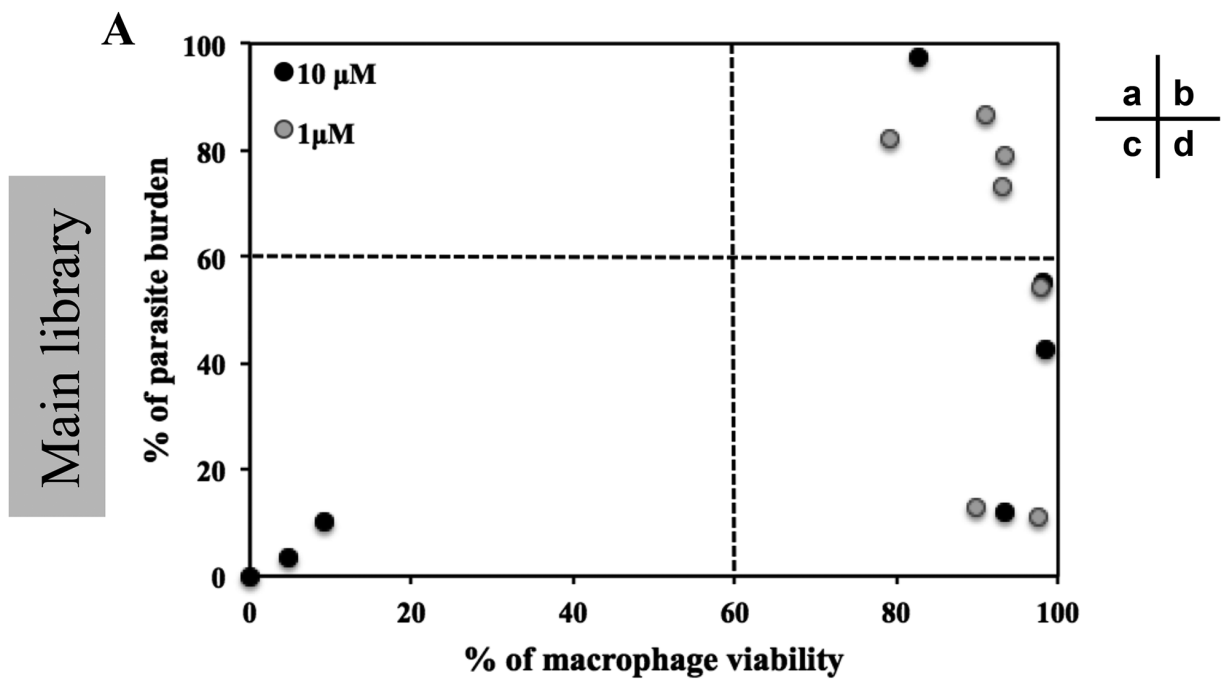


D





a	b
c	d



Elution

Ama

D44

PP2

Iodo

73

42

A

140 -

115 -

80 -

70 -

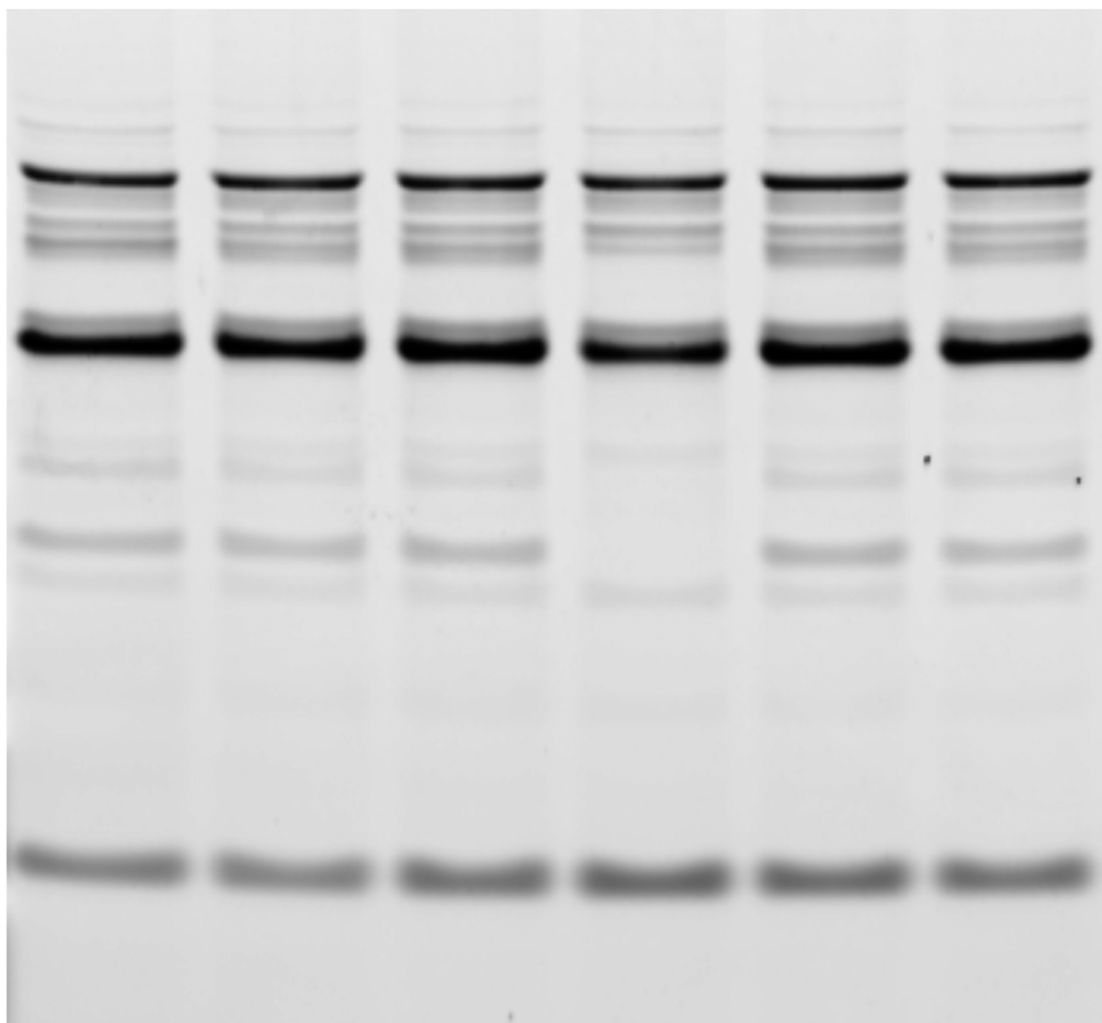
50 -

40 -

30 -

25 -

15 -



B

40 -



α CK1.2

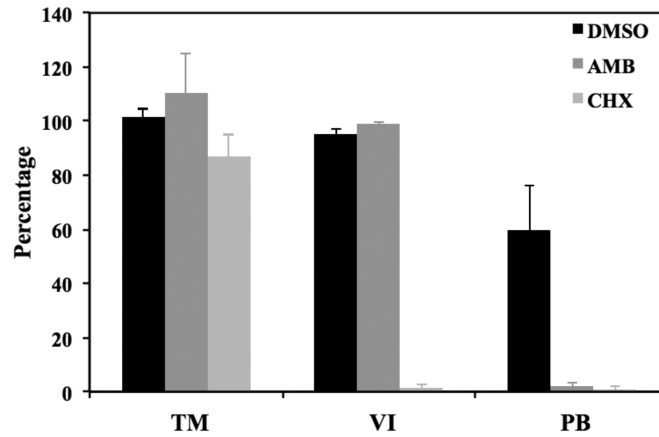


FIGURE S1. Controls for the phenotypic screen. We analysed the effect of DMSO, AMB and CHX on intracellular parasites using a visual high content phenotypic assay. We assessed several parameters including the percentage of total cells compared to control cells with DMSO (TM%), the percentage of viable cells (VI%) and the percentage of viable cells with parasitophorous vacuoles that is considered as an indication of parasite burden (PB%).

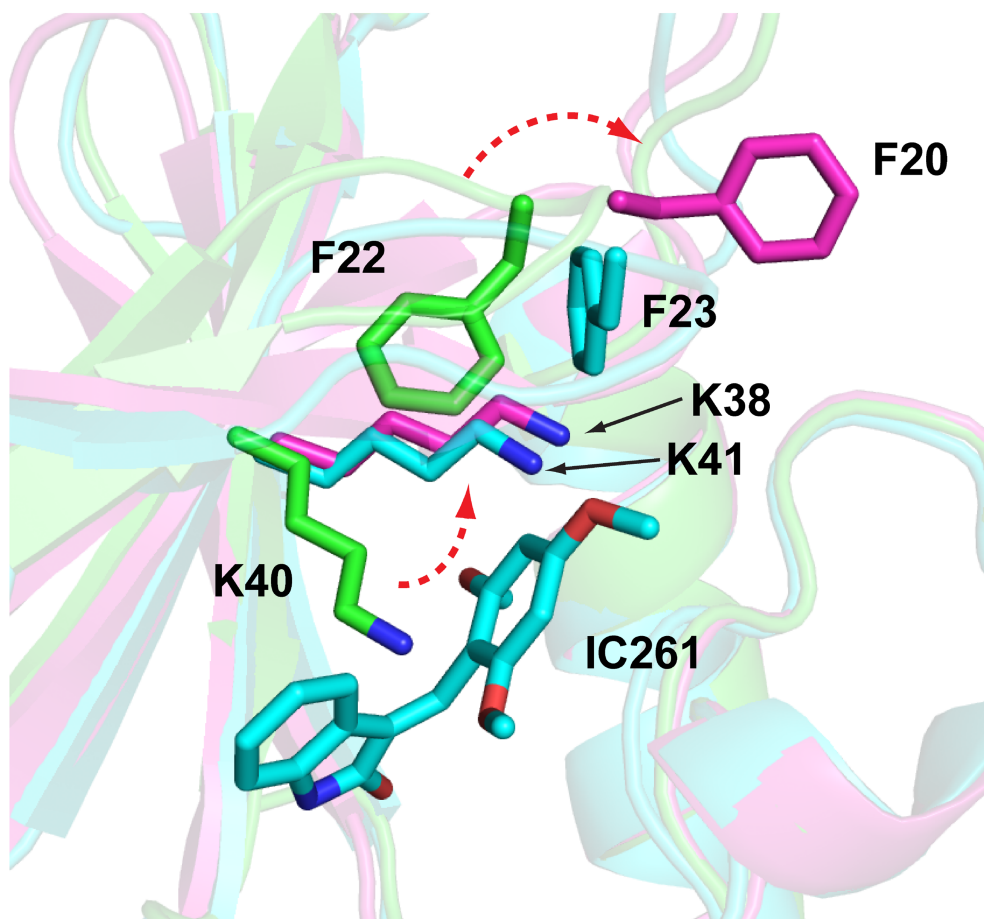


FIGURE S2. Model of the ATP binding pocket of LmCK1.2 compared to that of human and yeast CK1s. Comparison of yeast (cyan) and human (magenta) CK1 crystal structures with a structural model of LmCK1.2 (green). IC261 is represented in the ATP-binding pocket.

	Compound		IC ₅₀ (μM)		Metabolically active cells (%)				EC ₅₀ (μM)		intracellular parasites						EC ₅₀ (μM)	Macrophage viability EC ₅₀ (μM)	EC ₅₀ against human cells (μM)				Selectivity Index (SI)	
	Number	Name	SoCK1	LmCK1.2	Promastigote (%)		amastigote (%)		EC ₅₀ (μM)	amastigote (%)	TM %	PB %	VI %	TM %	PB %	VI %			RPE-1	SHSY-5Y	HFF-1	U2OS		
					50 μM	10 μM	50 μM	10 μM																
Main Library	1	PKC-412	>10	>10	63.8	85.0	102.2	93.0	>50	>50	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.								
	2	Hypericin	>10	6.2	76.5	127.4	92.9	106.0	>50	>50	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.								
	3	5-Iodotubercidin	0.1	0.2	14.5	22.7	25.2	39.0	0.4	5.0	77.0	10.2	9.3	68.0	13.0	90.0	0.1	3.5	1.2	> 25	> 25	1.2	20	
	4	SB-202190	0.4	0.1	69.0	129.4	112.3	111.0	>50	>50	87.7	72.8	89.4	94.9	83.6	93.5								
	5	PP2	0.5	1.4	41.2	114.0	99.1	101.0	>50	>50	59.9	97.6	82.9	83.7	54.3	97.8	1*	> 10	> 25	> 25	> 25	> 25	> 10	
	6	GW 5074	4.3	4.9	27.5	112.8	20.3	72.0	>10	>10	102.9	82.5	97.6	101.7	79.1	94.1	3*	> 10	> 50	> 50	> 50	39.0	> 3.3	
	7	Rotterlin	>10	4.9	15.7	90.2	32.2	104.0	>10	>10	58.5	12.1	93.4	101.8	82.0	79.1								
	8	Indirubin-3'-monoxime	0.4	0.1	70.1	125.0	85.2	110.0	>50	>50	99.6	75.2	96.5	104.9	80.5	95.9								
Purine Library	9	BML-265	2.2	0.9	36.9	124.0	87.2	126.0	>10	>50	96.1	66.8	95.6	104.0	80.9	96.4								
	10		0.1	0.4	13.8	51.8	49.8	99.0	>10	>10	54.5	64.9	65.8	105.1	80.4	87.4								
	11		1.6	1.8	27.9	68.4	83.2	101.0	>10	>50	67.5	79.1	90.0	98.9	83.1	95.3								
	12		0.2	1.3	18.1	83.3	56.4	97.0	>10	>50	90.9	65.8	89.7	108.2	79.7	88.7								
	13		0.8	0.9	61.9	102.6	104.3	100.0	>50	>50	100.5	88.4	96.4	104.3	83.8	94.3								
	14		0.4	0.5	90.7	104.3	109.1	104.0	>50	>50	88.1	74.8	94.6	94.6	81.8	95.7								
	15		0.8	0.8	26.1	64.8	77.9	95.0	>10	>50	84.8	81.4	95.8	103.6	87.9	95.6								
	16		0.1	0.7	54.3	114.6	100.3	101.0	>10	>50	64.3	77.0	27.6	52.1	74.0	48.5								
	17		0.3	1.0	35.0	116.5	78.5	96.0	>10	>50	61.7	51.5	15.2	61.2	58.6	18.6								
	18		0.1	0.9	43.1	95.8	81.0	103.0	>10	>50	62.7	57.8	17.3	67.8	50.5	13.6								
	19		0.1	0.7	31.2	110.1	86.3	94.0	>10	>50	64.8	66.2	19.3	65.0	55.2	15.6								
	20		0.6	1.1	44.2	105.0	92.9	94.0	>10	>50	55.6	67.4	26.6	57.1	54.6	19.6								
	21		1.1	2.4	10.6	104.0	99.8	104.0	>10	>50	85.1	18.1	8.5	79.5	51.7	82.2								
	22		0.7	1.2	9.9	12.1	19.6	75.0	0.8	>10	106.9	0.0	37.1	115.2	17.6	23.9								
	23		0.2	1.3	18.3	83.7	70.5	89.0	>10	>50	70.5	32.5	12.0	69.0	51.5	7.8								
	24		0.1	1.5	19.7	92.5	61.1	98.0	>10	>10	71.5	23.4	11.5	69.2	59.9	10.3								
	25		0.2	1.7	15.3	119.3	58.2	104.0	>10	>50	71.0	18.8	12.1	72.7	51.7	10.1								
	26		3.7	1.0	89.9	135.9	78.2	98.0	>50	>50	95.0	80.0	90.4	102.1	84.5	92.8								
	27		1.2	1.4	16.9	100.5	74.5	94.0	>10	>50	78.6	33.1	11.0	79.0	57.5	9.3								
	28		0.4	1.2	27.6	103.4	84.1	94.0	>10	>50	59.3	58.2	23.7	68.9	49.6	14.7								
	29		0.1	0.7	84.8	121.8	101.4	99.0	>50	>50	49.0	66.2	48.5	56.8	57.0	22.6								
	Indirubin Library	30		1.3	1.5	15.0	31.7	27.5	64.2	6.5	>10	58.9	45.8	46.2	77.8	65.5	9.8							
31			2.2	1.0	39.3	75.9	57.0	93.0	>10	>50	95.6	51.5	94.5	103.9	81.1	93.3								
32			0.7	0.6	71.8	75.6	63.2	94.3	>50	>50	92.7	48.7	96.2	104.2	84.8	92.0								
33			3.5	2.1	69.2	113.7	59.7	103.7	>50	>50	80.1	50.7	96.8	104.2	81.5	93.7								
34			0.3	0.2	69.9	92.0	58.3	96.8	>50	>50	87.8	32.6	98.6	104.9	78.7	92.6								
35			1.0	0.2	81.7	105.7	86.9	105.6	>50	>50	79.3	45.2	93.6	103.6	78.2	90.2								
36			0.6	0.2	79.8	101.3	92.8	106.8	>50	>50	83.9	42.0	97.3	101.4	85.4	92.2								
37			0.7	0.7	122.5	121.3	101.2	103.7	>50	>50	107.9	53.3	96.5	105.3	77.0	93.0								
38			0.7	1.2	56.5	122.0	72.8	115.1	>10	>50	106.6	25.9	98.8	110.5	68.1	95.5	0.6	> 10	> 25	> 25	> 25	> 25	> 17	
39			1.1	0.5	32.0	121.8	32.9	100.9	>10	>10	97.7	39.2	98.6	106.7	82.3	93.4								
40			0.3	0.1	38.4	95.2	48.8	82.2	>10	>10	96.9	44.1	98.2	103.8	79.1	95.0								
41			1.3	0.7	131.9	146.7	118.9	97.4	>50	>50	101.3	5.5	2.3	98.6	81.0	93.9								
42			2.1	0.9	9.3	11.6	19.3	59.6	2.0	>10	106.0	0.0	0.5	107.1	46.7	93.4	0.1	3.0	7.0	18.0	7.7	7.3	50	
43			0.7	0.7	10.9	48.7	26.6	29.6	1.0	8.0	83.9	22.8	15.3	102.6	72.0	92.3								
44			1.2	0.5	8.8	10.5	19.9	22.8	0.9	4.5	106.9	0.0	0.7	96.0	71.4	93.1								
45			1.2	0.4	9.4	10.7	20.5	22.1	0.7	4.5	106.6	0.0	1.2	103.0	74.4	90.8								
Indirubin Library		46		>10	4.2	10.1	106.7	25.3	73.6	>10	>10	103.2	44.1	99.0	105.1	81.6	93.4							
		47		>10	5.2	9.7	13.0	23.0	95.2	2.0	>10	75.6	23.4	13.5	107.5	79.2	97.2							
		48		10.0	5.1	9.5	10.5	19.6	27.5	0.4	7.0	74.1	0.0	0.3	112.6	53.9	99.0							
		49		1.2	0.7	9.7	12.7	23.5	80.8	2.0	>10	83.5	24.6	46.1	106.0	66.2	96.5							
		50		1.1	0.7	7.9	10.4	19.7	21.0	0.7	3.5	107.4	0.0	0.2	108.7	68.6	96.9							
		51		>10	8.5	98.0	106.3	96.0	97.1	>50	>50	111.7	51.0	98.0	104.1	74.8	91.2							
	52		0.2	0.1	106.9	118.6	100.0	86.9	>50	>50	103.6	61.8	95.9	102.4	85.1	89.9								
	53		>10	10.0	67.3	103.5	64.3	94.7	>50	>10	81.8	45.8	95.7	105.0	84.8	91.4								
	54		1.3	0.8	68.0	95.2	84.2	93.3	>50	>50	114.7	50.4	98.8	111.6	81.9	92.6								
	55		>10	5.3	99.0	107.7	88.2	96.3	>50	>50	118.1	60.9	96.8	111.2	83.2	93.0								
	56		>10	8.0	96.0	101.8	98.7	100.4	>50	>50	106.2	54.6	95.8	111.8	80.1	93.3								
	57		>10	10.0	9.4	90.3	19.2	72.2	>10	>10	97.0	0.1	6.8	114.4	81.9	90.7								
	58		9.2	7.3	79.3	94.2	26.9	83.0	>50	>10	106.8	63.7	95.8	109.8	81.2	92.2								
	59		0.2	0.1	85.7	94.6	57.7	82.5	>50	>10	86.5	34.3	98.0	106.8	77.8	92.7								
	60		>10	3.2	10.2	15.0	27.6	64.4	2.0	>10	70.7	26.5	70.1	105.9	69.5	95.0								
	61		>10	7.3	20.2	81.5	14.8	21.9	n.d.	>50	43.8	1.0	11.3	110.1	81.4	91.6	2.0	2.0	n.d.	n.d.	n.d.	n.d.	1	
	Main Library	71	NSC 146771	>10	1.5	59.2	116.3	108.9	119.4	>10	>50	104.3	55.2	98.2	102.6	73.3	93.0							
		72	NSC 610744	>10	7.0	104.2	112.6	99.7	109.1	>50	>50	104.0	78.1	88.0	105.1	84.3	93.1							
		73	NSC 699479	>10	8.0	n.d.	n.d.	n.d.	n.d.	<1	<1	107.9	3.6	10.9	105.7	97.3	92.6	0.3	3.5	10.5	36.5	12.0	3.0	12
		74	NSC 715055 (refimib)	>10	2.0	19.7	97.9	111.3	102.7	>10	>50	93.0	42.7	98.4	102.5	79.2	93.4	8.0	> 10	n.d.	n.d.	n.d.	n.d.	> 1.3
		75	NSC 750690 (gumilub)	0.8	0.6	8.5	13.1	96.3	111.5	4.0	>50	88.3	0.1											