

Drug Discovery for Kinetoplastid Diseases: Future Directions

Srinivasa Rao, Michael Barrett, Glenn Dranoff, Christopher J. Faraday, Claudio R. Gimpelewicz, Asrat Hailu, Catherine L. Jones, John M. Kelly, Janis K. Lazdins-Helds, Pascal Mäser, et al.

▶ **To cite this version:**

Srinivasa Rao, Michael Barrett, Glenn Dranoff, Christopher J. Faraday, Claudio R. Gimpelewicz, et al.. Drug Discovery for Kinetoplastid Diseases: Future Directions. ACS Infectious Diseases, 2018, 10.1021/acsinfecdis.8b00298 . pasteur-01974311

HAL Id: pasteur-01974311

https://pasteur.hal.science/pasteur-01974311

Submitted on 8 Jan 2019

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.



Distributed under a Creative Commons Attribution - NonCommercial - ShareAlike 4.0 International License

This is an open access article published under an ACS AuthorChoice License, which permits copying and redistribution of the article or any adaptations for non-commercial purposes.

ACS Infectious Diseases

Viewpoint

Cite This: ACS Infect. Dis. XXXX, XXX, XXX−XXX

pubs.acs.org/journal/aidcbc

Drug Discovery for Kinetoplastid Diseases: Future Directions

Srinivasa P. S. Rao,[*,†] Michael P. Barrett,[‡] Glenn Dranoff,[§] Christopher J. Faraday,[∥] Claudio R. Gimpelewicz,[⊥] Asrat Hailu,[#] Catherine L. Jones,[†] John M. Kelly,[∇] Janis K. Lazdins-Helds,[○] Pascal Mäser,[●] Jose Mengel,[$,@] Jeremy C. Mottram,[+] Charles E. Mowbray,[¶] David L. Sacks,[×] Phillip Scott,[&] Gerald F. Späth,[^] Rick L. Tarleton,[~] Jonathan M. Spector,[†] and Thierry T. Diagana[*,†]

[†]Novartis Institute for Tropical Diseases (NITD), 5300 Chiron Way, Emeryville, California 94608, United States

[‡]University of Glasgow, University Place, Glasgow G12 8TA, United Kingdom

[§]Immuno-oncology, Novartis Institutes for Biomedical Research (NIBR), 250 Massachusetts Avenue, Cambridge, Massachusetts 02139, United States

[∥]Autoimmunity, Transplantation and Inflammation, NIBR, Fabrikstrasse 2, CH-4056 Basel, Switzerland

[⊥]Global Drug Development, Novartis Pharma, Forum 1, CH-4056 Basel, Switzerland

[#]School of Medicine, Addis Ababa University, P.O. Box 28017 code 1000, Addis Ababa, Ethiopia

[∇]London School of Hygiene and Tropical Medicine, Keppel Street, London WC1E 7HT, United Kingdom

[○]Independent Consultant, Chemic Des Tulipiers 9, 1208 Geneva, Switzerland

[●]Swiss Tropical and Public Health Institute, Socinstrasse 57, 4501 Basel, Switzerland; University of Basel, CH 4000 Basel, Switzerland

[$]Laboratory of Clinical Immunology, Oswaldo Cruz Institute, FIOCRUZ-RJ, Av. Brasil 4365, Cep: 21040-900, Rio de Janeiro-RJ, Brazil

[@]Faculty of Medicine of Petropolis, University in Petròpolis, Av. Barao do Rio Branco 1003, Cep: 25680-120, Petropolis-RJ, Brazil

[+]University of York, Wentworth Way Heslington, York YO10 5DD, United Kingdom

[¶]Drugs for Neglected Diseases initiative, 15 Chemin Louis-Dunant, 1202 Geneva, Switzerland

[×]National Institute of Allergy and Infectious Diseases, 4 Memorial Drive, Bethesda, Maryland 20892, United States

[&]University of Pennsylvania, 380 South University Avenue, Philadelphia, Pennsylvania 19104, United States

[^]Institut Pasteur, 25 Rue du Docteur Roux, 75015 Paris, France

[~]University of Georgia, Coverdell Center, 500 DW Brooks Dr, Athens, Georgia 30602, United States

ABSTRACT: Kinetoplastid parasites have caused human disease for millennia. Significant achievements have been made toward developing new treatments for leishmaniasis (particularly on the Indian subcontinent) and for human African trypanosomiasis (HAT). Moreover, the sustained decrease in the incidence of HAT has made the prospect of elimination a tantalizing reality. Despite the gains, no new chemical or biological entities to treat kinetoplastid diseases have been registered in more than three decades, and more work is needed to discover safe and effective therapies for patients with Chagas disease and leishmaniasis. Advances in tools for drug discovery and novel insights into the biology of the host−parasite interaction may provide opportunities for accelerated progress. Here, we summarize the output from a gathering of scientists and physicians who met to discuss the current status and future directions in drug discovery for kinetoplastid diseases.

Nearly a billion people are at risk from the group of vector-borne kinetoplastid diseases comprised of Chagas disease, leishmaniasis, and human African trypanosomiasis (HAT, also known as sleeping sickness). These ancient parasitic illnesses have burdened humans for thousands of years, as evidenced by *Trypanosoma* DNA sequences found in South American mummies.[1] In the current era, kinetoplastid diseases cause an estimated 30 000 deaths annually and induce crippling morbidities in millions more.

There is reason to be optimistic about trends concerning HAT. Public and private partners have jointly tackled the disease in recent decades, with the World Health Organization (WHO) coordinating public health activities and the Drugs for Neglected Diseases *initiative* (DND*i*) directing global efforts for new therapies. The introduction of nifurtimox-eflornithine therapy in 2009 was a pivotal milestone, which was followed recently by the demonstrated efficacy of oral fexinidazole[2] for late-stage disease. (Approval for use is now pending assessment by medicine regulatory agencies.) Fewer than 1500 new cases were reported to WHO in 2017, making disease elimination a tangible goal.

Successes in combating HAT are encouraging and contrast with slower progress in containing other kinetoplastid diseases.

Received: November 1, 2018

Downloaded via INST PASTEUR DE PARIS on January 22, 2019 at 13:49:20 (UTC).
See https://pubs.acs.org/sharingguidelines for options on how to legitimately share published articles.

© XXXX American Chemical Society

DOI: 10.1021/acsinfecdis.8b00298
ACS Infect. Dis. XXXX, XXX, XXX−XXX

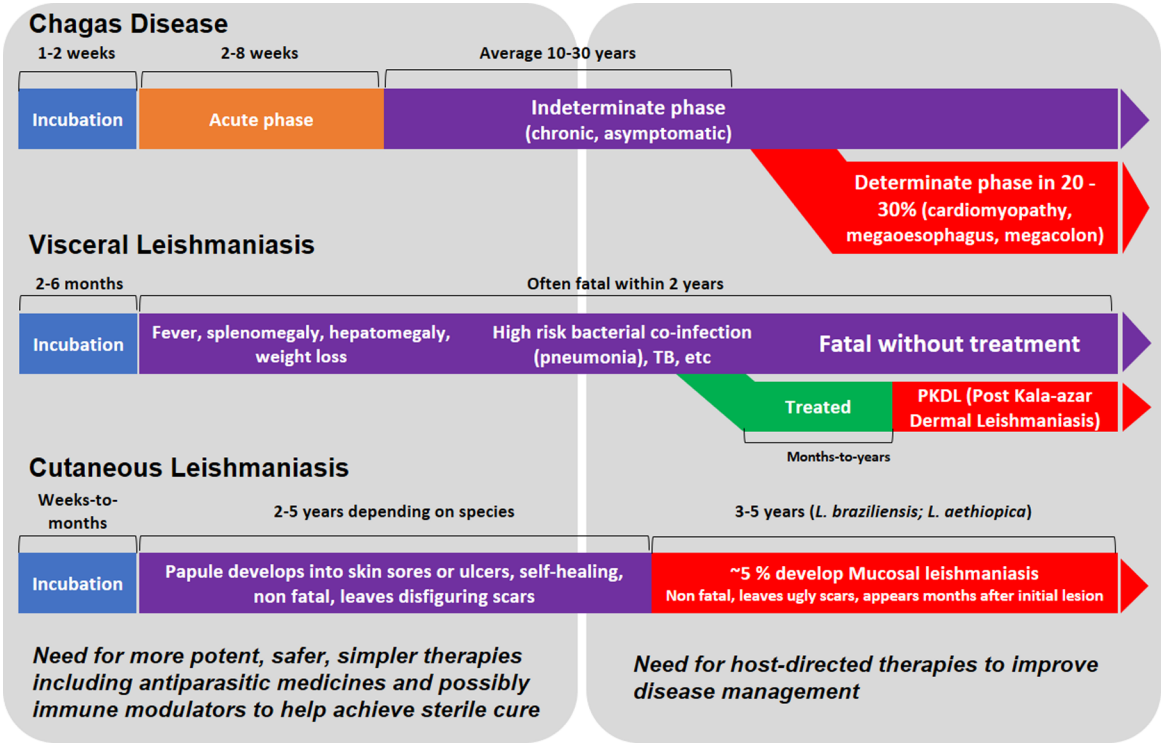


Figure 1. Clinical manifestations of kinetoplastid diseases and opportunities for intervention.

Most of the current kinetoplastid drugs are repurposed and are often not potent enough to render a sterile cure (i.e., to eliminate all parasites). Safe, effective, short-course practical therapies are urgently needed for Chagas disease and leishmaniasis yet remain elusive.

To understand the present-day challenges and opportunities related to new medicines for Chagas disease, visceral leishmaniasis (VL), and cutaneous leishmaniasis (CL), the Novartis Institute for Tropical Diseases convened a multidisciplinary group of scientific and medical specialists in parasitology, immunology, and drug discovery in June 2018. The scope of the discussion encompassed unmet medical needs, the global pipeline of preclinical drug candidates, parasite biology, assays, models, and the potential use of novel immunomodulatory and adjunct therapies to target disease sequelae. This Viewpoint summarizes key workshop learnings.

CURRENT DRUGS: OLD, TOXIC, AND OFTEN INEFFECTIVE

Chagas disease, which is endemic in the Americas, is caused by *Trypanosoma cruzi*. Inoculation typically occurs through infected feces from the triatomine bug, which is scratched or rubbed into the skin or mucosa. Transmission also takes place through blood transfusion and congenital and oral routes. The pathogenesis of Chagas disease is not fully understood, and it is currently impossible to predict which fraction of the patient population (approximately 30%) will develop the serious cardiac or gastrointestinal sequelae that appear years after the initial infection (Figure 1). Sudden death from chronic Chagas cardiomyopathy is an all too common outcome. Two drugs, nitroheterocyclic agents benznidazole and nifurtimox, are used for the treatment of Chagas disease; both were developed decades ago, are contraindicated during pregnancy, and can have serious adverse effects that substantially restrict their use. Benznidazole is the better-tolerated option in adults, although 15−30% patients are unable to finish the standard 60-day course, mainly because of skin and nervous system complications. In children, nifurtimox is better tolerated than benznidazole.

In both acute and chronic *T. cruzi* infection, treatment reduces the parasite load and can yield clearance from blood using available assays (e.g., PCR). Even so, in some cases, parasites presumably may persist intracellularly, and it is unclear in adults how the reductions in the parasite load modulate the severity of chronic disease in the absence of complete parasite clearance. Current drugs are inadequate because they fail too often and are not dependable. However, WHO recommends off-label use of benznidazole for the treatment of chronically infected patients, even though its efficacy in later stages of the disease is debatable. A large study of patients with chronic Chagas cardiomyopathy (the BENEFIT trial) demonstrated that benznidazole treatment reduced the parasite burden but did not significantly reduce disease progression. However, most subjects had New York Heart Association class I (largely asymptomatic) heart disease, which may have confounded the findings.[3] Some nonrandomized, unblinded studies using benznidazole in indeterminate patients without heart failure showed reduced disease progression, emphasizing the need for controlled randomized studies for indeterminate patients.[4]

Similarly, the approved therapeutic arsenal for leishmaniasis has important limitations. Leishmaniasis is distributed across the tropics and subtropics, though a majority of VL cases are reported in only seven countries: Brazil, Ethiopia, Kenya, Somalia, Sudan, South Sudan, and India. Patients succumb to VL gradually over a period of 2 years. Anorexia and pancytopenia give rise to wasting and increased susceptibility to bacterial superinfections. VL is fatal without treatment, and even those who undergo therapy remain at risk of a disfiguring dermal form of relapsing disease called post kala-azar dermal

DOI: 10.1021/acsinfecdis.8b00298
ACS Infect. Dis. XXXX, XXX, XXX−XXX

leishmaniasis (PKDL) that may also contribute to continued disease transmission (Figure 1). CL has a higher global burden than VL, with the greatest prevalence in Africa, the Mediterranean, and South America. It does not cause systemic morbidities or death but can result in grievous disfiguration and stigma. Drugs targeting *Leishmania* parasites have generally been repurposed from other indications. Antimonials, amphotericin B, paromomycin sulfate, and miltefosine have variable efficacy against the more than 20 *Leishmania* species that cause disease. While WHO-recommended treatment regimens for VL on the Indian subcontinent include liposomal amphotericin B or oral miltefosine, these medicines are poorly effective in patients in other global regions. Treatment courses are generally long, require hospitalization, and have significant toxicities that mandate frequent monitoring. Differences in the treatment protocol by region, high costs, and low availability of some drugs understandably stretch the limits of under-resourced health systems in countries where these diseases are endemic.

THE ANTIPARASITIC PIPELINE IS FILLING, BUT THERE ARE GAPS

Antiparasitics are the cornerstone of therapy for kinetoplastid diseases. It is well accepted that the clinical event cascades in Chagas disease and leishmaniasis are induced by the presence of parasites, and evidence suggests that eliminating parasites as early as possible after infection could mitigate severe disease. Unfortunately, the current preclinical pipeline for Chagas disease treatments is meager. Only three classes of compounds have been shown to achieve high cure rates in stringent mouse models of infection: nitroimidazoles (e.g., fexinidazole, currently in phase II), oxaboroles (e.g., DNDi-6148, active against both leishmaniasis and Chagas), and proteasome inhibitors (e.g., GNF6702[5]). The future is brighter in drug discovery for leishmaniasis, where there are at least six candidates in preclinical or clinical phases that have five distinct mechanisms of action.[6]

Proposed target product profiles for new drugs are listed in Box 1. For Chagas disease, medicines should achieve cures that prevent the development of chronic disease. Any treatment to be given beyond the acute stage must be simple to administer and safe because patients in the indeterminate phase typically feel healthy and are unlikely to comply with a complex or poorly tolerated drug regimen. In leishmaniasis, a short-course therapy that achieves a relapse-free cure with no or minor adverse effects would be ideal, but even a medicine with efficacy similar to that of current drugs and improved safety would be a step forward.

Whether a sterile cure is essential is a topic of debate. Some parasitologists advocate strongly that a sterile cure must be achieved in Chagas disease to prevent the reproliferation of parasites and enduring pathogenicity. A sterile cure may not be critical for VL and CL. Reducing the parasite load in these infections could be sufficient if the host immune system can complete the job of parasite control or clearance. A sterile cure is more likely needed for PKDL (which appears to result from latent parasites) and for VL in individuals with HIV coinfection or other immunodeficiency syndromes. A condition known as leishmaniasis recidivans in CL may also result from the recrudescence of latent parasites that survive therapy.

Box 1. Proposed Target Product Profile (TPP) for Chagas Disease and Leishmaniasis.

Proposed TPP for Chagas

- Eliminates all parasites, including in blood and tissue
- Active against all distinct typing units (DTUs)
- Oral, safe, and well tolerated for use at all ages and during pregnancy and lactation with no monitoring required
- Simple treatment regimen, amenable for use in a setting of weak health systems/infrastructure, accessible and affordable
- Potency and safety not affected by pharmacogenomic factors
- Can be used repeatedly (e.g., in the case of reinfections)
- No significant drug−drug interaction
- Low probability of resistance
- Shelf life >2 years under tropical conditions

Proposed TPP for Leishmaniasis

- Effective against all VL and CL parasites from varying geographic regions
- Potency and safety not affected by pharmacogenomic factors
- Potency/efficacy, >95% parasite clearance for VL, 99.9% parasite clearance from periphery, 99% from seclusion sites for CL
- Short treatment regimen (as short as 1 week for both VL and CL, 14 day maximum for VL, 21 day maximum for CL)
- Amenable for use in a setting of weak health systems/ infrastructure, accessible and affordable treatment regimen
- Oral, safe, and well tolerated for use at all ages and during pregnancy with no monitoring required
- Effective in immune-deficient individuals (e.g., HIV-VL) and against PKDL
- Avoids risk of resistance

NEW INSIGHTS INTO DISEASE BIOLOGY WILL INDICATE THE NEED FOR NEW MODELS

Given how little we know about the biology of *T. cruzi* and *Leishmania* species and the lack of validated drug targets, it is not surprising that most current pipeline compounds originated from phenotypic screens. Assays are available to test the growth inhibition of amastigotes for *T. cruzi* (intracellular) and *Leishmania* (intracellular and axenic), and these are compatible with high-throughput screening. It may be important to evaluate the antiparasitic effect of compounds by using intracellular parasites grown in disease-relevant tissues. Cidality, time-to-kill kinetics, and washout assays may be used to further enhance the confidence of hits and to assist prioritization.

Highly sensitive in vivo imaging with bioluminescent *T. cruzi* that enables the monitoring of the mouse parasite burden in real time has highlighted how the parasite load varies by tissue type over time.[7] Furthermore, this model has predictive power. It demonstrated the limited efficacy of posaconazole, a Chagas disease drug candidate that had previously shown potency in animal models but has failed to consistently eliminate parasitemia in patients. By comparison, benznidazole was shown to be efficacious in both mice and humans.[8] Similarly, novel murine and hamster models for VL and CL using

DOI: 10.1021/acsinfecdis.8b00298
ACS Infect. Dis. XXXX, XXX, XXX−XXX

bioluminescent parasites have improved our understanding of disease progression. New chemical entities should be tested in mouse models with specific questions in mind, such as how the treatment duration and curative exposures could translate from mice to humans.

An important unknown for Chagas disease is the role played by amastigotes that spontaneously adopt a "persister" phenotype. These nonreplicative and phenotypically drug-resistant forms of the parasite are later able to differentiate to trypomastigotes and reinfect new host cells.[8] Future work is needed to understand how the development of persistent forms is triggered, if they are metabolically active, whether they can be forced out of dormancy, and what their role is in disease progression. In the meantime, screening against persistent parasites to find novel inhibitors would be beneficial.[9]

Persistence in *Leishmania* may also be a concern. Persistent *L. mexicana* and *L. major* parasites have been reported in mouse models,[10,11] although similar forms have not yet been sought in animals for *L. donovani* or *L. infantum*. However, nonreplicating *L. donovani* were identified in a macrophage model, and these could represent persister-type cells, the existence of which is implicated through the recrudescence that can occur following VL treatment and manifests as PKDL.[12]

IMMUNE MODULATION HAS PROMISE IN ANTIPARASITIC THERAPY

Kinetoplastid infections provoke robust innate and adaptive immune reactions, which can be protective or disease-promoting. This provides a rationale for investigating host-directed strategies such as immune modulators as an add-on to antiparasitic therapy. Lessons from immuno-oncology may offer a roadmap. Indeed, there are similarities in the dynamics of host−tumor and host−parasite interactions. Both tumor cells and cells harboring intracellular parasites are perceived by the immune system as foreign, both retain features of normal cells that could trigger an immune tolerance, and both can create a microenvironment that facilitates immune escape and promotes disease progression. In certain types of cancer, adding immunotherapy to cytotoxic chemotherapy improves survival. For example, a monoclonal antibody that binds to T cells and blocks their inhibition by tumor cells is now part of the first-line treatment for some lung cancers.[13] An analogous approach could conceivably help antiparasitic medicines to work more quickly, more effectively, or with less variability.

Harnessing the immune system to treat kinetoplastid diseases is not a new idea. Beginning in the early 1990s, interferon-gamma was tested in VL and CL patients (usually in combination with antimony), with mixed results. Interleukin (IL)-10 has been studied extensively in VL. It appears to promote parasite growth, and experimental models suggest that the IL-10 blockade can reduce disease progression.[14,15] A clinical trial with a humanized anti-IL-10 antibody was planned but later withdrawn due to problems in securing quality drug for the study (NCT01437020). IL-10 neutralization may also provide a benefit in CL.[16] Additionally, TLR9 agonist CpG D35 is currently undergoing preclinical development in preparation for clinical trials for CL.[6]

In Chagas disease, the association of several pro- and anti-inflammatory cytokines has been observed with cardiac and indeterminate forms of the disease, respectively.[17] Some immunomodulation strategies postulated for Chagas disease include limiting regulatory T cells and increasing IL-17,[18] although overall there is less evidence to support immune modulation in Chagas disease compared with leishmaniasis.

Naturally, there are challenges to testing and deploying immunotherapies. Success or failure in experimental models is not necessarily predictive of outcomes in humans. Patients with leishmaniasis are at high risk of coinfection with bacteria; therefore, modulating immunity in these populations will require careful safety monitoring. Even if immunotherapy is successful in enhancing the response to treatment in acute disease, there are no tools to definitively assess latent infection. Finally, the immune system is dynamic and changes with age, pregnancy, coinfections, and other conditions, which would need to be considered.

ADJUNCT THERAPIES ARE ALSO NECESSARY IN THE CLINICAL ARMORY

Adjunct therapies that improve outcomes including quality of life should be pursued in parallel with work to discover parasite-specific agents. These include medicines to improve wound healing in CL, to address nutrition or coinfection complications in VL, and to better manage cardiovascular and gastrointestinal complications in Chagas disease. This also applies to preventative or therapeutic vaccines, which are in various phases of development.

Progress toward adjunct therapies is hampered in part by our limited understanding of many features of disease biology. There are, however, illustrative examples. In CL, the disease is in large part mediated by the inflammatory immune response. For example, lesions from *L. braziliensis* patients have few parasites but severe ulceration, and experimental studies indicate that a blockade of IL-1β or the NLRP3 inflammasome may ameliorate the disease in these patients.[19] There is evidence that wound treatment with pharmaceutical sodium chlorite 0.045% or radio-frequency-induced heat therapy has clinical benefits for CL.[20] In chronic Chagas cardiomyopathy, patients generally suffer worse outcomes than those with heart failure from other causes, despite the fact that Chagas disease patients are usually younger and have fewer comorbidities.[21] Recently, angiotensin receptor−neprilysin inhibition was found to reduce mortality and hospitalization in a large group of heart failure patients with a reduced ejection fraction, including a subgroup of patients with Chagas disease.[22] Future work will be needed to determine the specific implications for Chagas disease patients.

SUMMARY

While there have been substantial advances in recent years to address kinetoplastid diseases, on the whole these conditions remain severely neglected across the domains of health policy, advocacy, funding, and research. For HAT, more work is needed to ensure that the gains realized are not lost. With respect to finding safe and effective new therapies for Chagas disease and leishmaniasis, we highlight several key priorities. To start, the fundamental pathobiology of these diseases must be further demystified to pave the way for targeted treatments; the discovery of persister parasites is a sobering reminder that we have much to learn before definitive medicines can be generated. Novel tools will be needed to successfully validate clinical candidates in patients, including biomarkers capable of measuring intracellular parasite clearance and predicting the clinical benefit without the need for extended follow-up. The potential benefits in kinetoplastid diseases for immune

DOI: 10.1021/acsinfecdis.8b00298
ACS Infect. Dis. XXXX, XXX, XXX−XXX

modulation and adjunct therapies need to be carefully evaluated. Finally, we advocate continued and even greater multidisciplinary collaboration. In the face of limited resources, with an all too small scientific and medical community focused on these complex diseases, harmonized research and development strategies will be essential to accelerating progress toward the common good of transformative new therapies for patients.

AUTHOR INFORMATION

Corresponding Authors

*E-mail: srinivasa.rao@novartis.com.
*E-mail: thierry.diagana@novartis.com.

ORCID

Jeremy C. Mottram: 0000-0001-5574-3766

Notes

The authors declare the following competing financial interest(s): S.P.S.R., G.D., C.F., C.R.G., C.L.J., J.M.S., and T.T.D. are employees of Novartis.

ACKNOWLEDGMENTS

The authors thank additional participants at the kinetoplastid drug discovery workshop held at the Novartis Institute for Tropical Diseases on June 4 and 5, 2018: Diana Tay, Marcel Kaiser, Pamela Grewal, Frederic Bornancin, Calzascia Thomas, Jan Jiricek, Chen Yen Liang, Suresh B. Lakshminarayana, Gu Feng, Natasha Aziz, Cynthia Shafer, Manjunatha Ujjini, Sebastian Mikolajczak, Chris Lunde, and Christopher Sarko

REFERENCES

(1) Aufderheide, A. C., Salo, W., Madden, M., Streitz, J., Buikstra, J., Guhl, F., Arriaza, B., Renier, C., Wittmers, L. E., Jr., Fornaciari, G., and Allison, M. (2004) A 9,000-year record of Chagas' disease. *Proc. Natl. Acad. Sci. U. S. A. 101* (7), 2034−9.

(2) Mesu, V., Kalonji, W. M., Bardonneau, C., Mordt, O. V., Blesson, S., Simon, F., Delhomme, S., Bernhard, S., Kuziena, W., Lubaki, J. F., Vuvu, S. L., Ngima, P. N., Mbembo, H. M., Ilunga, M., Bonama, A. K., Heradi, J. A., Solomo, J. L. L., Mandula, G., Badibabi, L. K., Dama, F. R., Lukula, P. K., Tete, D. N., Lumbala, C., Scherrer, B., Strub-Wourgaft, N., and Tarral, A. (2018) Oral fexinidazole for late-stage African Trypanosoma brucei gambiense trypanosomiasis: a pivotal multicentre, randomised, non-inferiority trial. *Lancet 391* (10116), 144−154.

(3) Morillo, C. A., Marin-Neto, J. A., Avezum, A., Sosa-Estani, S., Rassi, A., Jr., Rosas, F., Villena, E., Quiroz, R., Bonilla, R., Britto, C., Guhl, F., Velazquez, E., Bonilla, L., Meeks, B., Rao-Melacini, P., Pogue, J., Mattos, A., Lazdins, J., Rassi, A., Connolly, S. J., Yusuf, S., and Investigators, B. (2015) Randomized Trial of Benznidazole for Chronic Chagas' Cardiomyopathy. *N. Engl. J. Med. 373* (14), 1295−1306.

(4) Viotti, R., Vigliano, C., Lococo, B., Bertocchi, G., Petti, M., Alvarez, M. G., Postan, M., and Armenti, A. (2006) Long-term cardiac outcomes of treating chronic Chagas disease with benznidazole versus no treatment: a nonrandomized trial. *Ann. Intern. Med. 144* (10), 724−34.

(5) Khare, S., Nagle, A. S., Biggart, A., Lai, Y. H., Liang, F., Davis, L. C., Barnes, S. W., Mathison, C. J., Myburgh, E., Gao, M. Y., Gillespie, J. R., Liu, X., Tan, J. L., Stinson, M., Rivera, I. C., Ballard, J., Yeh, V., Groessl, T., Federe, G., Koh, H. X., Venable, J. D., Bursulaya, B., Shapiro, M., Mishra, P. K., Spraggon, G., Brock, A., Mottram, J. C., Buckner, F. S., Rao, S. P., Wen, B. G., Walker, J. R., Tuntland, T., Molteni, V., Glynne, R. J., and Supek, F. (2016) Proteasome inhibition for treatment of leishmaniasis, Chagas disease and sleeping sickness. *Nature 537* (7619), 229−233.

(6) DNDi, Drugs for Neglected Diseases Initiative Research and Development Portfolio; https://www.dndi.org/diseases-projects/portfolio/, 2018.

(7) Lewis, M. D., Francisco, A. F., Taylor, M. C., and Kelly, J. M. (2015) A new experimental model for assessing drug efficacy against Trypanosoma cruzi infection based on highly sensitive in vivo imaging. *J. Biomol. Screening 20* (1), 36−43.

(8) Morillo, C. A., Waskin, H., Sosa-Estani, S., Del Carmen Bangher, M., Cuneo, C., Milesi, R., Mallagray, M., Apt, W., Beloscar, J., Gascon, J., Molina, I., Echeverria, L. E., Colombo, H., Perez-Molina, J. A., Wyss, F., Meeks, B., Bonilla, L. R., Gao, P., Wei, B., McCarthy, M., Yusuf, S., and Investigators, S.-C. (2017) Benznidazole and Posaconazole in Eliminating Parasites in Asymptomatic T. Cruzi Carriers: The STOP-CHAGAS Trial. *J. Am. Coll Cardiol 69* (8), 939−947.

(9) Sanchez-Valdez, F. J., Padilla, A., Wang, W., Orr, D., and Tarleton, R. L., Spontaneous dormancy protects Trypanosoma cruzi during extended drug exposure. *Elife* 2018, *7*, DOI: 10.7554/eLife.34039.

(10) Mandell, M. A., and Beverley, S. M. (2017) Continual renewal and replication of persistent Leishmania major parasites in concomitantly immune hosts. *Proc. Natl. Acad. Sci. U. S. A. 114* (5), E801−E810.

(11) Kloehn, J., Saunders, E. C., O'Callaghan, S., Dagley, M. J., and McConville, M. J. (2015) Characterization of metabolically quiescent Leishmania parasites in murine lesions using heavy water labeling. *PLoS Pathog. 11* (2), e1004683.

(12) Tegazzini, D., Diaz, R., Aguilar, F., Pena, I., Presa, J. L., Yardley, V., Martin, J. J., Coteron, J. M., Croft, S. L., and Cantizani, J. (2016) A Replicative In Vitro Assay for Drug Discovery against Leishmania donovani. *Antimicrob. Agents Chemother. 60* (6), 3524−32.

(13) Gandhi, L., Rodriguez-Abreu, D., Gadgeel, S., Esteban, E., Felip, E., De Angelis, F., Domine, M., Clingan, P., Hochmair, M. J., Powell, S. F., Cheng, S. Y., Bischoff, H. G., Peled, N., Grossi, F., Jennens, R. R., Reck, M., Hui, R., Garon, E. B., Boyer, M., Rubio-Viqueira, B., Novello, S., Kurata, T., Gray, J. E., Vida, J., Wei, Z., Yang, J., Raftopoulos, H., Pietanza, M. C., Garassino, M. C., and Investigators, K. (2018) Pembrolizumab plus Chemotherapy in Metastatic Non-Small-Cell Lung Cancer. *N. Engl. J. Med. 378* (22), 2078−2092.

(14) Murray, H. W., Lu, C. M., Mauze, S., Freeman, S., Moreira, A. L., Kaplan, G., and Coffman, R. L. (2002) Interleukin-10 (IL-10) in experimental visceral leishmaniasis and IL-10 receptor blockade as immunotherapy. *Infect. Immun. 70* (11), 6284−93.

(15) Gautam, S., Kumar, R., Maurya, R., Nylen, S., Ansari, N., Rai, M., Sundar, S., and Sacks, D. (2011) IL-10 neutralization promotes parasite clearance in splenic aspirate cells from patients with visceral leishmaniasis. *J. Infect. Dis. 204* (7), 1134−7.

(16) Belkaid, Y., Hoffmann, K. F., Mendez, S., Kamhawi, S., Udey, M. C., Wynn, T. A., and Sacks, D. L. (2001) The role of interleukin (IL)-10 in the persistence of Leishmania major in the skin after healing and the therapeutic potential of anti-IL-10 receptor antibody for sterile cure. *J. Exp. Med. 194* (10), 1497−506.

(17) Dutra, W. O., Menezes, C. A., Magalhaes, L. M., and Gollob, K. J. (2014) Immunoregulatory networks in human Chagas disease. *Parasite Immunol. 36* (8), 377−387.

(18) Magalhaes, L. M., Villani, F. N., Nunes Mdo, C., Gollob, K. J., Rocha, M. O., and Dutra, W. O. (2013) High interleukin 17 expression is correlated with better cardiac function in human Chagas disease. *J. Infect. Dis. 207* (4), 661−665.

(19) Novais, F. O., Carvalho, A. M., Clark, M. L., Carvalho, L. P., Beiting, D. P., Brodsky, I. E., Carvalho, E. M., and Scott, P. (2017) CD8+ T cell cytotoxicity mediates pathology in the skin by inflammasome activation and IL-1beta production. *PLoS Pathog. 13* (2), e1006196.

(20) David, J. R. (2018) The successful use of radiofrequency-induced heat therapy for cutaneous leishmaniasis: a review. *Parasitology 145* (4), 527−536.

(21) Shen, L., Ramires, F., Martinez, F., Bodanese, L. C., Echeverria, L. E., Gomez, E. A., Abraham, W. T., Dickstein, K., Kober, L., Packer,

DOI: 10.1021/acsinfecdis.8b00298
ACS Infect. Dis. XXXX, XXX, XXX−XXX

M., Rouleau, J. L., Solomon, S. D., Swedberg, K., Zile, M. R., Jhund, P. S., Gimpelewicz, C. R., McMurray, J. J. V., and Paradigm, H. F. Contemporary Characteristics and Outcomes in Chagasic Heart Failure Compared With Other Nonischemic and Ischemic Cardiomyopathy. *Circ. Heart Fail.* 2017, *10* (11), DOI: 10.1161/CIRCHEARTFAILURE.117.004361.

(22) McMurray, J. J., Packer, M., Desai, A. S., Gong, J., Lefkowitz, M. P., Rizkala, A. R., Rouleau, J. L., Shi, V. C., Solomon, S. D., Swedberg, K., Zile, M. R., and Investigators, P.-H.; Committees (2014) Angiotensin-neprilysin inhibition versus enalapril in heart failure. *N. Engl. J. Med. 371* (11), 993−1004.

NOTE ADDED IN PROOF

European Medicines Agency's Committee for Medicinal Products for Human Use recommended approval of fexinidazole for sleeping sickness in mid Nov 2018.

DOI: 10.1021/acsinfecdis.8b00298
ACS Infect. Dis. XXXX, XXX, XXX−XXX