

# Host-Directed Therapies for Tackling Multi-Drug Resistant Tuberculosis: Learning From the Pasteur-Bechamp Debates

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**Tuberculosis remains a global emergency causing an estimated 1.5 million deaths annually. For several decades the major focus of tuberculosis treatment has been on antibiotic development targeting *Mycobacterium tuberculosis*. The lengthy tuberculosis treatment duration and poor treatment outcomes associated with multi-drug resistant tuberculosis (MDR-TB) are of major concern. The sparse new tuberculosis drug pipeline and widespread emergence of MDR-TB signal an urgent need for more innovative interventions to improve treatment outcomes. Building on the historical Pasteur–Bechamp debates on the role of the “microbe” vs the “host internal milieu” in disease causation, we make the case for parallel investments into host-directed therapies (HDTs). A range of potential HDTs are now available which require evaluation in randomized controlled clinical trials as adjunct therapies for shortening the duration of tuberculosis therapy and improving treatment outcomes for drug-susceptible tuberculosis and MDR-TB. Funder initiatives that may enable further research into HDTs are described.**

**Keywords.** host-directed therapy; tuberculosis; treatment; multi-drug resistant tuberculosis; repurposed drugs.

Tuberculosis remains a global emergency causing an estimated 1.5 million deaths annually [1]. For several decades the major focus of tuberculosis treatment has been on antibiotic development targeting *Mycobacterium tuberculosis*. The lengthy tuberculosis treatment duration and poor treatment outcomes associated with multi-drug resistant tuberculosis (MDR-TB), and comorbidity of tuberculosis with human immunodeficiency virus (HIV) are also of major concern. In May 2014, the World Health Assembly adopted the World Health Organization (WHO) post-2015 global TB strat-

egy, which aims to reduce global tuberculosis incidence by 90% before 2035 [2]. Given the special challenges of tuberculosis in countries with low levels of the disease, WHO in collaboration with the European Respiratory Society, and with experts from low-incidence countries, has developed an 8-point framework adapted from the post-2015 global TB strategy to target pre-elimination and, ultimately, elimination [3].

Every year, progress being made toward achieving global tuberculosis control targets is reflected upon by the global tuberculosis community on World TB Day March 24th [4–6]. The tuberculosis community has been re-assured by WHO Annual Global TB reports over the past decade showing a steady decline of tuberculosis rates worldwide. Further optimism for achieving the Millennium Development Goal’s TB control targets came from a number of potentially important developments, including: introduction of a new rapid diagnostic test, the GeneXpert MTB/RIF assay [7] and its widespread rollout; new drugs entering phase II and III trials, including PA-824 [8]; fast-track approval by regulatory authorities of two new tuberculosis drugs, bedaquiline

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and delamanid [9]; and the expanding tuberculosis vaccine pipeline [10].

Although progress has been made toward achieving WHO global TB control targets, it appears to have slowed down over the past 2 years. The 2014 annual WHO Report [1] shows reversal in previous downward trends of estimated global tuberculosis case load. Half a million more cases of tuberculosis globally in 2013 than previously estimated brought the total number of tuberculosis cases to 9 million. Alarming, each year, 3 million people with tuberculosis are still being “missed” by health systems and approximately 1.5 million people die from tuberculosis. MDR-TB and extensively drug-resistant tuberculosis (XDR-TB) continue to spread relentlessly in Eastern Europe, Asia, and Africa, with an estimated 480 000 new MDR-TB cases in 2013 alone [1]. The actual case load of drug-susceptible and drug-resistant tuberculosis may be higher than current estimates as indicated by national surveys [11] and autopsy studies [12–14]. These are due to programmatic weaknesses of laboratory and diagnostic infrastructures, case detection, recording and reporting systems. Furthermore, lack of resources coupled with other operational challenges contributes to the low cure rates for MDR-TB [15–17] despite the use of tuberculosis drug treatment regimens recommended by WHO [1].

Further disappointment came from the long awaited results of the fluoroquinolone trials [18–20], which failed to demonstrate any usefulness of moxifloxacin or ofloxacin in reducing the duration of tuberculosis therapy from 6 to 4 months. The new tuberculosis drug and vaccines developmental pipeline remains slim [21]. Despite 2 decades of investment into development of new diagnostics, drugs, treatment regimens, and vaccines [9, 22], we are still faced with a global tuberculosis emergency. This worrying status quo indicates that prevailing approaches to preventing, diagnosing, treating, and managing tuberculosis requires critical appraisal by scientists, healthcare workers, funders, advocacy groups, and governments. The time has now come for a radical rethink to effect a game change in facilitating progress toward achieving improved treatment outcomes and for achieving the aims of the WHO end TB strategy [23].

Ever since the declaration of tuberculosis as a global emergency in 1993 by the WHO, a major focus has been on developing new drugs, diagnostics, and vaccines that target *Mycobacterium tuberculosis*, the microorganism central to pathogenesis of tuberculosis. For over 2 decades, funders, pharmaceutical companies, scientists, advocates, and policy makers have focused on eradication of *M. tuberculosis* via antibiotic therapy, a concept that *M. tuberculosis* is the main cause of the ongoing global tuberculosis pandemic. This thinking is in line with Louis Pasteur’s (1822–1895) “Germ Theory of disease causation,” which gained widespread acceptance starting in the mid-19th century [24]. This focus continues until today despite the fact that there are 2 billion people in the world infected with *M. tuberculosis* who

do not develop active tuberculosis disease [25], and that the dramatic decline of tuberculosis in much of Europe and North America in the first half of the 20th century occurred well before the discovery of anti-tuberculosis drugs [26–29].

In contrast to Pasteur’s theory, Pierre Jacques Antoine Béchamp (1816–1908) proposed an alternate theory of disease causation—a host–pathogen relationship that promoted the concept that it was not the microorganism that caused disease, but it was the human body’s “internal milieu” or “terrain” that was critical to development of disease after infection by the microorganism [24]. Claude Bernard, a renowned physiologist from the same era, tried for years to convince Pasteur of the importance and validity of Béchamp’s theory but failed to do so. Prior to his death, Pasteur finally acknowledged the “terrain” theory saying, “*Béchamp avait raison, le microbe n’est rien. Le terrain est tout.*” (“*Béchamp was right- The microbe is nothing. The terrain is everything*”) [16]. It is well known that a wide range of “host factors” alter the human body’s “internal milieu” (terrain) and are responsible for increased susceptibility to developing active tuberculosis disease, poor treatment response, and for increased mortality from tuberculosis [26–29]. These include: immune-dysregulation from any cause (including stress, poor living conditions, socioeconomic factors, micronutrient deficiencies, HIV), malnutrition, aberrant or excess host inflammatory response to infection, alcohol and substance abuse, co-morbidities with non-communicable diseases such as diabetes, smoking, and chronic obstructive airways disease, pneumoconiosis, all of which are important drivers of the global tuberculosis pandemic.

An important component of the WHO post-2015 global End TB strategy [23] is “research.” It is now important that in addition to the current investments into development of new diagnostics, drugs, biomarkers, and vaccines, a major investment is made into research on development of therapies that target a range of “host factors” involved in tuberculosis immunopathogenesis, increased susceptibility to developing tuberculosis disease, and development of excess inflammatory responses that result in tissue damage and end organ dysfunction. Host-directed therapies (HDTs) [30–34] constitute a diverse range of immunological, biological, and drug interventions that modulate anti-*M. tuberculosis* protective innate and adaptive immunity, reduce excess inflammation, repair or prevent tissue damage or enhance the effectiveness of tuberculosis drug therapy by modulating host factors. The use of HDTs as adjunct to standard anti-tuberculosis therapy could also reduce the duration of therapy, and result in improved treatment outcomes for drug-sensitive and drug-resistant tuberculosis, and may decrease relapse rates.

A wide range of HDTs [30–34] targeting the “host terrain” are now being investigated for use as adjunct to current tuberculosis drug treatment regimens. These include: “repurposing” commonly used drugs for diabetes, epilepsy, peptic ulcers, hypercholesterolemia, asthma, cancer, and arthritis, which have

shown promise in vitro and in animal models; immunomodulatory agents, use of Vitamin D and phenyl butyrate, heat killed environmental mycobacteria; and “cellular therapy” using the patient’s own bone marrow derived stromal cells. Selected list of HDTs under evaluation or ready for evaluation in clinical trials are listed in Table 1. These need serious consideration by scientists, pharma, governments, and the global community.

All these have potential to alter the “host terrain” in favor of the host and will require development and further evaluation in randomized controlled clinical trials. Importantly, the uptake of any research findings into policy and their effective translation into programmatic implementation into health services needs to

be innovatively addressed through more meaningful engagement of scientists, healthcare workers and end users (patients and governments) in high tuberculosis burden countries. A persisting bugbear of current basic science and clinical trials research being conducted in low resourced, high tuberculosis endemic countries is that much of frontline research is dominated and driven by researchers from high-income, developed country institutions without full and equitable engagement of those from developing countries [35–38]. This discrepancy needs to be seriously addressed and redressed through mechanisms that will ensure equitable and fair partnerships and must now be a priority for all funding agencies and research consortia.

**Table 1. Host-directed Therapies (Compiled From References [30–34])**

HDT Targeted Effect and HDT Groupings	Generic Product Group	Examples of Potential HDT	Mode of Action
Repurposing commonly used drugs for reduction of excess or tissue damaging inflammation and/or for modulation of innate and adaptive immune responses	Nonsteroidal anti-inflammatory drugs <sup>a</sup> (Analgesics and arthritis)	Ibuprofen	Inhibits prostaglandin production via cyclooxygenase (COX) inhibition. Reduces lung pathology, tissue inflammation and <i>M. tuberculosis</i> burden in mouse models.
	Biguanides <sup>a</sup> (Diabetes drugs)	Metformin	Inhibits mitochondrial glycerophosphate dehydrogenase. Inhibits <i>M. tuberculosis</i> growth by enhancing macrophage autophagy by promoting phagolysosome fusion and increasing mitochondrial ROS production. In mice infected with <i>M. tuberculosis</i> , metformin improves pulmonary pathology and reduces bacterial load.
	Tetracycline <sup>b</sup> (Antibacterial antibiotic)	Doxycycline	Matrix metalloproteinase inhibitor which prevents degradation of collagen and other structural proteins in lung tissue
	Statins <sup>b</sup> (Cholesterol lowering drugs)	Simvastatin Rosuvastatin	Inhibitors of 3-hydroxy-3-methylglutaryl-coenzyme A reductase and agonists of peroxisome proliferator activated receptor-γ. Statins reduce the formation of lipid droplets by mycobacteria and reduce survival of <i>M. tuberculosis</i> in macrophages by inducing autophagy and maturation of the phagosome
	Phosphodiesterase inhibitors <sup>b</sup> (Vascular and Anti-inflammatory agents)	Sildenafil (Viagra) Cilostazol (Pletal)	Modulation of host cyclic nucleotide phosphodiesterase (PDE). In mice cilostazol plus sildenafil accelerates the clearance of <i>M. tuberculosis</i> bacilli from the lungs.
	Protein kinase inhibitors <sup>b</sup> (Used for chronic myelogenous leukemia)	Imatinib (Gleevec)	Direct pharmacological effect on macrophage function, promoting acidification and maturation of phagosomes. In mouse models reduces intracellular <i>M. tuberculosis</i> survival in vitro. Also increases neutrophil and monocyte numbers contributing to anti- <i>M. tuberculosis</i> host immune response
Cellular therapy for reduction of excess or tissue damaging inflammation and modulation of immune responses	Bone-marrow derived stromal cells <sup>a</sup>	Patient’s own bone marrow derived stromal cells (MSCs)	MSCs produce prostaglandin E2 (PGE2) that decreases unproductive inflammation by limiting excess of type I – interferon production and decreased <i>M. tuberculosis</i> proliferation. They could modulate deleterious inflammation and may have tissue-repairing effects. Phase 2 trial underway.
Heat killed environmental saprophytic mycobacteria for modulation of immune responses	Environmental mycobacteria <sup>a</sup>	<i>M. vaccae</i> , <i>M. indicus pranii</i> ( <i>M. w</i> ), and <i>M. manresensis</i>	Heat killed environmental mycobacteria induce regulatory T lymphocytes and promote macrophage effects. <i>M. vaccae</i> enhances Th1 and switch off the Th2 response. Being evaluated for both treatment and prevention of tuberculosis.

Abbreviation: HDT, host-directed therapies.

<sup>a</sup> Under evaluation.

<sup>b</sup> Ready for evaluation.

Several recent developments provide further hope for taking forward evaluation of adjunct HDTs in randomized clinical trials and improving current status quo of tuberculosis treatment and control efforts. The formation of the Host-Directed Therapies Network (HDT-NET) [39] consortium, which held their inaugural symposium in Cape Town, South Africa on 7 April 2015 hosted by the South African Medical Research Council. Our network is all inclusive and open to any interested group, and will be extended to include Eastern Europe, Asia, and South American country partners. Currently it comprises partners from 19 African and 11 European countries. HDT-NET aims to evaluate through randomized controlled clinical trials (RCTs) a range of adjunct HDTs for potentially: (a) Shortening the duration of treatment for drug-susceptible tuberculosis (DS-TB) multi-/extensively-drug resistant tuberculosis (MDR-/XDR-TB); (b) Improving treatment outcomes (mortality/morbidity) for MDR-/XDR-TB patients; and for specific clinical conditions associated with tissue injury such as HIV coinfecting individuals with DS-TB and MDR/XDR-TB, miliary tuberculosis, and TB meningitis; (c) Preventing recurrence of tuberculosis; (d) Improving treatment outcome of tuberculosis- and/or HIV-positive individuals with comorbidities, such as NCDs (eg, diabetes) and any cancers. This will create a more holistic approach for high quality care and to regain the upper hand in the fight against tuberculosis.

Critically, this initiative is committed to developing and maintaining high quality clinical trials and laboratory infrastructure at all partner sites irrespective of current capabilities. This will include staffing, infrastructure, facilities for cell culture, immunology, mycobacteriology and drug sensitivity testing, diagnostics, data entry/storage, protocol harmonization, communication, biobanking, end user involvement, ethics, continuing professional development, and networking with other trials consortia. Central to its ethos is twinning of research closely to capacity development and training with an aim to develop and nurture high caliber cadre of African and other developing country researchers (scientists, health and laboratory personnel), who will be suitably empowered to take active independent leadership of high quality, locally relevant research. A range of postdoctoral fellows, PhDs, Masters, and Diploma students will be mentored in close alignment with the design, development, and conduct of clinical trials. The Africa-Europe HDT-NET consortium will allow for access to a broader range of multidisciplinary expertise for research, training and supervision, and will enable broader knowledge and resource acquisition to support trials of other poverty-related diseases to be hosted in each country.

Several funder initiatives also provide hope for trialing HDTs and aligning research with capacity development and training: (1) The German Ministry for Science and Education to fund five Research Networks for Health Innovations under African

Leadership with 8 million Euros per year [40]; (2) The National Institutes of Health (NIH), USA, partners with high-tuberculosis burden country governments to co-fund Regional Prospective Observational Research for Tuberculosis (RePORT) [41]; and (3) The European and Developing Countries Clinical Trials Partnership (EDCTP2) launched formally in Cape Town in December 2014 [42]. There are unique opportunities for tackling the tuberculosis epidemic through development of equitable north-south clinical trials research and training partnerships [43, 44]. Other funders such as the Wellcome Trust [45], the UK Medical Research Council [46], NIH Fogarty [47], and other initiatives are also aligning to build developing country-led development of internationally competitive researchers. Because a large range of HDTs require to be evaluated in randomized clinical trials over the next decade, the time is now ripe for these funders to harness and pool resources for better coordination of national and regional research programs and to reduce fragmentation and duplication and achieve optimal deliverables.

All these funder initiatives will require close engagement of developing country scientists, healthcare workers, patient groups, governments, and policy makers. This will facilitate timely translation of research findings into policy and practice and will enable trained scientists to secure better careers. We are of the firm belief that it is only through empowerment of the younger generation scientific and healthcare leaders of the future to conduct the best quality science and to think more collaboratively beyond individual agendas, that the current status quo can be changed significantly. The conduct of a numerous clinical trials using a whole range of HDTs trial will allow for basic science studies to be conducted on biological samples obtained from a large cohort of patients from wide geographical areas so that the specific mechanisms of action of HDTs, their value in tuberculosis management can be defined. Understanding the specific mechanisms by which these drugs act and the relationship of these mechanisms to *M. tuberculosis* pathogenesis will be important in selecting appropriate adjunct host-directed therapy. Investments into newer scientific research should be aligned with parallel international efforts at improving social and living conditions through policy and adequate social protection programmes which address health inequalities more generally. Only then will significant progress be made in achieving WHO post-2015 End TB strategy goals, and gains in achieving tuberculosis control will be enhanced and sustained.

## Notes

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## APPENDIX

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