Redox homeostasis in mycobacteria: the key to tuberculosis control?

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Mycobacterium tuberculosis (Mtb) is a metabolically flexible pathogen that has the extraordinary ability to sense and adapt to the continuously changing host environment experienced during decades of persistent infection. Mtb is continually exposed to endogenous reactive oxygen species (ROS) as part of normal aerobic respiration, as well as exogenous ROS and reactive nitrogen species (RNS) generated by the host immune system in response to infection. The magnitude of tuberculosis (TB) disease is further amplified by exposure to xenobiotics from the environment such as cigarette smoke and air pollution, causing disruption of the intracellular prooxidant–antioxidant balance. Both oxidative and reductive stresses induce redox cascades that alter Mtb signal transduction, DNA and RNA synthesis, protein synthesis and antimycobacterial drug resistance. As reviewed in this article, Mtb has evolved specific mechanisms to protect itself against endogenously produced oxidants, as well as defend against host and environmental oxidants and reductants found specifically within the microenvironments of the lung. Maintaining an appropriate redox balance is critical to the clinical outcome because several antimycobacterial prodrugs are only effective upon bioreductive activation. Proper homeostasis of oxido-reductive systems is essential for Mtb survival, persistence and subsequent reactivation. The progress and remaining deficiencies in understanding Mtb redox homeostasis are also discussed.

In 1890, Koch stated publicly that he had 1921, Calmette and Guerin introduced the discovered the cure for tuberculosis (TB). In vaccine against TB, and between 1944 and 1966,
streptomycin, isoniazid (INH), ethambutol, rifampin and pyrazinamide were discovered as remedies for TB. Yet Mycobacterium tuberculosis (Mtb), the aetiological agent of TB, is still responsible for ~1.7 million deaths each year. In the majority of affected persons, Mtb enters a latent or persistent phase during infection (Fig. 1) associated with a state of drug unresponsiveness wherein the bacilli are not killed by currently available antimycobacterial agents (Refs 1, 2, 3). This situation, together with the emergence of multi-drug-resistant (MDR), extensively drug-resistant (XDR) and super XDR Mtb strains and the synergy with HIV infection, has created a frightening scenario. Studies show that malnutrition, tobacco smoking and indoor air pollution from solid fuel are the most important risk factors for TB worldwide, followed by HIV infection, diabetes and excessive alcohol intake (Fig. 1) (Ref. 4). This strongly suggests that improved nutrition and implementation of effective intervention strategies against tobacco smoke and indoor air pollution will have global socioeconomic and public health implications.

Dormancy refers to a physiological state of the bacillus generally typified by the absence of replication and the presence of metabolic shutdown. Latency is a clinical state characterised by purified protein derivative (PPD) skin test responsiveness coincident with a lack of clinical representation of disease. For a more in-depth discussion of these terms, see Refs 5, 6, 7.

More than a hundred years of research has shown that Mtb is an obligate aerobe, but the phrase ‘Mtb anaerobic respiration’ is frequently, albeit incorrectly, used in the TB literature. Nonetheless, it has been demonstrated that Mtb can survive in vitro for more than a decade under apparently anaerobic conditions.

Redox reactions have a key role in aerobic and anaerobic respiration. Within aerobic microbes, reactive species or oxidants are more or less balanced by the presence of antioxidants (Ref. 8). Mtb, similar to other bacterial species, has evolved pathways to monitor redox signals (such as O₂, NO and CO) and the alterations in intra- and extracellular redox states (Refs 2, 9, 10). We will begin this review by describing the basics of bacterial redox homeostasis and will then summarise the best-characterised redox mechanisms used by mycobacteria to sense and maintain redox homeostasis. A better understanding of these mechanisms should open new avenues for the development of improved diagnostic tools and effective vaccines, and lead to the identification of new drug targets.

**Maintaining the balance: oxidative stress and oxidative damage**

Oxidative stress can be defined as a disturbance in the prooxidant–antioxidant balance in favour of the former, leading to potential injury. Oxidative damage is characterised as the biomolecular impairment caused by the attack of reactive species upon the constituents of living organisms (Ref. 8). Oxidation can be described as a gain in oxygen (C + O₂ → CO₂), a loss of hydrogen or a loss of electrons (Na⁺ → Na⁻ + e⁻ or O₂⁻ → O₂ + e⁻), whereas reduction is defined as a loss of O₂ (CO₂ + C → 2CO), a gain in hydrogen (C + 2H₂ → CH₄) or a gain of electrons (O₂ + e⁻ → O₂⁻) (Ref. 8). Redox homeostasis can be defined as a ‘relatively stable state of equilibrium or a tendency towards such a state between the different but interdependent elements or groups of elements of an organism, population, or group’ (Merriam-Webster). Redox homeostasis is important to effectively harness reducing power produced through the catabolism of various substrates and to utilise this power in the anabolism of cellular components such as DNA, lipids and proteins.

**Why is Mtb redox balance important?**

During the course of infection, Mtb is exposed to a range of microenvironments that induce novel, as yet uncharacterised, compensatory metabolic pathways in an attempt by the bacillus to maintain balanced oxidation–reduction. It can be argued that redox imbalance can trigger mechanisms in the bacillus, which result in persistence and dormancy. Host-generated gases, carbon sources and pathological conditions such as hypoxic granulomas have a profound effect on bacterial metabolism and therefore redox balance, which through unknown mechanisms allow Mtb to successfully subvert the immune system and cause disease. These in vivo environmental conditions that cause intracellular redox imbalance might also affect antimycobacterial drug efficacy. For example, INH (Ref. 5), ethionamide (ETA) (Ref. 6) and PA-824 (a nitroimidazole
Figure 1. Virulence life cycle of *Mycobacterium tuberculosis* and progression of TB. *Mtb* is transmitted by aerosol, and in 95% of cases, wherein the tubercle bacilli are inhaled, a primary infection is established. This is either cleared by the surge of the cell-mediated immunity or contained inside the granuloma in the form of latent TB, defined by no visible symptom of disease, but persistent, yet dormant, live bacilli within the host. The progress of TB can be stalled at this stage in some cases by isoniazid preventive therapy. This state might last for the lifespan of the infected individual, or progress to active TB by reactivation of the existing infection, with a lifetime risk of 5–10%. This risk of progression is exacerbated by immune-compromising factors such as HIV-AIDS, diabetes, indoor air pollution and tobacco smoke. Reactivation of TB is shown to occur at the upper and more oxygenated lobe of the lung, which can be cured by compliance with drug therapy. However, untreated or poorly treated TB might lead to the formation of tuberculous lesions in the lung. The development of cavities close to airway spaces allows shedding (e.g. coughing) of the bacilli through the airway, a stage of transmission. Subsequently, in a cyclic manner, the TB bacilli are transmitted to other individuals to establish primary infection.
CO2 (ROS) is a collective term that refers to O2 such as HNO2, NO, H2O2, ONOO−, ROONO and RO2ONO. Reactive oxygen species (ROS) refer to radicals such as O2•−, NO•−, HOCl, and NO3•−, on the one hand, and nonradicals such as HNO2, NO2−, NO2•−, N2O4, N2O3, NO2•+, ROONO and RO2ONO. Reactive oxygen species (ROS) is a collective term that refers to O2 radicals such as O2•−, HO•−, HO2•+, RO•−, RO2•− and CO2•− and nonradical derivatives of O2 such as H2O2, ONOO−, ONOOH, ONOOCO2−, HOCl, HOB and O3(Ref. 8).

Reduction potential is an important thermodynamic property that allows the prediction of the course of free radical reactions (Table 1). Important redox couples such as NAD+/NADH (E0′ = −316 mV), NADP+/NADPH (E0′ = −315 mV), FAD/FADH2 (E0′ = −219 mV), ferredoxin (Fdox/Fdred) E0′ = −398 mV) and GSSG/GSH [E0′ = −250 mV (10 mM)] present in cells might function independently or be linked to other couples. Using linked sets of redox pairs, the redox environment can be defined as the summation of the products of the reduction potential and reducing capacity of the linked set of redox couples found in that cellular compartment (Ref. 17). In living systems, the reduction potential values predict what is feasible, but not what necessarily occurs (Ref. 8) (Table 1). Although a system of more negative reduction potential (E0′) should reduce one with a less negative, zero or positive E0′, there exists a hierarchy of oxidants. For example, the hydroxyl radical (HO•) will virtually always serve as an oxidant, whereas NO• or H2O2 can function as oxidants or reductants depending on whether they react with molecules of lower or higher hierarchy (Ref. 18).

Measurement of all linked redox couples within bacterial cells is impractical and probably impossible, because some couples remain unidentified. Thus, quantification of a representative redox couple is used to infer changes in the redox environment. For example, in most bacteria (albeit not mycobacteria) the GSSG/GSH couple represents the major intracellular redox buffer and can therefore be used to infer the status of the bacterial redox environment. Using this redox-couple-specific approach, the intracellular redox potential of Escherichia coli (E0′ = −220 to −245 mV) (Refs 19, 20) has been determined, which augurs well with that of a recent noninvasive fluorescent-based assessment (E0′ = −259 mV) (Ref. 19). The intracellular redox potential of mycobacteria has not yet been determined.

Free radicals and microbes
Endogenous oxidative stress arises from the univalent reduction of O2 by various components of the electron transport chain (ETC) under normal aerobic conditions, resulting in the production of ROS such as superoxide radicals (O2•−). The mechanism of O2-mediated reoxidation of many reduced electron carriers such as reduced flavins, Fe(III) and NADH has been shown to occur by the formation of O2•−. Although O2•− is less reactive than HO• and does not react with most...
### Table 1. Standard reduction potentials of biologically relevant redox couples

<table>
<thead>
<tr>
<th>Redox couple</th>
<th>Redox potential (mV)</th>
<th>Highly oxidizing</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ / CO₂</td>
<td>−1800</td>
<td></td>
</tr>
<tr>
<td>CO₂ / CO</td>
<td>−520</td>
<td></td>
</tr>
<tr>
<td>Acetyl-CoA / Apyruvate</td>
<td>−500</td>
<td></td>
</tr>
<tr>
<td>Succinyl-CoA / 2-oxoglutarate</td>
<td>−491</td>
<td></td>
</tr>
<tr>
<td>CO₂ / HCOO</td>
<td>−421</td>
<td></td>
</tr>
<tr>
<td>H⁺ / H₂</td>
<td>−414</td>
<td></td>
</tr>
<tr>
<td>NAD⁺ / NADH</td>
<td>−316</td>
<td></td>
</tr>
<tr>
<td>NADP⁺ / NADPH</td>
<td>−315</td>
<td></td>
</tr>
<tr>
<td>CO₂ / acetate</td>
<td>−291</td>
<td></td>
</tr>
<tr>
<td>Trx C [TrxSS / Trx(SH₂)]</td>
<td>−269</td>
<td></td>
</tr>
<tr>
<td>TrxB [TrxSS / Trx(SH₂)]</td>
<td>−262</td>
<td></td>
</tr>
<tr>
<td>TrxA [TrxSS / Trx(SH₂)]</td>
<td>−248</td>
<td></td>
</tr>
<tr>
<td>2H⁺ / 2Cys-SH (cystine)</td>
<td>−230</td>
<td></td>
</tr>
<tr>
<td>FAD⁺ / FADH₂</td>
<td>−219</td>
<td></td>
</tr>
<tr>
<td>FMN⁺ / FMNH₂</td>
<td>−219</td>
<td></td>
</tr>
<tr>
<td>Pyruvate, H⁺ / lactate</td>
<td>−183</td>
<td></td>
</tr>
<tr>
<td>Oxaloacetate, 2H⁺ / malate</td>
<td>−166</td>
<td></td>
</tr>
<tr>
<td>Menaquinone</td>
<td>−74</td>
<td></td>
</tr>
<tr>
<td>ESSE / 2ESH (ergothioneine)</td>
<td>−60</td>
<td></td>
</tr>
<tr>
<td>CoQ⁺ / CoQ⁻</td>
<td>−36</td>
<td></td>
</tr>
<tr>
<td>Fumarate / succinate</td>
<td>+32</td>
<td></td>
</tr>
<tr>
<td>Ubiquinone / ubiquinol</td>
<td>+45</td>
<td></td>
</tr>
<tr>
<td>Fe³⁺ / Fe²⁺ (aq)</td>
<td>+110</td>
<td></td>
</tr>
<tr>
<td>Ascorbate⁺ / ascorbate⁻</td>
<td>+282</td>
<td></td>
</tr>
<tr>
<td>O₂ / H₂O₂</td>
<td>+295</td>
<td></td>
</tr>
<tr>
<td>Cytochrome a₃ (Fe³⁺) / cytochrome a₃ (Fe²⁺)</td>
<td>+350</td>
<td></td>
</tr>
<tr>
<td>NO₃⁻ / NO₂⁻</td>
<td>+421</td>
<td></td>
</tr>
<tr>
<td>α-Tocopheroxyl⁺ / α-tocopherol</td>
<td>+500</td>
<td></td>
</tr>
<tr>
<td>O₂ / H₂O</td>
<td>+818</td>
<td></td>
</tr>
<tr>
<td>RS⁺ / RS⁻ (cysteine)</td>
<td>+920</td>
<td></td>
</tr>
<tr>
<td>GS⁺ / GS⁻ (glutathione)</td>
<td>+920</td>
<td></td>
</tr>
<tr>
<td>NO₂⁻ / NO₂⁺</td>
<td>+990</td>
<td></td>
</tr>
<tr>
<td>ROO⁺, H⁺ / ROOH (alkyl peroxy radical)</td>
<td>+1000</td>
<td></td>
</tr>
<tr>
<td>HO₂⁻, H⁺ / H₂O₂</td>
<td>+1060</td>
<td></td>
</tr>
<tr>
<td>ONOO⁻ / NO₂⁻ (aq)</td>
<td>+1400</td>
<td></td>
</tr>
<tr>
<td>RO⁺, H⁺ / ROH (aliphatic alkoxyl radical)</td>
<td>+1600</td>
<td></td>
</tr>
<tr>
<td>NO₂⁺ / NO₂⁻</td>
<td>+1600</td>
<td></td>
</tr>
<tr>
<td>CO₂⁺⁻, H⁺ / HCO₃⁻</td>
<td>+1780</td>
<td></td>
</tr>
<tr>
<td>HO⁺, H⁺ / H₂O</td>
<td>+2310</td>
<td></td>
</tr>
</tbody>
</table>

For a given couple, the reduction potential relative to the potential of the standard couple, hydrogen (H⁺ / H₂), is shown. Standard concentrations are 1.0 M for solutes and ions and 1 atm pressure for gases (e.g. H₂). The standard reduction potentials are symbolised by $E^0$. Note that the ‘true’ redox potentials within a cell can differ dramatically from standard values. The Nernst equation is used to correct $E^0$ values for the effect of temperature ($T$) and concentration: $E^0 = E^0 + \frac{-RT \log_{10} \text{[oxidised]}}{nF \log_{10} \text{[reduced]}}$. Because protons are involved in many reactions, the values in the table are corrected to pH 7 ($E^0$) rather than $E^0$. This is particularly important because the intracellular microbial and host pH probably vary widely during the course of infection. The bottom of the list (more positive) represents the highly oxidising couples, whereas the top of the list (more negative) represents the highly reducing couples. Therefore, the hydroxyl radical (HO⁺) at the bottom of the list is capable of oxidising everything else on the list. The data are largely from Refs 8, 17, 18.
biological molecules, it readily reacts with NO\(^•\) to generate peroxynitrite (ONOO\(^–\)) (Ref. 8). O\(^2–\) also oxidises the 4Fe-4S clusters of dehydrogenases such as aconitase, leading to enzyme inactivation and release of Fe\(^2+\). The released Fe\(^2+\) can then reduce H\(_2\)O\(_2\) to intracellular HO\(^•\). Free Fe\(^2+\) is maintained in reduced form by intracellular reductants and will continue to reduce H\(_2\)O\(_2\) to generate HO\(^•\). Further, Fe\(^2+\) can nonspecifically bind to DNA, proteins and membranes, facilitating the localised production of HO\(^•\), which may result in oxidative damage to these molecules (Ref. 8).

Superoxide dismutase (SOD) catalyses the dismutation reaction between two superoxide radicals, resulting in the formation of molecular O\(_2\) and H\(_2\)O\(_2\) [equation (1)]:

\[
\text{O}_2^- + \text{O}_2^- + 2\text{H}^+ \rightarrow \text{H}_2\text{O}_2 + \text{O}_2 \tag{1}
\]

H\(_2\)O\(_2\) can be detoxified by enzymes such as catalase and peroxidase as shown in equation (2), but its production in the presence of metal ions (such as Fe\(^2+\) and Cu\(^+\)) leads to the formation of extremely potent oxidant, HO\(^•\), through the Fenton reaction: [equation (3)]:

\[
2\text{H}_2\text{O}_2 \rightarrow 2\text{H}_2\text{O} + \text{O}_2 \tag{2}
\]

\[
\text{Fe}^{2+} + \text{H}_2\text{O}_2 \rightarrow \text{Fe}^{3+} + \text{HO}^• + \text{HO}^- \tag{3}
\]

The superoxide anion generated as an unwanted byproduct of normal aerobic respiration can subsequently reduce the metal ion as shown in equation (4):

\[
\text{Fe}^{3+} + \text{O}_2^- \rightarrow \text{Fe}^{2+} + \text{O}_2 \tag{4}
\]

Reactions (3) and (4) combined are known as the Haber–Weiss reaction [reaction (5)], which was first described in 1934 (Ref. 21):

\[
\text{O}_2^- + \text{H}_2\text{O}_2 \rightarrow \text{HO}^• + \text{HO}^- + \text{O}_2 \tag{5}
\]

The low reactivity of O\(^2–\) and H\(_2\)O\(_2\) allows them to diffuse from their site of production, which, on reaction with free iron or copper ions in the cellular pool, leads to the generation of HO\(^•\). In *E. coli*, aerobic respiration leads to the generation of 0.1–0.2 μM H\(_2\)O\(_2\) (Ref. 22). It is estimated that the intracellular stoichiometry of O\(^2–\) to HO\(^•\) is 2:1. The HO\(^•\) radical is particularly unstable and reacts rapidly with numerous bacterial components such as lipids, DNA and proteins (Ref. 22) to induce site-specific lesions. Studies have demonstrated that *Mtb* is susceptible to H\(_2\)O\(_2\)-induced damage in vitro (Ref. 23).

O\(^2–\) in aqueous solution can react as a reductant wherein it donates an electron to cytochrome c, and can also serve as an oxidant with ascorbic acid (AH\(_2\)) (Ref. 8):

\[
\text{Cyt}\,\text{c} (\text{Fe}^{3+}) + \text{O}_2^- \rightarrow \text{O}_2 + \text{Cyt}\,\text{c} (\text{Fe}^{2+}) \tag{6}
\]

\[
\text{AH}_2 + \text{O}_2^- \rightarrow \text{A}^•^- + \text{H}_2\text{O}_2 \tag{7}
\]

O\(^2–\) can also interact with NADH bound to the active site of lactate dehydrogenase and possibly other enzymes to generate a NAD\(^•\) radical; however, it does not oxidise free NADPH or NADH (Ref. 8).

**Free radicals and the host**

*Mtb* is a slow-growing bacillus transmitted by the respiratory route. The infection initiates on ingestion of the bacilli by alveolar macrophages. On phagocytosis of *Mtb*, lung macrophages and neutrophils produce large quantities of ROS and RNS. NADPH oxidase catalyses the one-electron reduction of O\(_2\) using NADPH as electron donor, generating O\(^2–\), as depicted in the following (reviewed in Refs 24, 25, 26, 27):

\[
2\text{O}_2 + \text{NADPH} \rightarrow \text{O}_2^- + \text{NADP}^+ + \text{H}^+ \tag{8}
\]

Superoxide generated in the above reaction can be converted to H\(_2\)O\(_2\) by SOD as described in equation (1).

A highly reactive hypochlorite ion (ClO\(^–\)) could be generated by myeloperoxidase, which catalyses the oxidation of chlorine, resulting in the formation of ClO\(^–\) according to the reaction below [equation (9)] (Ref. 28). Hypochlorite is an extremely reactive oxidant and can lead to oxidative damage of lipids, proteins and DNA:

\[
\text{Cl}^- + \text{H}_2\text{O}_2 \rightarrow \text{ClO}^- + \text{H}_2\text{O} \tag{9}
\]

ClO\(^–\) also acts as a precursor of several other ROS (Refs 29, 30, 31) and RNS (Refs 32, 33, 34). In response to mycobacterial infection, another major antimicrobial pathway that acts through inducible NO synthase is activated, leading to increased production of NO (Refs 35, 36)
NO is produced in parallel with O$_2^-$ and they both react with each other to produce highly reactive OONO$^-$. In addition to the generation of OONO$^-$, NO also leads to the generation of NO$^-$, NO$_2$, NO$_3$, N$_2$O$_3$, N$_2$O$_4$, S-nitrosothiols and dinitrosyl-iron complexes (Refs 37, 38), which are all effective in killing bacteria (Ref. 39).

To dissect the role of ROS in TB, different murine knockout models lacking active NADPH oxidase components have been generated and compared with the wild-type strain for their capability to control the growth of Mtb. These experiments produced conflicting data among different laboratories. Two independent studies (Refs 40, 41) showed that Mtb growth was enhanced in the absence of active NOX (NADPH oxidase), whereas another study found no difference between Phox$^{-/-}$ and wild-type mice in their ability to control Mtb infection (Ref. 42).

Several murine studies (Refs 35, 43, 44, 45, 46) have shown that inducible NO synthase (iNOS or NOS2) produces NO, which is capable of killing mycobacteria. Furthermore, iNOS-deficient mice were demonstrated to be highly susceptible to TB infection (Refs 42, 47, 48), and NO was shown to be crucial in maintaining a latent TB infection in mice (Ref. 49). Clinical evidence in support of a role for NO in TB includes studies indicating increased iNOS protein and mRNA levels in bronchoalveolar lavage specimens from active pulmonary TB patients (Ref. 45), single-nucleotide polymorphism variations of NOS2A (Ref. 50), and increased exhaled NO and NO$_2$ in patients with active pulmonary TB (Refs 43, 51).

**Mtb physiology and the intracellular redox state**

*Mtb* is a prototrophic, obligate aerobe that cannot replicate in the absence of O$_2$. However, the tubercle bacillus has an uncanny ability to survive extended periods of anaerobiosis even though classic manometric studies showed that several days of anaerobic exposure completely stalled bacterial respiration and the ability to grow on laboratory media (Ref. 52). In recent years, research into the mechanisms associated with the bacilli adaptive response to anaerobiosis has received much attention primarily because TB granulomas were shown to be hypoxic (Ref. 53), and because all current antimycobacterial drugs are ineffective against nonreplicating Mtb present in hypoxic granulomas. Thus, a more thorough understanding of Mtb redox physiology is critical to TB control.

Aerobic respiration is one of the most widespread bioenergetic pathways in microbial biology. Oxidation of a typical carbohydrate such as glucose can be divided into three separate phases: (1) a catabolic pathway (e.g. glycolysis) that breaks down glucose to pyruvate; (2) the TCA cycle, which oxidises organic molecules to CO$_2$ and H$_2$O, ATP and reduced coenzymes; and (3) oxidative phosphorylation, during which reduced coenzymes are oxidised and their electrons and protons establish a proton motive force across the membrane. Electrons are channelled (through NADH and FADH$_2$) to the ETC, which sequentially oxidises and reduces multiple redox centres before reducing O$_2$ to H$_2$O, and producing ATP. The respiratory metabolism is complex and regulated by many endogenous and exogenous (host) factors, including the carbon source, pH, O$_2$ (and ROS), NO (and RNS), CO, CO$_2$, etc. (Ref. 54).

The central role that redox reactions have in maintaining metabolic processes makes them essential to mycobacterial persistence. Unfortunately, the mechanisms used by Mtb to maintain redox homeostasis during active disease, persistence and reactivation are poorly understood and warrant further investigation. It is unknown how Mtb simultaneously regulates metabolic and signalling events in endogenous cellular compartments (e.g. the reducing environment of the cytoplasm and the oxidised periplasmic space and outer cell surface). Likewise, it is poorly understood how the bacterium senses and responds to the diverse environments encountered in vivo, for example in different organs or in different regions of the same organ (e.g. the natural O$_2$ gradients within the lung).

**Important physiological players: gases and ATP**

*Mtb* resides within a hypoxic microenvironment in the lungs (Ref. 55). However, aerobic and
anaerobic microenvironments almost certainly exist, which in theory can explain the capacity of dormant bacilli to survive chemotherapy. Aerobic respiratory systems produce energy that comes from the movement of electrons from oxidisable organic substrates to O₂. Components of the ETC contain redox centres (redox-active prosthetic groups such as FMN, haem and iron–sulfur clusters (Fe–S)), with progressively greater affinities for electrons (from lower to higher standard reduction potentials). In general, these redox centres are very susceptible to host-generated ROS and RNS, which typically bind to or oxidise the prosthetic groups to affect protein activity, and therefore respiration. In agreement with the known mode of action of NO, which targets components of the respiratory chain, studies have shown that NO inhibits *Mtb* respiration. In fact, NO and lack of O₂ synergistically block respiration (Ref. 56). Lack of O₂ causes a loss of energy, which destroys the ordered state (life) of a cell, leading to its death. However, evidence suggests that *Mtb* has the extraordinary capacity to decrease respiration to a low, albeit not zero, level, and still remain viable (Ref. 52). Although nitrate (NO₃⁻) prolongs the survival of *Mtb* under anaerobic growth conditions as demonstrated in vitro (Refs 57, 58), active replication was not promoted. By contrast, the *M. tuberculosis* *narGHJI* operon was capable of complementing a *nar E. coli* mutant, which acquired the ability to actively replicate anaerobically only in the presence of nitrate (Ref. 59). Therefore, because NO₃⁻ was unable to stimulate replication of *Mtb* under anaerobic conditions, this compound cannot be regarded as a terminal electron acceptor. Furthermore, it suggests that the reduction of NO₃⁻ could be redox balancing, or it might help provide energy under anaerobic conditions.

Consistent with the consequences of respiratory inhibition, ATP decreases to 25% of aerobic levels during hypoxic growth of *Mtb* (Ref. 60). A recent study has shown that *Mtb* maintains a fully energised cytoplasmic membrane to preserve ATP homeostasis during hypoxia without the use of alternate terminal electron acceptors (NO₃⁻, fumarate, etc.) for respiration (Ref. 61). This suggests that *Mtb* retains a low level of metabolic activity to sustain an energised membrane even in the absence of respiration during hypoxic persistence.

### Redox couples and electron transfer in *Mtb*

The NAD⁺/NADH coenzyme system is required for catabolism, whereas the NADP⁺/NADPH system is required for anabolism. NAD⁺ is an efficient electron sink and hence is used as a cofactor in several oxidising reactions. A constant level of NADH is maintained during various phases of growth in vitro, whereas the concentration of NADH is variable and is a major contributor to a change in NADH/NAD⁺ ratio. In *Mtb*, the ratio of NADH/NAD⁺ is typically ~1:3 to 1:10 (Refs 61, 62, 63), but a higher ratio of *Mtb* NADH/NAD⁺ is generated during the transition from aerobic to anaerobic mycobacterial growth, owing to depletion of the NAD⁺ pool, and is maintained by type II NADH dehydrogenase (Ref. 61). Although NAD⁺ has an important role as an electron sink, NADPH acts as a major electron donor in many reductive reactions. Hence the NADPH/NAD⁺ ratio is an indicator of reductive energy available to a cell. The concentration of the NADH/NAD⁺ couple is submillimolar and is often higher than the phosphorylated form. In *Mtb*, the ratios of NAD⁺/NADP⁺, NADPH/ NADH, NADP⁺/NADPH and NAD⁺/NADH are 1.95, 2.25, 2.39 and 10.5, respectively (Ref. 62).

Being an obligate aerobe, *Mtb* has to regenerate NAD⁺ because the respiratory chain is downregulated in the absence of O₂ as terminal electron acceptor. An unexpected finding in the anaerobic model for in vitro dormancy was that the *Mtb* NAD⁺ and NADH levels were only approximately 50% of the aerobic levels when O₂ was consumed, whereas the NAD⁺/ NADH ratio was similar to that in aerobic conditions (Ref. 60). These findings suggest that *Mtb* has evolved an as yet unidentified mechanism to survive severe hypoxia and regenerate NAD⁺. Three plausible mechanisms that might allow regeneration of NAD⁺ from NADH under hypoxic or nitrosative stress conditions exist: (1) nitrate reduction (*narGHJI*; Rv1161–1164) that catalyses the reduction of NO₃⁻ to NO₂⁻; (2) triacylglycerol (TAG) anabolism (Ref. 64); or (3) electron bifurcation mechanisms by which two electrons bifurcate to a high and low potential pathway (Ref. 65). A recent in vivo study has shown that *Mtb* generates massive quantities of NAD(P)H in infected mouse lungs (Ref. 63) and therefore experiences significant reductive stress (see also Ref. 54 for a review). This finding again raises...
the issue of how reducing equivalents are regenerated to produce NAD(P)^+.

The carbon oxidation state
In vivo sources of energy include carbohydrates, organic acids, amino acids, nucleic acid precursors and fatty acids (Ref. 66). Several recent and historic studies have demonstrated that fatty acids are potential in vivo carbon sources for Mtb (Ref. 67). Isocitrate lyase (Icl), an enzyme from the glyoxylate cycle, has been shown to have an important role in fatty acid carbon utilisation in vivo (Ref. 68). Fatty acid utilisation has a profound effect on the amount of reducing equivalents produced [e.g. NAD(P)^+H]. For example, palmitate and oleate have highly reduced carbon oxidation states (COS values) of −28 and −30, respectively, compared with other fatty acid precursors such as propionate (COS = −1) and valerate (COS = −6) and carbohydrates such as glucose (COS = 0). Subsequent β-oxidation of palmitate generates 106 units of ATP, whereas oxidation of glucose produces only 38 ATP molecules. The β-oxidation of fatty acids yields one NADH and one FADH2 molecule for every acetyl-CoA generated. Clearly, the ‘type’ of in vivo carbon source (most likely a mixture) has a profound effect on the energetics of the microbial cell, for example the amount of NAD(P)H to be recycled to maintain redox balance.

Redox balance and excretion
During aerobic respiration, the electron donor (e.g. organic substrates such as glucose) undergoes net oxidation whereas the external electron acceptor (e.g. O_2) is reduced to form a balanced oxidation–reduction process. Thus, the oxidation of the substrate is balanced by the reduction of the electron acceptor. E. coli regenerates NAD^+ under anaerobic conditions with the excretion of metabolic intermediates such as formate, ethanol and succinate (Ref. 69). By contrast, historical studies have shown that Mtb generates alkaline supernatants as opposed to acidic supernatants produced by other bacteria (Ref. 70). The lack of secreted acid intermediates suggests that carbohydrates are completely oxidised by Mtb and that unknown mechanisms are responsible for the generation of NAD^+ under hypoxic (dormant) conditions in which the TCA cycle is nonfunctional.

Mtb machinery that maintains intracellular redox homeostasis
Mycothiol
Although mycobacteria contain redox couples such as thioredoxin [TrxSS/Trx(SH)_2], NADH/ NAD^+ and NADPH/NADP^+, the conventional redox couple glutathione (GSSG/2GSH) is absent in mycobacteria. Rather, mycobacteria contain oxidised–reduced mycothiol (MSSM/2MSH) in millimolar quantities as the major redox buffer.

Mycothiol is a low-molecular-weight thiol produced by many members of the actinomycetes, including mycobacteria. It functions like glutathione, the archetypal redox buffer, which is not produced by mycobacteria (Ref. 71). The reduction potential of MSSM–2MSH has not yet been determined, and studies are restricted to examining MSSM/2MSH ratios. Oxidised mycothiol is reduced by the FAD-binding mycothione reductase using NADPH as cofactor, which is indicated in equation (11) (Refs 72, 73):

\[
\text{NADPH + H}^+ + \text{MSSM} \rightarrow \text{2MSH} + \text{NADP}^+ + \text{H}_2 \text{O}
\]

Another low-molecular-weight thiol produced by mycobacteria is ergothioneine (ERGox/ERGred; \(E^0 = −60 \text{ mV}\)) (Ref. 74). However, little is known about the role of this uncharacterised thiol in mycobacteria, but it has been shown to protect mammalian cells from oxidative stress (Refs 75, 76).

MSH consists of myo-inositol linked to glucosamine, which is in turn ligated to a cysteine residue with an acetylated amino group (Refs 77, 78, 79). There are five steps in MSH biosynthesis; the first is catalysed by a glycosyltransferase encoded by mshA (Ref. 80), which fuses 1L-myoinositol-1-phosphate (derived from glucose-6-phosphate) and UDP-N-acetylgucosamine (Ref. 81). The resulting N-acetylgucosaminylinositol phosphate [1-O-(2-acetamido-2-deoxy-\(\alpha\)-D-glucopyranosyl)-\(\alpha\)-myo-inositol 3-phosphate] is then dephosphorylated by MshA2 (its gene has not yet been identified) (Ref. 81) and deacetylated by MshB (Ref. 82). This glucosaminylinositol [1-O-(2-amino-1-deoxy-\(\alpha\)-D-glucopyranosyl)-\(\alpha\)-myo-inositol] is then ligated to the cysteine carboxyl group through MshC in an ATP-dependent reaction (Ref. 83). Finally, an acetyl group is added to the
amino group of cysteine by an acetyltransferase encoded by mshD (Ref. 84). Published data strongly suggest that MSH has a pivotal role in maintaining the redox balance of mycobacterial cells. Evidence for this includes the sensitivity of various MSH mutants to oxidative stress caused by H_2O_2, cumene hydroperoxide and O_2^- (Refs 85, 86, 87, 88). Inactivation of mshA1 in Mtb and Mycobacterium smegmatis (Msm) results in loss of the production of mycothiol and its intermediates (Ref. 89). Msm and Mtb mutants of mshD accumulated the MshB substrate N-acetylg glucosaminylinositol and were capable of producing low levels of MSH, which is probably due to the presence of an unidentified enzyme with overlapping function (Refs 86, 90). By contrast, in Msm mutants, the loss of MshC activity completely blocks the production of MSH and causes increased levels of glucosaminylinositol (Ref. 87). Mtb mutants lacking mshC are not viable (Ref. 86), suggesting that mycothiol is necessary for Mtb survival; however, MSH-deficient mshA1 mutants have been recovered in various Mtb strains (Ref. 89). mshD mutants of Mtb and Msm produce low levels of MSH and high levels of its immediate precursor, as well as two novel thiols (Refs 85, 91). As stated previously, increased sensitivity to oxidative stress is a common characteristic of the mycothiol mutants. Msm mutants independently disrupted in the four known mycothiol synthesis genes and the Mtb mshD mutant are more sensitive to H_2O_2 compared with the wild type (Refs 85, 88, 92). Additionally, increased sensitivity to cumene hydroperoxide was demonstrated for the Mtb mshD mutant (Ref. 86), whereas the Msm mycothiol mutants, compared with Mtb, are less resistant than the wild type to plumbagin, a superoxide generator (Refs 87, 88). Many of the mycothiol mutants are also more resistant to the prodrugs INH and ETA (Refs 80, 88, 90, 92).

**Thioredoxin (Trx)**

Trx is a small redox protein with two redox-active Cys residues in its active site. It is a superior thiol reductant that binds proteins and reduces disulfide bonds by a thiol-exchange reaction through the two Cys residues to generate a disulfide or dithiol. This results in oxidised Trx [equation (10)], which is then reduced by the FAD-containing enzyme Trx reductase (TrxR) that extracts electrons from NADPH (Ref. 93)

\[
\text{Trx-(SH)_2} + \text{protein} \rightarrow \text{Trx-S_2} \nonumber \\
+ \text{protein-(SH)_2} \quad (12)
\]

\[
\text{NADPH} + \text{H}^+ + \text{Trx-S_2} \overset{\text{TrxR}}{\rightarrow} \text{NADP}^+ + \text{Trx-(SH)_2} \quad (13)
\]

NADPH, TrxR and Trx comprise the thioredoxin system that is universally conserved. Trx is responsible for maintaining a reducing intracellular environment, regenerating the reduced forms of methionine sulfoxide reductase and peroxiredoxins, the redox regulation of enzymes and regulatory proteins by oxidoreduction and the detoxification of ROS (Refs 94, 95, 96). Mtb contains three types of Trx proteins, TrxA, TrxB and TrxC, with mid-point redox potentials of −248, −262 and −269 mV, respectively, along with one TrxR (Ref. 94). Trx and TrXR have also been shown to reduce H_2O_2 and dinitrobenzenes (Ref. 97).

A particularly interesting function of *E. coli* Trx, and probably also of *Mtb* Trx, is the reduction of a unique disulfide bond in ribonucleotide reductase (RNR), which allows RNR to reduce ribonucleotides to deoxyribonucleotides that feed into subsequent reactions (Ref. 98). Intriguingly, several *E. coli* thioredoxin and glutaredoxin double mutants were shown to be nonviable under aerobic conditions, but were rescued by DTT (a thiol-specific reductant) or anaerobiosis (Ref. 99).

The *Mtb* sigH (σH) mutant was found to be more susceptible to disulfide stress generated by diamide (a thiol-specific oxidant) and plumbagin (Refs 100, 101), suggesting that σH has a central role in protection against oxidative stress. The *Mtb* σH mutant was found to be attenuated for virulence in mice (Ref. 102), and microarray analysis has shown that σH regulates *trxB, trxA* and *thx* (a hypothetical *trx* expression. *Mtb* sigH exists in an operon with an antisigma factor *rshA* (Ref. 103). Dissociation of the σH and RshA interaction by oxidation allows expression of the *trx* and *trxR* genes and the σH operon (Ref. 103).

**The Dsb disulfide oxidoreductases**

Disulfide bond formation is a two-electron oxidation event in which two Cys residues (2RSH) are covalently bonded (RS–SR). Two protons and two electrons are released during
this process, as shown below:

\[
\text{RSH} + \text{RSH} \rightarrow \text{RS-SR} + 2\text{H}^+ + 2e^- \quad (14)
\]

Disulfide bond formation inside a cell is a rapid process, whereas in vitro conditions might require hours or days for the reaction to proceed. Dsb proteins are thioredoxin-like proteins that promote rapid disulfide formation and folding of periplasmic or secreted proteins. Although many Dsb proteins have been characterised, most in \textit{E. coli} are present in the periplasmic or secreted proteins. Although many Dsb proteins have been characterised, most in \textit{E. coli}, only three Dsb homologues, DsbE (Ref. 104), DsbF (Ref. 105) and the transmembrane protein DsbD (Ref. 104), are present in \textit{Mtb}.

**Catalase peroxidase**

Catalase peroxidases (Kat) are enzyme systems that efficiently protect the bacterium from ROS damage (Refs 106, 107, 108) and are used to detoxify \text{H}_2\text{O}_2. \textit{Mtb} harbours one catalase, KatG (Ref. 109), that shows catalase, peroxidase and peroxinitritase activity. KatG has been demonstrated to be a virulence factor (Ref. 110) that mediates resistance against the prodrug INH. Additionally, clinical \textit{Mtb} strains resistant or sensitive to INH that were exposed to the drug show higher levels of AhpC (alkyl hydroperoxide reductases) (Ref. 111), a member of the peroxiredoxin family.

**Alkyl hydroperoxide reductases**

Reaction of peroxides with cellular components such as lipids could lead to the generation of highly reactive alkyl hydroperoxides. Mycobacteria use a nonhaem peroxiredoxin called alkyl hydroperoxidase (AhpC) to detoxify by reduction such organic peroxides into less reactive alcohol derivatives (Ref. 112). Peroxiredoxins typically use two redox-active Cys residues to reduce their substrates; however, mycobacterial AhpC contains three Cys residues that are directly involved in this catalysis. AhpC was demonstrated to confer protection against both oxidative and nitrosative stress (Ref. 113). \textit{Mtb} Trx and TrxR are not capable of reducing AhpC (Ref. 97); AhpD, which is reduced by dihydrolipoamide and dihydrolipoamide dehydrogenase (Lpd) (Ref. 114), is needed for the physiological reduction of AhpC. AhpC is linked to dihydrolipoamide dehydrogenase (Lpd) and dihydrolipoamide succinyltransferase (SucB) through AhpD, which acts as an adapter protein (Ref. 114). Lpd is a component of three major enzymatic complexes: the pyruvate dehydrogenase complex, the branched amino acid dehydrogenase complex and the peroxynitrite reductase complex. Thus, the peroxidase activity is uniquely linked to the metabolic state of \textit{Mtb}. More recently, another peroxiredoxin system, thioredoxin reductase (TPx), was shown to be highly effective in protecting \textit{Mtb} against oxidative and nitrosative stress (Refs 95, 115). The TPx system depends on TrxR, TrxB and TrxC for its activity and was recently shown to be involved in virulence (Ref. 116).

**Superoxide dismutases**

SODs are metalloproteins produced by prokaryotes and eukaryotes to detoxify superoxide radicals. They catalyse the dismutation of \text{O}_2^- into \text{H}_2\text{O}_2 and molecular oxygen. \textit{Mtb} contains two SODs, an iron-containing SOD called SodA or FeSOD (Ref. 117) and a Cu- and Zn-containing SOD called SodC or CuZnSOD (Ref. 118). SodA is constitutively expressed under normal conditions and is demonstrated to be a major secretory protein of \textit{Mtb} that lacks a clearly defined signal peptide sequence (Refs 117, 118). Its expression is enhanced by \text{H}_2\text{O}_2 exposure and on nutrient starvation (Ref. 119). An antisense approach has successfully been used to show that SodA protects \textit{Mtb} against superoxide in vitro (Ref. 120), whereas another study has demonstrated the role of \textit{Mtb}SodC in protection against ROS (Ref. 121).

**Methionine sulfoxide reductases**

MSRs use NADPH, Trx and TrxR as the system to reduce methionine sulfoxide to methionine and to protect bacteria against ROS and RNS (Ref. 122). Usually bacteria contain two MSRs, one active on both free and peptidyl methionine-(S)-sulfoxide, and one or more MSRs active on peptidyl, but not free, methionine-(R)-sulfoxide (Ref. 123). Few studies on MSRs in \textit{Mtb} have been reported. However, recent studies have shown that \textit{Mtb} produces two MSRs, MsrA and MsrB, which are both required for protection against ROS and RNS (Ref. 124).

**Truncated haemoglobins**

Truncated haemoglobin (trHbs) are small haem-binding globin proteins related to, but smaller than, haemoglobin and myoglobin (Refs 125,
shown to significantly affect Cys (Ref. 130). Not surprisingly, cigarette smoke was a defence mechanism against oxidant damage that glutathione is a vital component of the redox homeostasis (Ref. 130).

The high concentration of GSH in the lungs (60–150 mmHg), spleen (∼16 mmHg demonstrated in rats) and thymus (10 mmHg) (Refs 53, 57, 135, 136). The diffusion distance of O2 is ∼100–200 μm, resulting in a pO2 of zero within this distance from blood vessels. Using redox-active dyes that are reduced at pO2 lower than 10 mmHg, studies in guinea pigs and monkeys have shown that the granulomas are indeed hypoxic (Ref. 53). Notably, Mtb is an obligate aerobe but has evolved as yet undefined mechanisms to survive within this hypoxic and perhaps anaerobic environment. Furthermore, O2 is a highly diffusible gas, and despite the remarkable difference in pO2 pressure between the granuloma (1.59 mmHg) and adjacent tissue (Refs 57, 53), it is not yet known how this pressure differential is maintained (Fig. 2).

The Mtb diet in the lung

The precise mechanism of nutrient acquisition by which Mtb senses nutrient availability and adjusts its metabolism in response to different carbon sources in vivo has not yet been elucidated. An additional level of complexity is added by the fact that nutrient availability and utilisation might change over the course of infection: for example, intracellular bacilli versus the late stages of infection where tissue has undergone caseation and liquefaction. Nonetheless, several studies suggest that host fatty acids might serve as the carbon and energy source in vivo (Refs 137, 138). The identification and current studies on Icl (Ref. 68), the fatty acid regulator Ksr (Ref. 139) and an intracellular redox sensor, WhiB3, which controls the switchover from glucose to fatty acids (Refs 10, 140, 141), should give important information on how a persistent infection is established using fatty acids as a source of carbon.

The amount of fatty acids and lipids available for Mtb growth in vivo (g/l) considerably exceeds that of obtainable carbohydrates (Ref. 66). Lipids can be oxidised by β-oxidation to yield valuable ATP and

Hypoxia in the lung

It is widely accepted that oxygen depletion facilitates entry of Mtb into the nonreplicating persistent state. Within the lung, regional differences exist in ventilation and perfusion, and in the degree of blood oxygenation. In a seminal study using resected lung tissue, lesions classified as ‘open’ (oxygen rich) were found to contain actively growing, predominantly drug-resistant bacteria, whereas bacilli isolated from ‘closed’ (oxygen poor) lesions showed delayed growth and were drug sensitive (Ref. 131). This observation suggests that Mtb drug resistance could be due to the physiological heterogeneity of the bacilli caused by regional differences in O2 levels. In agreement with this is the recent evidence suggesting that granulomas can be caseous, non-necrotising or fibrotic, sometimes within the same individual (Ref. 55), which is also supported by in vitro studies demonstrating that anaerobically exposed Mtb is a poor target for antimycobacterial drugs (Ref. 132).

High O2 tension exists in the upper lung, whereas the ventral lung experiences low O2 tension (Refs 133, 134). Consistent with anatomy and function, the partial O2 pressure (pO2) of atmospheric O2 (~150–160 mmHg) drops in the lungs (60–150 mmHg), spleen (~16 mmHg) (Ref. 53) and thymus (10 mmHg) (Refs 57, 135, 136). The diffusion distance of O2 is ∼100–200 μm, resulting in a pO2 of zero within this distance from blood vessels. Using redox-active dyes that are reduced at pO2 lower than 10 mmHg, studies in guinea pigs and monkeys have shown that the granulomas are indeed hypoxic (Ref. 53). Notably, Mtb is an obligate aerobe but has evolved as yet undefined mechanisms to survive within this hypoxic and perhaps anaerobic environment. Furthermore, O2 is a highly diffusible gas, and despite the remarkable difference in pO2 pressure between the granuloma (1.59 mmHg) and adjacent tissue (Refs 57, 53), it is not yet known how this pressure differential is maintained (Fig. 2).

The environment of the lung

The human lung is the primary organ involved in uptake of atmospheric O2 and is therefore naturally susceptible to oxidative damage because of its function. ROS production in the lung is further enhanced on exposure to exogenous oxidants such as tobacco smoke, diesel exhaust, ozone and nitrogen oxides. Antioxidants of the lungs include GSH, ascorbate, β-carotene, albumin-SH, mucus, uric acid, SODs, catalases and peroxidases (Ref. 129). The high concentration of GSH in the extracellular lining fluid (>400 μM) suggests that glutathione is a vital component of the defence mechanism against oxidant damage (Ref. 130). Not surprisingly, cigarette smoke was shown to significantly affect Cys/CySS and GSSG/GSH ratios, suggesting an imbalance in thiol homeostasis (Ref. 130).

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Effect of exogenous environmental and endogenous host redox factors on the pathogenesis of TB

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Figure 2. Effect of exogenous environmental and endogenous host redox factors on the pathogenesis of TB.

Infectious Mycobacterium tuberculosis (Mtb) bacilli are inhaled as aerosols from the atmosphere and phagocytosed by alveolar macrophages in the lung. A localised proinflammatory immune response causes the recruitment of mononuclear cells, leading to the establishment of a granuloma. However, Mtb cells are also present in lesion-free tissue. During the course of infection, caseous (typically hypoxic), fibrotic and non-necrotic granulomas can develop. The containment of Mtb by these granulomas never operates in isolation, and can fail as a consequence of malnutrition, diabetes, indoor air pollution, tobacco smoke and HIV infection, which are major risk factors for TB. Thus, any condition that weakens the immune status (in particular, a decrease in the function of CD4+ T cells) of the host can lead to TB. Exogenous environmental pollutants, which consist largely of redox-active molecules, not only affect the host immune response, but also target the infecting bacilli. Exposure to these environmental agents, production of host redox molecules such as O₂⁻, NO, ONOO⁻, etc. that are generated during the oxidative burst, and the pathological and physiological host responses induced on infection (e.g. hypoxic granuloma, dysregulated host lipid production) can collectively cause an imbalance in Mtb redox homeostasis, leading to oxidative stress or damage. Conversely, exogenous factors and the dysregulation of endogenous host redox factors might lead to the establishment of Mtb infection, maintaining a persistent state or allowing the bacillus to emerge from persistence. Dormant Mtb cells residing inside hypoxic granulomas are resistant to current antimycobacterial drugs and therefore have substantial implications on therapeutic intervention strategies. Moreover, the dynamic physiology and structure of the lung further complicate the situation because no two regions inside the lungs are similar in terms of their architecture and oxygen tension. This also makes it extremely difficult to study the progression of TB using animal models. Inside the lung, Mtb cells are exposed during transmission to a range of oxygen levels that varies from 150 to 180 mmHg in the upper respiratory tract to 1.9 mmHg within the granuloma, compared with pO₂ levels of healthy lungs (~59 mmHg). In addition, host pH and the type of in vivo carbon source, along with its concentration, will also have an impact on Mtb redox homeostasis. Nonetheless, it is still not clear how exposure of Mtb to these exogenous and endogenous redox molecules affects Mtb physiology and redox homeostasis in vivo to favour disease.
acetyl-CoA. Because the COS of fatty acids is highly reduced, substantial quantities of reducing equivalents [NAD(P)H] will be generated during β-oxidation, which must be dissipated to maintain intracellular equilibrium. This begs the question: does Mtb experience ‘reductive stress’ (Ref. 54) during its in vivo growth, and if so, how is that stress dissipated? The serendipitous discovery that Mtb NAD(P)⁺/NAD(P)H present in infected lungs of mice predominantly exists in the reduced [NAD(P)H] state (Ref. 63) provides strong evidence that Mtb experiences substantial reductive stress during infection (for a review, see Ref. 54). Furthermore, recent findings have suggested a role for Mtb WhiB3 in the modulation and dissipation of reductive stress (Ref. 140), which implicates host fatty acids as a source of reductive stress, and perhaps a signal acting synergistically with hypoxia, NO and CO to modify the course of infection. Recently, Mtb TAG, which is under control of the Dos dormancy regulon and WhiB3, was suggested to be a source of carbon and energy when the bacilli emerge from a latent state (Ref. 64). Finally, studies have shown that cholesterol can also be used as a carbon source during infection (Ref. 142).

Mtb redox-sensing mechanisms: model paradigms

Although Mtb contains 11 paired two-component signalling systems and ~180 regulatory proteins, only a few proteins have been shown to directly react with NO, CO or O₂, and the downstream effects of these interactions are mostly unexplored. Nonetheless, in recent years the DosR–S/T two-component haem sensor system and the intracellular WhiB Fe–S cluster family of proteins, particularly WhiB3 (Refs 9, 10), have emerged as model signalling pathways that specifically respond to these gases.

The DosR/S/T dormancy regulon

The DosR/S/T (Dos) dormancy system [first reported as the DevR/S system (Ref. 143)] is a ‘three-component’ system capable of integrating two haem histidine kinase sensors (DosS and DosT) with a single response regulator, DosR. The Dos system has been implicated in virulence and is probably the most characterised system in Mtb. An identical overlap exists between the gene expression profiles of Mtb cells treated with NO or CO, and when cultured under low O₂ conditions (Wayne model for in vitro dormancy) (Refs 9, 144, 145, 146). The Dos regulon comprises ~47 genes thought to have crucial roles in the metabolic shift of Mtb to the persistent state (Refs 60, 147). Several of these genes are speculated to have a role in adaptation to hypoxic stress, such as acr (rv2031c; chaperone function), narX (rv1736c; unknown function), narK2 (rv1737c; nitrate/nitrite transport), fdxA (rv2007c; ferredoxin), nrdZ (rv0570; ribonuclease reductase), tgs1 (rv3130; triglyceride synthase) and Mtb orthologues of the universal stress protein family (rv1996, rv2005c, rv2028c, rv2623, rv2624c, rv3134c) (Ref. 148).

A key finding was the discovery that DosS and DosT are haem proteins that can be oxidised by O₂ or can directly bind NO and/or O₂ through their haem irons (Refs 9, 149, 150). The discovery that CO directly binds the haem irons of DosS and DosT, induces the Dos dormancy regulon (Refs 144, 146), and is produced at the site of Mtb infection has profound implications for the importance of CO generated by host haem oxygogenase I (HO-1) in Mtb pathogenesis. A role for environmental CO in TB was described as early as 1923 (Ref. 151) and has been recently discussed in more detail (Ref. 152). The induction of the identical genetic expression profile in response to three diatomic gases (O₂, NO and CO) is an unparalleled finding in bacteriology, and suggests that Mtb has evolved an exquisite sensory system to allow the bacilli to continuously monitor and counter the effects of host NO, CO and O₂ levels during the course of infection (Fig. 3).

The survival of Mtb under hypoxic conditions depends on many factors in general and oxidative phosphorylation in particular. By contrast, it was shown that the NAD⁺/NADH ratio in the hypoxic Wayne model remained comparable to aerobic cultured cells (Ref. 60). This is an unusual finding because this ratio in bacteria typically decreases with a diminished O₂ concentration. As expected, ATP levels decrease under hypoxia (Ref. 60), but are then maintained at a constant low level. Any further reduction in the ATP levels led to rapid death of Mtb (Ref. 61).

Although the clinical role and significance of the Dos regulon in human TB is yet to be established, an indication of its clinical relevance emerges by its ~50-fold overexpression in Mtb Beijing (W2) clinical strains (Ref. 153) and the
strong immune responsiveness of latently infected patients to the DosR regulon antigens (Refs 154, 155). In addition, the Dos regulon genes have been shown to be upregulated in sputum (Ref. 156) and in adipose tissue (Ref. 157) of Mtb-infected individuals.
WhiB3 and redox homeostasis

It is known that *Mtb* survives a constant threat of redox stress either as a consequence of its aerobic metabolism or as infliction by the host to prevent the establishment of a successful infection. The nondividing persistent state of *Mtb* is attributable mainly to hypoxia, wherein mycobacteria adapt to low oxygen pressures by transcriptional regulatory networks that function to maintain redox homeostasis. Identification of such mechanisms allowing mycobacteria to counter oxidoreductive stress during infection, latency and reactivation is central to the development of effective intervention strategies.

The WhiB-like proteins are found in actinomycetes, and virtually all members of this family contain four conserved Cys residues that coordinate the Fe–S cluster. WhiB orthologues have been implicated in sporulation in *Streptomyces coelicolor* (Ref. 158), in pathogenesis and cell division in mycobacteria (Refs 140, 141, 159, 160), in oxidative stress in *Corynebacterium glutamicum* (Ref. 161), and in antibiotic resistance in mycobacteria and streptomycyces (Ref. 162). However, the mechanistic basis for how these WhiB homologues sense and respond to endogenous and exogenous signals to exert their effect is not known. A comprehensive study examining the expression profiles of all seven *Mtb* whiB genes (*whiB1–whiB7*) after exposure to antibiotic and in vitro stress conditions provides insight into the biological function of the WhiB family (Ref. 163).

*Mtb* WhiB3, a homologue of a putative sporulation transcription factor in *Streptomyces*, has a role in virulence in mice and guinea pigs (Ref. 141), and was shown to contain a (4Fe–4S) cluster that directly associates with NO and is degraded by O₂ (Ref. 10). It was also proposed that *Mtb* WhiB3 senses changes in the intracellular redox environment associated with O₂ depletion and the metabolic switchover to the preferred in vivo carbon source, fatty acids (Ref. 10). Several lines of evidence (Refs 10, 140) suggest that WhiB3 is involved in maintaining redox homeostasis through its 4Fe–4S cluster by regulating catabolic metabolism and polyketide biosynthesis in *Mtb*. This has important implications for understanding how *Mtb* persists within the host, because it is widely accepted that fatty acids serve as a major source of carbon and energy in chronic infection. It was also shown that WhiB3 induces a metabolic shift that differentially modulates the assimilation of propionate into the complex virulence polyketides polyacyltrehaloses, sulfolipids, plthiocerol dimycocerosates and the storage lipid TAG in defined oxidising and reducing environments (Ref. 140) (Fig. 3). What seems to be emerging is a link between *Mtb* virulence lipid production and the response to oxidoreductive stress (Ref. 10). Because TAG production, which is under conditional WhiB3 control, is also induced on exposure to NO, CO and hypoxia through the Dos dormancy system (Refs 147, 164, 165), these data establish a novel link between an intracellular (WhiB3) and extracellular (Dos) signalling pathway.

Future challenges and conclusions

Redox reactions in the microbial cell have key roles in intracellular and extracellular signalling, DNA, RNA and protein synthesis, energy production and metabolic homeostasis. However, to date, we lack knowledge on the intracellular *Mtb* redox environment, the identity of all main redox couples and buffers, the behaviour of these redox couples under different environmental conditions, and the mechanisms of sustained redox homeostasis in *Mtb*. In particular, a fundamental challenge in the oxidative stress biology of *Mtb* is to understand how carbonyl, nitrosative and oxidative stress modulate *Mtb* pathogenesis. Using genome-wide tools, it is important to refine our understanding of the *Mtb* ‘redoxome’. It should be possible to generate numerical indicators of the intracellular *Mtb* redox environment, the redox state of each redox pair, and determine how these indicators change on exposure to various environmental signals, particularly NO, O₂ and CO. Noninvasive technology such as the redox-sensitive green fluorescent protein (Ref. 166) can serve as a novel tool to explore global intracellular redox status and should be exploited to examine these changes in *Mtb* during infection. An important issue is the identification of the major redox couples and buffers in *Mtb*, and to ascertain their roles in pathogenesis and drug resistance. Is MSSM/2MSH the major redox buffer in *Mtb*? What is the function of ERGox/ERGred in redox homeostasis? Presently, the ERGox/ERGred redox couple is an understudied system, but it might have important implications for maintaining redox homeostasis and in disease progression.
Another particularly interesting and unexplored area is the link between redox homeostasis and drug efficacy. For example, the identity of redox couples that participate in the bioreductive activation of antimycobacterial prodrugs (e.g. INH, ETH and PA-824) and an understanding of the underlying mechanisms involved will have a major impact on drug development strategies. Although some progress has been made in this field (Ref. 7), our knowledge remains sparse. Proper treatment of latent Mtb infection requires a more precise understanding of the true physiological status of Mtb within the microenvironment of the host, for example the granuloma. Lase-capture microdissection combined with mass spectroscopy and RNA amplification strategies could be exploited to quantitatively catalogue host and bacterial proteins, lipids and metabolites within granulomas. This would help to define what a true dormant bacillus is, and how we differentiate ‘dead’ from ‘live’ dormant bacilli. Recently, progress has been made in this regard, and stochastic Mtb phenotypes have been identified as a possible mycobacterial strategy to rapidly adjust to changing in vivo conditions (Ref. 167).

A fundamentally important subject to be addressed is the extent of Mtb respiration within a hypoxic granuloma. Do fully anaerobic granulomas exist? Identification of the terminal electron acceptors used, and determination of the mechanisms of NAD(P)H electron acceptors used, and determination of the redox state of Mtb within the microenvironment of the host, for example the granuloma. Lase-capture microdissection combined with mass spectroscopy and RNA amplification strategies could be exploited to quantitatively catalogue host and bacterial proteins, lipids and metabolites within granulomas. This would help to define what a true dormant bacillus is, and how we differentiate ‘dead’ from ‘live’ dormant bacilli. Recently, progress has been made in this regard, and stochastic Mtb phenotypes have been identified as a possible mycobacterial strategy to rapidly adjust to changing in vivo conditions (Ref. 167).

A fundamentally important subject to be addressed is the extent of Mtb respiration within a hypoxic granuloma. Do fully anaerobic granulomas exist? Identification of the terminal electron acceptors used, and determination of the mechanisms of NAD(P)H+ regeneration used under hypoxic (and perhaps anaerobic) conditions are crucial to understanding TB pathogenesis. An attractive hypothesis is that Mtb resides within a spectrum of aerobic, hypoxic and anaerobic microenvironments in the lungs (Ref. 55), which in theory can explain the capacity of dormant bacilli to tolerate chemotherapy. Other important areas to study include the mechanisms of how pO2 levels are maintained in these microenvironments and the independent or combined roles of NO, CO and O2 in Mtb persistence.

Although it is likely that the preferred in vivo carbon source for Mtb includes fatty acids or cholesterol, conclusive experimental evidence in vivo is still lacking. The use of labelled fatty acids in in vivo studies should allow us to identify metabolic pathways that are specifically geared towards in vivo growth and survival. Similar studies will also shed light on Mtb reductive stress (Ref. 54) in vivo, and whether it impacts the course of human TB. Furthermore, the role of H2 as an energy source has been reported for other infectious agents (Ref. 168), but is an unexplored area for Mtb pathogenesis. Interestingly, because the oxidation of H2 generates protons, some bacteria use it to dispose of excess reducing equivalents (Ref. 169). Study of the impact of complex host risk factors for TB such as tobacco smoke, indoor air pollution, malnutrition and diabetes on the bacilli by exploiting metabolomics, proteomics and microarray analyses will have broad public health and socioeconomic implications.

In conclusion, a fundamental challenge faced by investigators is the translation of their combined research findings into novel in vitro and in vivo experimental tools and ultimately into successful TB intervention and control strategies. This will dictate the success of ongoing and future efforts to combat the unrelenting threat of TB.

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Redox homeostasis in mycobacteria: the key to tuberculosis control?


This is a comprehensive review paper that describes the role of reductive stress in mycobacteria.


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This outstanding review describes the chemical basis and mechanism of action of mycothiol biosynthetic enzymes.


This article describes the role of the *M. tuberculosis* intracellular redox sensor WhiB3 in the redox-mediated regulation of complex virulence lipids. The concept of reductive stress emerged from these findings.


This article demonstrates that haem oxygenase (HO-1)-derived CO produced by macrophages is primarily sensed by DosS, and to a lesser extent by DosT, to induce the *Mtb Dos* dormancy program. The identification of host-generated CO as a third in vitro dormancy signal is a major contribution towards understanding the mechanism of signal sensing and represents a hitherto unexplored area of mycobacterial research.


This article links mycobacterial metabolism with the redox signalling molecules NO and O2 through the *M. tuberculosis* WhiB3 [4Fe–4S] cluster. Importantly, WhiB3 was shown to function as an intracellular redox sensor involved in the metabolic switchover to the preferred in vivo carbon source, fatty acids.

Kumar, A. et al. (2007) *Mycobacterium tuberculosis* DosS is a redox sensor and DosT is a hypoxia sensor. Proceedings of the National Academy of Sciences of the United States of America 104, 11568–11573

This is the first report demonstrating that the *M. tuberculosis* haem proteins DosS and DosT sense CO. The paper also describes the mechanisms of how O2, NO and CO affects DosS and DosT autokinase activity.

Features associated with this article

Figures

- Figure 1. Virulence life cycle of *Mycobacterium tuberculosis* and progression of TB.
- Figure 2. Effect of exogenous environmental and endogenous host redox factors on the pathogenesis of TB.
- Figure 3. Mycobacterial mechanisms of sensing and countering endogenous or exogenous stress.

Table

- Table 1. Standard reduction potentials of biologically relevant redox couples.

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