Inhibition of Respiration by Nitric Oxide Induces a Mycobacterium tuberculosis Dormancy Program

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Abstract

An estimated two billion persons are latently infected with Mycobacterium tuberculosis. The host factors that initiate and maintain this latent state and the mechanisms by which M. tuberculosis survives within latent lesions are compelling but unanswered questions. One such host factor may be nitric oxide (NO), a product of activated macrophages that exhibits antimycobacterial properties. Evidence for the possible significance of NO comes from murine models of tuberculosis showing progressive infection in animals unable to produce the inducible isoform of NO synthase and in animals treated with a NO synthase inhibitor. Here, we show that O2 and low, nontoxic concentrations of NO competitively modulate the expression of a 48-gene regulon, which is expressed in vivo and prepares bacilli for survival during long periods of in vitro dormancy. NO was found to reversibly inhibit aerobic respiration and growth. A heme-containing enzyme, possibly the terminal oxidase in the respiratory pathway, likely senses and integrates NO and O2 levels and signals the regulon. These data lead to a model postulating that, within granulomas, inhibition of respiration by NO production and O2 limitation constrains M. tuberculosis replication rates in persons with latent tuberculosis.

Key words: M. tuberculosis • latency • nitric oxide • cytochrome oxidase • microarray

Introduction

Current clinical models of tuberculosis postulate a three-stage pathogenic sequence. Inhalation of an infectious aerosol begins the process leading to unimpeded replication of Mycobacterium tuberculosis in alveolar macrophages. The onset of cell-mediated immunity causes bacteriostasis and initiates a period of bacterial persistence in the granulomatous lesions of asymptomatic hosts. Finally, in ~10% of infected hosts, declining immune competence permits resumption of bacterial replication leading to overt disease. The second of these stages, clinical latency, is of surpassing importance for the epidemiology and control of tuberculosis. An estimated one-third of the world’s population is latently infected (1) and most active cases of tuberculosis arise from this vast reservoir. The eradication of bacilli in latent lesions by antimicrobials is notoriously inefficient.

Little is known about the nature of the persistent state in vivo or the host factors that induce and maintain it. Control of bacterial replication in murine models of latency requires interferon-γ, tumor necrosis factor-α, and nitric oxide (NO; reference 2). Long-term survival in the murine lung requires that M. tuberculosis express isocitrate lyase (3), and in vitro studies show that a persistent or dormant state can be generated by nutrient deprivation (4) and O2 depletion (5). Of these, O2 depletion has been the most comprehensively studied. Furthermore, it provides a mechanistic link between the pathology of latent lesions in humans (which are often in avascular or poorly aerated foci of the lung)

The online version of this article includes supplemental material.

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Abbreviations used in this paper: CcO, cytochrome c oxidase; DETA/NO, diethylenetriamine/nitric oxide adduct; DosR, dormancy survival regulator; GSNO, nitrosoglutathione; NO, nitric oxide; qRT, quantitative real-time reverse transcriptase.

705 J. Exp. Med. © The Rockefeller University 2003
Volume 198, Number 5, September 1, 2003
http://www.jem.org/cgi/doi/10.1084/jem.20030205

Supplemental material can be found at http://doi.org/10.1084/jem.20030205
and the capacity of *M. tuberculosis* to adapt to hypoxic conditions. Seminal studies by L.G. Wayne et al. (5) with an in vitro O$_2$ depletion model of latency demonstrate the following. A gradual depletion of O$_2$ leads to a nonreplicating persistent state characterized by bacteriostasis and metabolic, chromosomal, and structural changes of the dormant bacteria. Further reductions in O$_2$ tension lead to a more quiescent state, characterized in part by the onset of sensitivity to metronidazole and resistance to other antimicrobials. Provision of O$_2$, even after long periods of hypoxia-induced bacteriostasis, results in resuscitation of the dormant bacteria.

In this work, we have focused on NO as an immune factor that could restrain mycobacterial replication rates in vivo and play a role, in conjunction with low tissue concentrations of O$_2$, in the initiation and maintenance of the latent state. NO from activated murine macrophages or exogenous sources exhibits antimycobacterial properties, and can irreversibly damage bacteria (6). However, NO also acts as a potent reversible inhibitor of aerobic respiration in mitochondria and in bacteria (7) and is a versatile signaling agent in eukaryotic systems (8). In view of these properties, we designed experiments to test the hypothesis that NO controls *M. tuberculosis* growth by inhibiting aerobic respiration. During the course of these studies, we corroborated this hypothesis and, in addition, showed that NO induces an *M. tuberculosis* genetic program that is expressed in vivo and adapts the organism for survival during extended periods of in vitro dormancy.

**Materials and Methods**

**Culture Conditions.** Clinical isolate 1254, H9 medium (supplemented with BSA, NaCl, glucose, and glycerol), 250-ml vented tissue culture flasks, 90 rpm shaking, and a starting culture density of OD 0.15 were used, unless otherwise indicated. RNA samples isolated from OD 0.15 cultures of the *M. tuberculosis* strain being assayed on the same day were used for the reference sample in each experiment. Cells were collected with a 4-min centrifugation step and frozen on dry ice.

**RNA Isolation.** Cell pellets were suspended in 1 ml TRIzol reagent (GIBCO BRL) and transferred to 2-ml screw cap tubes containing 0.5 ml 0.1-mm diameter zirconia/silica beads (Bio-Spec Products). Three 30-s pulses in a bead beater disrupted cells. Cell debris was separated by a 45-s centrifugation. The supernatant was transferred to 2-ml Heavy Phase Lock Gel I tubes (Eppendorf) containing 300 µl chloroform, inverted rapidly for 15 s, and incubated 2 min. Samples were centrifuged for 5 min, and the aqueous phase was added to 270 µl isopropanol, followed by addition of 270 µl of the following mixture: 0.8 M sodium citrate and 1.2 M NaCl. Samples were incubated for 10 min at 4°C and centrifuged for 15 min at 4°C. The RNA pellets were washed with 1 ml 75% ethanol, centrifuged 5 min, and air-dried. After suspension of the RNA pellets in 90 µl water, 10 µl DNase I 10× buffer, and 6 U DNase I (Ambion) were added, and the samples were incubated for 30 min. Final purification of RNA was by RNeasy column (QIAGEN).

For the murine infection experiments, groups of 15 6–8-wk-old C57BL/6 mice were infected by the low dose aerosol method (87 cfu) with the wild-type H37Rv strain of *M. tuberculosis*. 21 d later, the mice were killed, and lung tissue was obtained for quantitative culture and RNA. Viable plate counts were conducted with serial dilutions of the left lung homogenized in PBS/0.5% NP-40, plated onto 7H10 agar, and incubated at 37°C. Colonies were counted 2–3 wk after inoculation, giving a value of 2.8 × 10$^6$ cfu of *M. tuberculosis* per lung. Quantitative cultures at later time points (6, 12, and 21 wk) showed a persistent steady-state infection with viable plate counts averaging 5.8 × 10$^5$ cfu/lung. For the preparation of RNA, mouse lungs were ground with a tissue homogenizer in a mixture of phenol, chloroform, and guanidine thiocyanate, and RNA was isolated as described in the previous paragraph.

**cDNA Labeling and Microarray Hybridization.** Both a PCR gene product microarray and a 70-mer oligonucleotide-based microarray (tuberculosis oligonucleotide set; QIAGEN) were used. Labeled cDNA was prepared as follows: 2 µg total RNA and 4.4 µg of random oligonucleotide hexamers were incubated for 2 min at 98°C, cooled on ice, combined with Stratascript RTase buffer, 0.5 mM dA,G,CTP, 0.02 mM dTTP, 1.5 nmol Cy3 or Cy5-dUTP (Amersham Biosciences), and 1.8 µl Stratascript RTase (Stratagene) in a total volume of 25 µl, and incubated for 10 min at 25°C and 90 min at 42°C. cDNA was purified by microcon-10 (Amicon) filtration, 10 µl of hybridization solution (labeled cDNA, 5 µg tRNA, 3.8× SSC, 0.27% SDS) was sealed under a coverslip with rubber cement and hybridized overnight at 56°C for the DNA microarray. Oligonucleotide microarrays were first prehybridized for 1 h in 5× SSC, 1% BSA, and 0.1% SDS and washed with H$_2$O and isopropanol. After the prehybridization, 10 µl of hybridization solution (labeled cDNA, 5 µg tRNA, 2× SSC, 25% formamide, and 0.1% SDS) was hybridized overnight at 54°C.

**Data Analysis.** Microarrays were scanned using a GenePix 4000A (Axon Instruments, Inc.). The intensities of the two dyes at each spot were quantified using Scanalyze (M. Eisen, Lawrence Berkeley National Lab, Berkeley, CA). All gene-specific spots on the microarray other than those whose induction ratio was in the top or bottom 5% were used to normalize the intensities of Cy3 and Cy5 from each spot. After Cy3 and Cy5 channel normalization, we eliminated large percentage fluctuation in low background spot values by adjusting low signal intensity spots to a minimum noise value. The noise value for each channel was determined by calculating the average intensity value for the 20% lowest intensity spots, and every value below this average noise value was raised to the noise value. Microarray-determined ratios were calculated from three biological replicates and two microarrays for each biological replicate, except for Fig. 2 (A and B), where data was from two biological replicates and four microarrays (8a).

**Online Supplemental Material.** Table S1 includes induction ratios for dormancy regulon genes after exposure of wild-type and mutant *M. tuberculosis* strains to NO, hypoxia, and 4 d into the low O2–induced dormancy model of latency. Fig. S1 illustrates that growth of the Rx3134c dormancy regulon mutant and its parent were equally impaired in growth after NO exposure. The online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20030205/DC1.

**Results**

**Low (Nontoxic) Concentrations of NO Signal *M. tuberculosis* to Induce a Set of 48 Genes.** Microarray expression profiling was used to capture the transcriptional response of *M. tuberculosis* to low and high concentrations of NO.
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...50-μM pulse of diethylenetriamine/nitric oxide adduct (DETA/NO) generated nanomolar concentrations of NO and rapidly induced a set of 48 genes (Fig. 1; and Fig. 2, A and B). The expression kinetics of all the 48 genes appears to be the same. Time course studies showed that induction of the genes was rapid with accumulated mRNA detectable by microarray within 5 min of NO exposure. As NO dissipated from the reaction vessel, expression levels declined to basal levels (Fig. 2 B; and see Fig. 4 B). An additional low dose pulse of DETA/NO elicited renewed induction, indicating that exposure to low concentrations of NO does not diminish the response to a subsequent dose (Fig. 2 B). This NO-induced gene set was also up-regulated 13.2 ± 3.6-fold by 0.5 mM of the nitrosothiol compound, nitrosoglutathione (GSNO). However, when coincubated with 1 mM carboxy-PTIO, a NO-specific trap, induction of the NO-responsive genes by GSNO was prevented, showing that gene induction was not due to S-nitrosation via GSNO, but rather to NO release from GSNO. None of the genes induced by low concentrations of NO (Fig. 1) was found to be regulated by several other in vitro conditions believed to simulate the intraphagosomal environment of the macrophage, including oxidative stress (0.05–200 mM H$_2$O$_2$), low iron (9), and nutrient deprivation (4) or exposure to the detergent sodium dodecyl sulfate (10). These data, and the absence of desensitization to repeated doses of NO, show that the induction of these genes by low concentrations of NO is not part of a general stress response. By contrast, exposure of M. tuberculosis to high concentrations of NO, generated by 1 mM pulse of DETA/NO, induces 400 genes (Fig. 2 A). Thus, higher concentrations of NO cause a pleiotropic reaction, including an oxidative stress response, which is fundamentally different than the circumscribed induction of 48 genes by low concentrations of NO. Genes induced by high concentrations of NO that are responsible for oxidative stress defense include katG (catalase), ahpC (alkyl hydroperoxide reductase), trxC (thioredoxin), trxB2 (thioredoxin reductase), and sigB and sigH, which code for two alternative sigma factors. Microarray expression–derived induction values provide a relative measure of transcript abundance. Therefore, quantitative real-time reverse transcriptase PCR (qRT-PCR) was used to measure the induction magnitude of five sentinel NO-induced genes after exposure to low concentrations of NO. Induction ratios ranged from 2,000 to 15,000 (Fig. 2 C) and mRNA levels reached up to 140 times the highly transcribed sigA control transcript.

**Figure 1.** Dormancy regulon. Comparison of microarray expression results from M. tuberculosis strain 1254 exposed for 40 min to 50 μM of the NO donor DETA/NO (NO), and strain H37Rv exposed for 2 h to 0.2% O$_2$ (hypoxia-HYP) and at day 4 during the gradual adaptation, to low O$_2$ as described previously (11), resulting in an in vitro dormant state (DOR). DNA microarrays were used for the NO and low O$_2$ experiments, whereas oligonucleotide microarrays were used for the DOR experiments. (A) All M. tuberculosis genes are represented and organized based on their regulatory profile by average linkage clustering, using the Cluster andTreeView programs. Red indicates induced, green indicates repressed, and black indicates no change in gene expression. (B) The initial selection of genes in the dormancy regulon was based on their induction by NO, low O$_2$, and adaptation to an in vitro dormant state, as well as their failure to be induced in the presence of KCN (see Fig. 3 A). Rv numbers designate genes in genomic order, and arrows indicate transcript direction. Annotations are from TubercuList (http://genolist.pasteur.fr/TubercuList; reference 34). CHP and HP indicate conserved hypothetical and hypothetical proteins.
previously to be induced in hypoxic cultures provided with a continuous supply of 0.2% O₂ in the head space gas (12). Thus, low concentrations of NO, entry into the low O₂–induced in vitro dormant state or cultivation in hypoxic cultures induce a common set of 48 genes. The 48 genes induced by NO, dormancy, and hypoxia are not distributed randomly across the chromosome, but are clustered in nine discrete modules (Fig. 1). Seven of these modules contain contiguous genes, whose orientations indicate the presence of multiple transcription units, an arrangement suggestive of a supra-operonic organization that might facilitate a rapid, pronounced, and coordinated transcriptional response.

In Vivo Gene Expression of the NO/Dormancy/Hypoxia-induced Response. To determine if this gene set is also expressed within infected tissue, C57BL/6 mice were killed 21 d after aerosol infection with M. tuberculosis, and total RNA from lung tissue was assayed by qRT-PCR. During infection, M. tuberculosis highly expressed each of five sentinel genes from the group of 48 genes (Fig. 2 C). In a separate paper focused on the transcriptional response of M. tuberculosis in the macrophage phagosome, Schnappinger et al. confirmed that the five dormancy genes depicted in Fig. 2 C were highly expressed in mouse lung 21 d after infection and showed, in addition, that they remained expressed at high levels 56 d after infection (13). These in vivo results and the selective induction of these genes by NO and hypoxia provide compelling evidence that M. tuberculosis encounters one or both of these conditions during the course of infection in the murine lung. This idea is further supported by the studies of Schnappinger et al. with primary bone marrow–derived murine macrophages showing that most genes in the NO/dormancy/hypoxia gene set are strongly induced by M. tuberculosis within INFγ-activated macrophages from wild-type mice, but not by M. tuberculosis in activated macrophages from inducible nitric oxide synthase knockout (NOS2−/−) mice (13). Thus, in the intraphagosomal environment of the INFγ-activated macrophage, the induction of these genes is NO dependent. This interpretation of these data is also supported by a recent work by Shi et al. showing that expression of three dormancy genes (acr, Rv2623, and Rv2626c) within M. tuberculosis–infected murine lungs is delayed in INFγ−/− mice compared with wild-type mice (14). Because NOS2 was not detected in the INFγ−/− mice, in contrast to wild-type mice, the delayed induction of the three genes in the INFγ−/− mice might be due to NO generated by endothelial NO synthase (15) and/or to localized areas of hypoxia resulting from inflammation. This paper also demonstrates that these genes are not expressed early in infection (days 10–12) and that expression commences by days 15–18 after infection, coincident with activation of the immune system and slowing of bacterial growth.

Two observations suggest that these conditions might also prevail in M. tuberculosis–infected human lungs. First, analysis of human tuberculosis granulomas demonstrates elevated levels of inducible and endothelial NO synthases as well as nitrotyrosine, an indicator of the presence of NO (15). Second, 85% of tuberculosis patients have antibodies to the protein encoded by acr, a NO/dormancy/hypoxia-induced gene (Fig. 1 B; reference 16).
The 48-gene NO/Dormancy/Hypoxia Response Defines the Dormancy Regulon. The two-component response regulator, dormancy survival regulator (DosR) encoded by Rv3134c, but not a sensor histidine kinase encoded by the adjacent gene Rv3132c, is required for induction of arco by hypoxia (12, 17). Microarray expression profiling was used to determine if DosR also regulates the NO/dormancy/hypoxia-induced gene set. Inactivation of Rv3134c, the first gene of a presumed three-gene operon (composed of Rv3134c, dosR, and R/Rv3132c; reference 12), fully or partially reduced induction of each of the 48 genes in response to NO and during adaptation to the low O2-induced dormant state. Complementation of the mutant with Rv3134c/dosR largely restored this effect (Table S1, available at http://www.jem.org/cgi/content/full/jem.20030205/DC1). We have demonstrated recently that hypoxia fails to induce any of the 48 genes when dosR is selectively disrupted (18). Thus, the capacity of NO or low O2 to partially induce some of the genes in the Rv3134c mutant was likely due to a low level of dosR expression by this strain. Together, these results show that NO, hypoxia, and adaptation to an in vitro dormant state induce a common set of 48 genes and do so via DosR. In view of these results and evidence that a DosR binding site is present in the upstream promoter regions of several NO/dormancy/hypoxia-induced genes (18), we designate the gene set listed in Fig. 1 B the “dormancy regulon”.

To determine if the dormancy regulon contributes to the survival of M. tuberculosis during the in vitro dormant state, we compared the viability of the wild-type parent with the Rv3134c mutant during the adaptive phase and after 40 and 50 d in the low O2–induced dormant state (11). The dormancy regulon mutant grew to the same level as the wild-type strain during the initial adaptive phase after O2 limitation (Fig. 3). After 40–50 d of oxygen limitation, 200-fold more wild-type bacteria were recovered compared with the dormancy regulon mutant (Fig. 3). The experiment demonstrating the survival phenotype of the Rv3134c mutant (Fig. 3) did not include the use of the complemented strain. Thus, in principle, this phenotype could have resulted from an unintended effect of this mutation. However, disruption of dosR in the nonpathogenic bacillus Calmette-Guerin vaccine strain of M. bovis was recently shown to yield a mutant with a 1,500-fold reduced survival phenotype during the low O2–induced dormant state. Complementation of this mutant with a wild-type copy of dosR restored the survival phenotype of the parent strain (17). Together, these data show that the dormancy regulon increases the fitness of M. tuberculosis in an in vitro model of clinical latency.

Inhibition of Respiration and Growth by NO. Aerobic respiration declines and stops as O2 levels fall during adap-
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Figure 5. Competition between O2 and NO for heme-containing protein. (A) Average linkage clustering comparison of expression data from all M. tuberculosis genes after a 40-min exposure to 50 μM DETA/NO, 50 μM KCN, KCN plus DETA/NO, 2-h hypoxia, and 500 μM KCN plus 2-h hypoxia. (B) Competition between NO and O2 for control of dormancy regulon expression. DETA/NO was added to a 300-ml culture stirring at 100 rpm for low aeration and maximum rpm for high aeration. Induction of the regulon was assayed by DNA microarray after 40 min NO exposure.

To determine if concentrations of NO that cause growth arrest, dormancy regulon induction, and respiratory inhibition are bacteriostatic or bacteriocidal, viable plate counts were obtained after exposure of M. tuberculosis strain are equally impaired in growth immediately after being exposed to NO. This indicates that the initial growth arrest by NO does not require full induction of the dormancy regulon, but instead is most likely due to respiratory inhibition after NO exposure (Fig. S1, available at http://www.jem.org/cgi/content/full/jem.20030205/DC1).

Because both NO and low O2 induce dormancy regulon expression, we investigated whether the presence of NO and the absence of O2 are sensed by the same molecular sensor. First, we determined if NO could competitively inhibit NO-mediated induction of the dormancy regulon. Gene induction was assayed by microarray expression profiling after exposing M. tuberculosis, growing in high or low aerated cultures, to different concentrations of NO. In this experiment, aeration was controlled by culture stirring speed; therefore, in addition to the degree of aeration, it is possible that other factors affected by stirring could have influenced the results. At low aeration, only 1–5 μM DETA/NO was necessary to initiate dormancy regulon induction. By contrast, at least 5 times more NO was required to induce the dormancy regulon under conditions of high aeration (Fig. 5 B). This finding (the capacity of O2 to inhibit NO-mediated regulon induction) is consistent with the idea that the same molecular sensor monitors the levels of O2 and NO. One such sensor could be a heme-containing protein that binds both NO and O2. To test this possibility, microarray expression profiling was used to determine if low levels of cyanide (CN−), a heme-protein inhibitor, would prevent induction of the dormancy regulon by NO and hypoxia. Cyanide was found to block the expression of dormancy regulon genes by NO and low O2, without significantly affecting the expression of genes outside the dormancy regulon (Fig. 5 A). CN− did not prevent overall transcription or gene induction even when 10-fold more CN− than necessary to block NO or low O2 signaling of the dormancy regulon was used, as illustrated by the large number of genes induced after 2-h hypoxia in the presence of 0.5 mM KCN− (Fig. 5 A). The interaction of NO and O2 in dormancy regulon signaling and inhibition of signaling by cyanide strongly implicate a heme-containing protein as a component of the NO/lows O2 signal transduction system.

Characterization of the NO and O2 Sensor. Because both NO and low O2 induce dormancy regulon expression, we investigated whether the presence of NO and the absence of O2 are sensed by the same molecular sensor. First, we determined if NO could competitively inhibit NO-mediated induction of the dormancy regulon. Gene induction was assayed by microarray expression profiling after exposing M. tuberculosis, growing in high or low aerated cultures, to different concentrations of NO. In this experiment, aeration was controlled by culture stirring speed; therefore, in addition to the degree of aeration, it is possible that other factors affected by stirring could have influenced the results. At low aeration, only 1–5 μM DETA/NO was necessary to initiate dormancy regulon induction. By contrast, at least 5 times more NO was required to induce the dormancy regulon under conditions of high aeration (Fig. 5 B). This finding (the capacity of O2 to inhibit NO-mediated regulon induction) is consistent with the idea that the same molecular sensor monitors the levels of O2 and NO. One such sensor could be a heme-containing protein that binds both NO and O2. To test this possibility, microarray expression profiling was used to determine if low levels of cyanide (CN−), a heme-protein inhibitor, would prevent induction of the dormancy regulon by NO and hypoxia. Cyanide was found to block the expression of dormancy regulon genes by NO and low O2, without significantly affecting the expression of genes outside the dormancy regulon (Fig. 5 A). CN− did not prevent overall transcription or gene induction even when 10-fold more CN− than necessary to block NO or low O2 signaling of the dormancy regulon was used, as illustrated by the large number of genes induced after 2-h hypoxia in the presence of 0.5 mM KCN− (Fig. 5 A). The interaction of NO and O2 in dormancy regulon signaling and inhibition of signaling by cyanide strongly implicate a heme-containing protein as a component of the NO/lows O2 signal transduction system.
Discussion

The results presented here show that low, nontoxic concentrations of NO induce a 48-gene regulon via the response regulator DosR, inhibit aerobic respiration, and reversibly slow replication. The correspondence of these effects by NO and the previously reported effects of hypoxia indicate that these apparently quite different treatments share a common mechanism of action. Differences in the survival of the wild-type and DosR mutant in a low-O₂ model of clinical latency were also demonstrated, indicating that this regulon adapts the organism for survival during prolonged periods of in vitro dormancy.

The individual contributions of the 48 genes that comprise this regulon to the enhanced survival of the wild-type strain during low O₂–induced dormancy are unknown. However, the predicted roles of some of the dormancy regulon genes appear to explain many of the previously reported biochemical or physiological properties of the low O₂–induced dormant state (5). Thus, a shift from aerobic to anaerobic respiration during adaptation to the dormant state, where nitrate rather than O₂ would serve as the terminal electron acceptor (19), is signaled by the induction of narX, which encodes nitrate reductase, nark2, which specifies a nitrite/nitrate transport function, and fdxA, which encodes ferredoxin A, a protein involved with alternative electron transport. Induction of narZ, which encodes ribonucleotide reductase class II, an enzyme that converts nucleoside triphosphates to deoxynucleoside triphosphates to nucleotide reductase class II, an enzyme that converts dietary nitrate to nitrite (20). Six of the dormancy regulon genes contain an Escherichia coli UspA motif. UspA is believed to be a nucleoid-associated DNA-binding protein that confers DNA resistance to UV radiation and mitomycin C (21). Recent findings support this correlation protein that confers DNA resistance to UV radiation and UspA is believed to be a nucleoid-associated DNA-binding protein.

These hypothesized host-to-pathogen NO signaling functions differ significantly from most previously reported effects of NO on bacterial physiology and gene regulation. One such difference is the reported capacity of NO to modulate gene regulation in a manner that reproduces the effect of reactive O₂ species or molecular O₂. For example, in E. coli, NO is known to affect gene expression by modulating the oxidative stress-responsive transcriptional regulators, OxyR (28) and SoxR (29). Similarly, the anaerobic regulator, FNR, is inactivated by both O₂ and NO (30). We see effects of this kind with M. tuberculosis only at high concentrations of NO, which like H₂O₂, initiate an oxidative stress response. By contrast, O₂ and low concentrations of NO were found in this paper to mediate opposing, rather than analogous, effects on gene expression, as NO induces and O₂ represses dormancy regulon expression. Consequently, it seems unlikely that an OxyR, SoxR, or an FNR-like mechanism is used to monitor NO and O₂ levels for dormancy regulon regulation.

Alternatively, the truncated hemoglobin HbN (trHbN) and cytochrome c oxidase (CcO) are two heme-containing M. tuberculosis proteins that interact with NO and O₂ and, thus, could perform a NO/low O₂-sensing function. trHbN efficiently detoxifies NO and protects stationary phase Mycobacterium bovis from NO respiratory inhibition (31). CcO, the terminal oxidase in the aerobic respiratory pathway, catalyzes the reduction of O₂ to H₂O, and in the...
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process, pumps protons across the cell membrane, which contribute to the proton gradient and ATP generation. Comprehensive studies of human mitochondrial aa3-type cytochrome oxidase (7) (homologous to the aa3-type cytochrome oxidase from M. tuberculosis) show that CcO is inhibited reversibly by very low (nM) concentrations of NO. By contrast, irreversible damage to the iron-sulfur centers of mitochondrial proteins requires ~1 mM NO (7). Cytochrome oxidase can also double as an O2 sensor for the induction of genes responding to low O2 in yeast (32) and for the repression of genes responding to high O2 levels in the bacterium Rhodobacter sphaeroides (33). In view of these functional attributes and the effects of NO and O2 on M. tuberculosis respiration, growth, and dormancy regulon signaling, we propose CcO as the most likely candidate for a NO/O2 sensor. However, proof of this conjecture will require O2 and NO binding studies with purified M. tuberculosis CcO and functional studies with CcO M. tuberculosis mutants.

The findings that NO competes with O2 to inhibit respiration, slow growth, and induce the dormancy regulon provide the basis for a model that describes the relationship between the tissue concentrations of NO and O2 and the in vivo growth state of M. tuberculosis (Fig. 6). The main postulate of this model is the following: an important function of NO production and granuloma formation by the immune system is to limit aerobic respiration and impair growth of M. tuberculosis, an obligate aerobe. Granulomas in the middle and lower lung lobes of an immunocompetent person, particularly if surrounded by an avascular fibro-calcific capsule, exemplify this circumstance. The bacilli respond to the decrease in respiration by initiating a transcriptional response that transforms the pathogen. This transformation stabilizes vital components of the bacterial cell and enables survival during extended periods of latency. The fact that this response is exquisitely regulated and occurs at nontoxic concentrations of NO, points to the possibility that NO serves as an environmental signal from the host to the pathogen that discloses the level of immune activation.

We thank K. Chong and S. Balakrishnan for DNA microarray assistance.

Figure 6. Model of O2 and NO control of respiration, growth, and gene regulation. Cytochrome oxidase is postulated as the sensor/integrator of O2/NO levels in this model.

The Walter V. and Idun Y. Berry Foundation, the American Lung Association, the Sequella Global Tuberculosis Foundation, and grants from the Action Tuberculosis Program, National Institutes of Health (AI 44826 to G.K. Schoolnik), and the Defense Advanced Research Projects Agency (BAA-00-33 to G.K. Schoolnik) supported this work.

Submitted: 6 February 2003
Revised: 1 August 2003
Accepted: 1 August 2003

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