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(54) IMMUNOGENIC COMPOSITIONS AGAINST TUBERCULOSIS

- (71) Applicant: Wisconsin Alumni Research Foundation, Madison, WI (US)
- Inventors: Adel M. Talaat, Madison, WI (US);
 Sarah K. Ward, Madison, WI (US);
 Bassam Abomoelak, Orlando, FL (US)
- (73) Assignee: WISCONSIN ALUMNI RESEARCH FOUNDATION, Madison, WI (US)
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Primary Examiner — Gary B Nickol

Assistant Examiner — Lakia J Jackson-Tongue

(74) Attorney, Agent, or Firm - Quarles & Brady LLP

(57) **ABSTRACT**

Methods of preparing mutants of *Mycobacterium tuberculosis* with one or more disrupted genes are presented, where the disrupted genes include ctpV, rv0990c, rv0971c, and/or rv0348. Compositions containing mutants with attenuated virulence and pathogenesis, which are capable of stimulation of an immune response against tuberculosis, are described. Compositions and methods relating to immunogenic compositions, which include an attenuated M. tb strain in which the M. tb genome includes a disruption of at least one of the ctpV gene, the rv0990c gene, the rv0971c gene, and the rv0348 gene, are also provided.

12 Claims, 28 Drawing Sheets

Specification includes a Sequence Listing.

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FIG. 26A



FIG. 26C

FIG. 26D

FIG. 26B



FIG. 26E







FIG. 27A

FIG. 27B





FIG. 28

























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IMMUNOGENIC COMPOSITIONS AGAINST **TUBERCULOSIS**

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 14/950,197, filed Nov. 24, 2015; which is a continuation of U.S. patent application Ser. No. 13/733,777, filed Jan. 3, 2013, now U.S. Pat. No. 9,220,764, issued Dec. 29, 2015; which is a continuation of U.S. patent application Ser. No. 12/800,374, filed May 13, 2010, now U.S. Pat. No. 8,367,055, issued Feb. 5, 2013; which claims priority to U.S. Provisional Patent Application No. 61/216,167, filed May 15 14, 2009; each of the disclosures of which are expressly incorporated herein by reference in their entirety.

STATEMENT AS TO RIGHTS TO INVENTIONS MADE UNDER FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under A1066235 awarded by the National Institutes of Health. The government has certain rights in the invention.

SEQUENCE LISTING

This application contains a Sequence Listing, which has been submitted via EFS-Web and is hereby incorporated by 30 reference in its entirety. Said ASCII copy, created on Aug. 12, 2010, is named "99943825.txt" and is 25,188 bytes in size.

BACKGROUND

The Mycobacterium tuberculosis ("M. tb") genome is one of the largest bacterial genomes known, including more than 4 million base pairs and nearly four thousand predicted protein coding sequences. Approximately one-third of the 40 world's population is infected with M. tb, the causative agent of the disease tuberculosis ("TB") in humans. Infection with M. tb is commonly the result of an uninfected person inhaling M. tb bacilli that have become airborne as a result of some action of an infected person, e.g., coughing, 45 sneezing, spitting, or talking. Clinically, infection with M. tb in humans can be divided into three stages.

In the first stage of infection, which typically lasts from three to eight weeks, M. tb bacilli are taken up by alveolar macrophages in the lungs, where they multiply. In the 50 second stage of the infection, which typically lasts from two to five months, M. tb multiplies within inactivated macrophages until they burst, whereupon M. tb circulates via the bloodstream to all body organs including the brain, bone marrow, and other parts of the lung. In the third stage of the 55 infection, which typically lasts from six months to two years, the host commonly develops a cell-mediated immune response to M. tb and may experience pleurisy accompanied by severe chest pain. In the fourth stage of infection, there is either resolution of the primary complex or persistence of 60 the infection until reactivation, which may occur many years after initial exposure to M. tb. While only 5-10% of nonimmunocompromised persons exposed to TB develop active TB during their lives, it is estimated that each person with active TB infects about 10-15 others annually. Ultimately, 65 TB causes nearly two million deaths every year and is a leading killer of HIV-infected persons.

A vaccine for tuberculosis, Bacille Calmette Guérin ("BCG"), prepared with an attenuated strain of the bovine pathogen Mycobacterium bovis, is routinely used worldwide. However, the vaccine utilizes bacteria that do not normally cause disease in humans and provides little to no protection against tuberculosis in adults. Drugs are also available to treat TB, but bacterial resistance has developed against every available drug. Moreover, multi-drug resistant ("MDR") and extensively drug-resistant ("XDR") strains of TB pose a serious threat to human health.

SUMMARY

The present application relates to M. tb mutants, which may exhibit reduced virulence in test subjects as compared to the counterpart wild-type M. tb. As a result of this reduced virulence, the mutants described herein may be useful for eliciting an immune response in a subject that has been 20 exposed to the mutant. For example, in some embodiments, a pharmaceutically acceptable immunogenic composition comprising the M. tb mutants may be administered to a subject. The M. tb mutants described herein are commonly characterized by disruptions in the ctpV, rv0990c, rv0971c, 25 and/or rv0348 (also known as "mosR") genes of M. tb.

For example, in some embodiments, engineered Mycobacterium tuberculosis ("M. tb") strains are provided in which the M. tb genome includes a disruption of at least one of the ctpV gene, the rv0990c gene, the rv0971c gene, and the rv0348 gene. In some embodiments, the disruption results in a knock-out of the disrupted gene; in other embodiments, the disrupted gene exhibits decreased expression of the corresponding gene product (i.e., RNA, protein). In further embodiments, the disruption prohibits the transcription of a full-length, wild-type mRNA and/or the production of a functional wild-type protein from the disrupted gene.

Gene disruptions may be generated by methods known in the art. For example, in some embodiments, the disruption includes an insertion of a heterologous sequence, such as a gene cassette, into the gene. In other embodiments, the disruption includes the replacement of at least a portion of the wild-type gene sequence with a heterologous sequence, such as a gene cassette. In some embodiments the heterologous sequence encodes a selectable marker, such as a hygromycin resistance gene.

In some embodiments, the engineered M. tb strains exhibit attenuated virulence. For example, in some embodiments, mice infected with the engineered M. tb strain have an increased average post-infection lifespan compared to mice infected with the corresponding wild-type strain. For example, in some embodiments, the post infection life span of mice infected with an engineered attenuated M. tb strain is at least about 125% compared to mice infected with the corresponding wild-type M. tb strain. In other embodiments, the post infection life span of mice infected with an engineered attenuated M. tb strain is at least about 125% to about 200% of that of mice infected with the corresponding wild-type M. tb strain. In other embodiments, the post infection life span of mice infected with an engineered attenuated M. tb strain is at least about 130% to about 190%; at least about 140% to about 180%; is at least about 150% to about 170%; is at least about 160% to about 165%; is at least about 162%; or at least about 138% of the post infection life span of mice infected with the wild-type strain. In some embodiments, the engineered attenuated M. tb strain is Δ ctpV, Δ rv0348, Δ 0990c, or Δ 0971c.

10

In some embodiments, the engineered M. tb strains exhibit a different response to stress as compared to the wild-type counterparts. For example, in some embodiments, the average lifespan of an engineered M. tb strain in 500 µM $CuCl_2$, is decreased by at least about 10% to about 50% as 5 compared to a corresponding wild-type M. tb strain. In other embodiments, the lifespan of an engineered M. the strain in 500 µM CuCl₂, is decreased by at least about 15% to about 40%; by at least about 20% to about 30%; or by at least about 25% as compared to a corresponding wild-type M. tb strain. In further embodiments, the engineered M. tb strains exhibit enhanced expression of hypoxia-related genes under low oxygen conditions as compared to the corresponding wild-type strains. In some embodiments, the engineered M. 15 tb strain is $\Delta rv0348$.

In some embodiments, the engineered M. tb strains exhibit a different response to stress as compared to the wild-type counterparts. For example, in some embodiments, the engineered M. tb strains exhibit enhanced expression of 20 times after infection with either wild-type M. tb (H37Rv) or hypoxia-related genes under low oxygen conditions as compared to the corresponding wild-type strains. In some embodiments, the expression of hypoxia-responsive genes under low-oxygen conditions is not repressed by an rv0348 protein. In some embodiments, the engineered M. tb strain 25 is Arv0348.

In further embodiments, the engineered M. tb strains exhibit enhanced expression of one or more of the following genes: Rv0823c-Rv0824c; Rv1622c; Rv1623c; Rv2031c; Rv2629-Rv2630; Rv3048c; and Rv3139-Rv3140. In other 30 embodiments, the engineered M. tb strains exhibit decreased expression of one or more of the following genes: Rv0167-0177; Rv0684-0685; Rv0700-0710; Rv0718-0723; Rv1613-1614; Rv2391, 2392; Rv2948c; Rv3148-Rv3154; Rv3460c; Rv3824c-Rv3825c; Rv3921c-Rv3924c. In some embodi- 35 ments, the engineered M. tb strain is $\Delta rv0348$.

The present disclosure also relates to immunogenic compositions including engineered M. tb strains. For example, in some embodiments, immunogenic compositions include an attenuated M. tb strain in which the M. tb genome includes 40 a disruption of at least one of the ctpV gene, the rv0990c gene, the rv0971c gene, and the rv0348 gene. Some embodiments of immunogenic compositions also include a pharmaceutically acceptable carrier and/or a pharmaceutically acceptable adjuvant. 45

Also disclosed herein are methods of eliciting or stimulating an immune response in a subject against tuberculosis (e.g., vaccinating a subject against tuberculosis). In some embodiments, an immunogenic composition including an attenuated M. tb strain in which the M. tb genome includes 50 a disruption of at least one of the ctpV gene, the rv0990c gene, the rv0971c gene, and the rv0348 gene is administered to the subject. In some embodiments, the subject is a mammal and the immunogenic composition is administered orally, nasally, subcutaneously, intravenously or by inhala-55 tion.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a diagram of an in vivo expressed genomic 60 island ("iVEGI") of M. tb preferentially expressed in murine host during tuberculosis.

FIG. 2 is a representation of the ctpV coding region from which 2.1 kB are deleted (shown in black) to produce the $\Delta ctpV$ mutant. 65

FIG. 3 shows Southern blot confirmation of the $\Delta ctpV$ mutant.

FIG. 4 shows the results of RT-PCR verifying transcription of ctpV and the downstream gene rv0970 in the wildtype strain but only transcription of the rv0970 gene in the isogenic mutant $\Delta ctpV$.

FIG. 5 shows the fold changes in expression of ctpV in H37Rv and isogenic mutants after exposure to 500 µM copper relative to cultures kept copper-free.

FIG. 6 shows growth curves of wild-type M. tb, its isogenic mutant $\Delta ctpV$, and the complemented strain $\Delta ctpV$: ctpV.

FIG. 7 shows growth curves of wild-type M. tb (H37Rv), its isogenic mutant $\Delta ctpV$, and the complemented strain Δ ctpV:ctpV in the presence of 0 μ M and 50 μ M and 500 μ M CuCl₂

FIG. 8 shows growth curves of the wild-type M. tb in the presence 0 µM and 50 µM and 500 µM CuCl₂ and growth curves of the M. tb isogenic mutant $\Delta ctpV$ and the complemented strain Δ ctpV:ctpV in the presence of 500 μ M CuCl₂.

FIG. 9 shows the bacterial load of mouse lungs at various its isogenic mutant $\Delta ctpV$.

FIG. 10 shows survival of mouse groups (N=10) at various times after infection with either wild-type M. tb (H37Rv) or its isogenic mutant Δ ctpV.

FIG. 11A-D shows acid-fast staining of sectioned mouse lung tissue of mice infected with wild-type ("WT") and Δ ctpV at two weeks (top A, B) and four weeks (bottom C, D) post infection.

FIG. 12A-D shows histological analysis of lung sections of mice lungs at 4 weeks (top A, B) and 38 weeks (bottom C, D) of infection with wild-type ("WT") and Δ ctpV.

FIG. 13 shows qRT-PCR and microarray data for fold change of expression of selected genes in ActpV relative to wild-type.

FIG. 14 shows a qRT-PCR survey of the response to copper of all predicated metal-transporting P-type ATPases within the M. tb (H37Rv) genome.

FIG. 15 shows the organization of the rv0348 operon and the strategy for gene disruption.

FIG. 16A-C shows Southern blot analysis of SalI-digested genomic DNA of the H37Rv WT and Δ rv0348 mutant (A); PCR analysis of cDNA synthesized from RNA samples purified from H37Rv (lanes 1, 3, 5) or Arv0348 mutant (lanes 2, 4, 6) (B); and Western blot analysis for different M. tb strains using polyclonal antibodies raised in rabbits against MBP-rv0348 protein (C).

FIG. 17 shows growth curves of four different M. tb strains in Middlebrook 7H9 broth.

FIG. 18 shows lung CFU/GM in murine lungs following aerosol infection with H37Rv, Arv0348, and Arv0348:: rv0348.

FIG. 19 shows survival curves of three mice groups (N=10) infected with H37Rv, $\Delta rv0348$, and $\Delta rv0348$:: rv0348.

FIG. 20A-F shows histological analysis of lung sections of mice lungs at 2 weeks (A-C) and 20 weeks (D-F) after infection with H37Rv, Arv0348 and Arv0348::rv0348.

FIG. 21 shows CFU/g tissue in murine lungs at time of death for H37Rv wild-type strain (37 weeks) and for $\Delta rv0348$ strain (62 weeks).

FIG. 22 shows a transcriptional profile of rv0348 in M. tb (H37Rv) under variable stressors.

FIG. 23 shows colony counts of four different M. tb strains subjected to different stressors.

FIG. 24 shows fold changes of ten genes utilizing RNA from both mutant $\Delta rv0348$ and complemented $\Delta rv0348$:: rv0348 strains relative to H37Rv wild type strain.

FIG. **25** shows a comparative analysis of the transcriptome of M. tb exposed to variable conditions.

FIG. **26**A-F shows Western blot analysis of the recombinant strain of *M. smegmatis* mc²155 expressing rv0348 protein (A); the survival curve of *M. smeg*::pML21 under ⁵ aerobic and anaerobic conditions (left scale) and fold change in mosR transcripts as measured by qRT-PCR (right scale) (B); Lac-Z repression for constructs for rv03130c promoter (C); Lac-Z repression for constructs for rv0347 (D); Lac-Z repression for constructs for rv0700 (E); Lac-Z induction for ¹⁰ constructs for rv0167 (F) ("*" denotes significant change in a Student's t-Test (p<0.001)).

FIG. 27A-C shows results of various EMSA assays.

FIG. **28** shows recombinant colonies of *M. smegmatis* $_{15}$ without (left) or with (right) promoters for the target genes.

FIG. **29** shows CFU/g tissue in murine lungs at various times for H37Rv wild-type strain, $\Delta rv0990c$ strain, and $\Delta rv0971c$ strain.

FIG. **30** shows survival curves of three mice groups $_{20}$ infected with H37Rv wild-type strain, $\Delta rv0990c$ strain, and $\Delta rv0971c$ strain.

FIG. **31** shows the colonization and survival data of Δ ctpV and the corresponding wild-type H37Rv M. tb strain.

FIG. **32**A-D shows histopathology of mouse tissue at 4 ²⁵ weeks post infection with Δ ctpV (B, D) and the corresponding wild-type H37Rv M. tb strain (A, C).

FIG. **33**A-F shows histopathology at early, chronic stages of mouse tissue at 4 weeks post infection with $\Delta rv0971c$, $\Delta rv0990c$ (B, C, E, F) and the corresponding wild-type ³⁰ H37Rv M. tb strain (A, D).

FIG. **34**A-C shows mouse lung tissue stained with IFN- γ antibody at 8 weeks post infection with wild-type and M. tb mutant strains. The left panel (A) shows mouse lung infected with wild-type M. tb, the middle panel (B) shows mouse ³⁵ lung infected with Δ ctpV mutant, and the right panel (C) shows mouse lung infected with the Δ ctpV:ctpV mutant.

FIG. **35** is a graph showing fold change in expression of csoR at 500 μ M copper in the Δ ctpV mutant and the Δ ctpV:ctpV mutant relative to csoR expression in the cor- 40 responding WT M. tb strain.

FIG. **36**A-C shows histological analysis of lung sections of mice lungs at 4 weeks post infection with wild-type ("WT") M. tb (A) and Δ ctpV (B) and Δ ctpV::ctpV (C).

FIG. **37** shows CFU/g tissue in murine lungs at various 45 times for H37Rv wild-type strain, Δ ctpV strain, and Δ ctpV:: ctpV strain.

FIG. **38** shows survival curves of three mice groups infected with H37Rv wild-type strain, Δ ctpV strain, and Δ ctpV::ctpV strain.

FIG. **39**A-L shows histological (A-F) and immunohistochemisty (G-L) analysis of lung sections of mice lungs at 8 (A-C and G-I) or 38 (D-F and J-L) weeks post infection with wild-type ("WT") M. tb and Δ ctpV and Δ ctpV::ctpV.

FIG. **40** shows a schematic depicting several scenarios in ⁵⁵ which rv0348 can play a role in M. tb survival strategies.

DETAILED DESCRIPTION

The present application relates to novel M. tb mutants ⁶⁰ which exhibit reduced virulence in test subjects as compared to the wild-type M. tb counterpart. Due to the reduced virulence, the mutants described herein are useful for eliciting an immune response in a subject that has been exposed to the mutant. For example, in some embodiments, the ⁶⁵ mutants are provided as a pharmaceutically acceptable immunogenic compound, such as a vaccine.

The novel M. tb mutants described herein are characterized by disruptions in the ctpV, rv0990c, rv0971c, and/or rv0348 (also known as "mosR") genes of M. tb.

The present invention is described herein using several definitions, as set forth below and throughout the specification.

As used herein, the term "subject" refers to an animal, preferably a mammal, more preferably a human. The term "subject" and "patient" may be used interchangeably.

The term "pharmaceutically acceptable carrier" refers to any carrier that has substantially no long term or permanent detrimental effect when administered to an individual. Pharmaceutically acceptable carriers include diluents, fillers, salts, dispersion media, coatings, emulsifying agents, wetting agents, sweetening or flavoring agents, tonicity adjusters, absorption delaying agents, preservatives, antibacterial and antifungal agents, buffers, anti-oxidants, stabilizers, solubilizers, bulking agents, cryoprotectant agents, aggregation inhibiting agents, or formulation auxiliary of any type. Suitable carriers are described in Remington's Pharmaceutical Sciences (Remington's Pharmaceutical Sciences, 2000, 20th Ed., Lippincott, Williams & Wilkins), incorporated herein by reference. Preferred examples of such carriers or diluents include, but are not limited to, water, sodium chloride, mannitol, trehalose dihvdrate, polysorbate 80, various pharmaceutically acceptable buffers for adjusting pH (e.g. phosphate buffers, citrate buffers, acetate buffers, and borate buffers).

The term "immunogenic composition" is used herein to refer to a composition that will elicit an immune response in a mammal that has been exposed to the composition. In some embodiments, an immunogenic composition includes at least one of four M. tb mutants Δ ctpV, Δ rv0990c, Δ rv0971c, and/or Δ rv0348. In some embodiments, the immunogenic composition includes at least two, at least three or at least four of the mutants Δ ctpV, Δ rv0990c, Δ rv0971c, and/or Δ rv0348.

In some embodiments, the immunogenic compositions described herein may be formulated for administration (i.e., formulated for "exposure" to the mammal) in a number of forms. For example, in some embodiments, the immunogenic compositions are prepared for oral, pulmonary, intravenous, intramuscular, subcutaneous, parenteral, nasal, or topical administration. Compositions may also be formulated for specific dosage forms. For example, in some embodiments, the immunogenic composition may be formulated as a liquid, gel, aerosol, ointment, cream, lyophilized formulation, powder, cake, tablet, or capsule. In other embodiments, the immunogenic composition is formulated as a controlled release formulation, delayed release formulation, extended release formulation, pulsatile release formulation, and mixed immediate release formulation. In some embodiments, the immunogenic composition is provided as a liquid. In other embodiments, the immunogenic composition is provided in lyophilized form.

The terms "mutation" and "disruption" are used interchangeably herein to refer to a detectable and heritable change in the genetic material. Mutations may include insertions, deletions, substitutions (e.g., transitions, transversion), transpositions, inversions and combinations thereof. Mutations may involve only a single nucleotide (e.g., a point mutation or a single nucleotide polymorphism) or multiple nucleotides. In some embodiments, mutations are silent, that is, no phenotypic effect of the mutation is detected. In other embodiments, the mutation causes a phenotypic change, for example, the expression level of the encoded product is altered, or the encoded product itself is altered. In some embodiments, a mutation may result in a disrupted gene with decreased levels of expression of a gene product (e.g., protein or RNA) as compared to the wild-type strain (e.g., M. tb). In other embodiments, a mutation may result in an expressed protein with activity that is lower as ⁵ compared to the activity of the expressed protein from the wild-type strain (e.g., M. tb).

The term "knockout mutant" is used herein to refer to an organism in which a null mutation has been introduced in a gene. In a knockout mutant, the product encoded by the ¹⁰ wild-type gene is not expressed, expressed at levels so low as to have no effect, or is non-functional. In some embodiment, the knockout mutant is caused by a mutation in the knocked out gene. In some embodiments, the knockout mutation is introduced by inserting heterologous sequences into the gene of interest. In other embodiments, the knockout mutation is introduced by replacing a portion of the wild-type gene or allele, or a majority of the wild-type gene or allele, with a heterologous sequence, or an engineered (e.g., ²⁰ manually altered, disrupted, or changed), non-functional, copy of the wild-type sequence.

A "knocked out gene" refers to a gene including a null mutation (e.g., the wild-type product encoded by the gene is not expressed, expressed at levels so low as to have no 25 effect, or is non-functional). In some embodiments, the knocked out gene includes heterologous sequences or genetically engineered non-functional sequences of the gene itself, which renders the gene non-functional. In other embodiments, the knocked out gene is lacking a portion of 30 the wild-type gene. For example, in some embodiments, at least about 10%, at least about 20%, at least about 30%, at least about 40% or at least about 60% of the wild-type gene sequence is deleted. In other embodiments, the knocked out gene is lacking at least about 70%, at least about 75%, at 35 least about 80%, at least about 90%, at least about 95% or at least about 100% of the wild-type gene sequence. In other embodiments, the knocked out gene may include up to 100% of the wild-type gene sequence (e.g., some portion of the wild-type gene sequence may be deleted) but also include 40 one or more heterologous and/or non-functional nucleic acid sequences inserted therein.

Generally, a heterologous sequence may be any sequence which does not affect the expression of other genes in the organism (e.g., does not encode a regulatory protein). Additionally, in some embodiments, a heterologous sequence includes a marker sequence (e.g., a gene that the organism does not have, and that confers resistance to a drug or other harmful agent, or that produces a visible change such as color or fluorescence). For example, in some embodiments, 50 the heterologous sequence is the hygromycin resistance gene, as described in Bardarov, et al., 2002, Microbiol., 148:3007-3017, herein incorporated by reference in its entirety. By way of example, but not by way of limitation, other suitable heterologous sequences include selectable 55 markers such as a kanamycin resistance marker or other antibiotic resistance marker, β -galactosidase, or various other detectable markers known to those of skill in the art.

In a knockout mutant, the heterologous sequence may be expressed (e.g., may be transcribed and/or translated) or it 60 may be silent (e.g., not transcribed and/or translated). For example, in the case of M. tb knockout mutants Δ ctpV, Δ rv0990c, Δ rv0971c, and Δ rv0348, the heterologous sequence includes the hygromycin resistance gene. The hygromycin resistance gene is expressed in the knockout 65 mutants, and mutant knockouts are selected, inter alia, by virtue of their ability to grow in the presence of hygromycin.

Mutants, such as knockout mutants may be constructed using methods well known in the art, although methods involving homologous recombination are frequently used. In some embodiments, such methods include techniques such as electroporation or transduction. In other embodiments, transposons may be used to disrupt the gene of interests and insert heterologous sequence. By way of example, but not by way of limitation, other methods of constructing mutants in M. tb include, for example, the use of a suicide vector and chemical mutagenesis.

A knockout mutant may include a single knocked out gene or multiple knocked out genes. For example, in some embodiments, an M. tb knockout mutant includes a knockout of one or more of the following genes: ctpV, rv0990c, rv0971c, and rv0348.

The term "M. tb Δ ctpV," " Δ ctpV mutant," " Δ ctpV knockout," or " Δ ctpV" is used herein to refer to an M. tb knockout, in which the ctpV gene is not expressed, expressed at levels so low as to have no effect or the expressed protein is non-functional (e.g., is a null-mutation). In some embodiments, the Δ ctpV mutant includes a heterologous sequence in place of all or a majority of the ctpV gene sequence. In some embodiments, the heterologous sequence includes the hygromycin resistance gene.

The term "M. tb $\Delta rv0990c$," " $\Delta rv0990c$ mutant," " $\Delta rv0990c$ knockout" or " $\Delta rv0990c$ " is used herein to refer to an M. tb knockout, in which the rv0990c gene is not expressed, expressed at levels so low as to have no effect or the expressed protein is non-functional (e.g., is a nullmutation). In some embodiments, the $\Delta rv0990c$ mutant includes a heterologous sequence in place of all or a majority of the rv0990c gene sequence. In some embodiments, the heterologous sequence includes the hygromycin resistance gene.

The term "M. tb $\Delta rv0971c$," " $\Delta rv0971c$ mutant," " $\Delta rv0971c$ knockout," or " $\Delta rv0971c$ " is used herein to refer to an M. tb knockout, in which the rv0971c gene is not expressed, expressed at levels so low as to have no effect or the expressed protein is non-functional (e.g., is a nullmutation). In some embodiments, the $\Delta rv0971c$ mutant includes a heterologous sequence in place of all or a majority of the rv0971c gene sequence. In some embodiments, the heterologous sequence includes the hygromycin resistance gene.

The term "M. tb $\Delta rv0348$," " $\Delta rv0348$ c mutant," " $\Delta rv0348$ knockout," " $\Delta rv0384$," "*M. tb* $\Delta mosR$ " " $\Delta mosR$ mutant," " $\Delta mosR$ knockout," or " $\Delta mosR$ " is used herein to refer to an M. tb knockout, in which the rv0348 gene is not expressed, expressed at levels so low as to have no effect or the expressed protein is non-functional (e.g., is a null-mutation). In some embodiments, the $\Delta rv0348$ mutant includes a heterologous sequence in place of all or a majority of the rv0348 gene sequence. In some embodiments, the heterologous sequence includes the hygromycin resistance gene. As used herein, the term rv0348 and mosR are used interchangeably.

The term "vaccine" is used herein to refer to a composition that is administered to a subject to produce or increase immunity to a particular disease. In some embodiments, vaccines include a pharmaceutically acceptable adjuvant and/or a pharmaceutically acceptable carrier.

The term "live attenuated vaccine" is used herein to refer to a vaccine prepared from live bacteria or viruses, which have been weakened so they produce immunity when exposed to a subject, but do not cause disease, or cause a less severe form, duration, onset or later onset of the disease.

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In some embodiments, a live attenuated vaccine includes at least one of the four M. tb knockout mutants $\Delta ctpV$, $\Delta rv0990c$, $\Delta rv0971c$, and $\Delta rv0348$. In other live attenuated vaccine embodiments, at least two, at least three or at least four of the M. tb knockout mutants are provided. In still 5 other embodiments, a live attenuated vaccine includes an M. tb knockout that includes multiple "knocked out" genes. For example, in some embodiments, the live attenuated vaccine includes M. tb with a knockout of one or more of the ctpV, rv0990c, rv0971c, and rv0348 genes. 10

In other embodiments, the "live attenuated vaccine" is a pharmaceutical composition that includes a pharmaceutically acceptable adjuvant and/or a pharmaceutically acceptable carrier.

The term "gene cassette" is used herein to refer to a DNA 15 sequence encoding and capable of expressing one or more genes of interest (e.g., a selectable marker) that can be inserted between one or more selected restriction sites of a DNA sequence. In some embodiments, insertion of a gene cassette results in a disrupted gene. In some embodiments, 20 disruption of the gene involves replacement of at least a portion of the gene with a gene cassette, which includes a nucleotide sequence encoding a selectable marker. In some embodiments, a gene cassette may be an antibiotic resistance gene cassette. In some embodiments, the antibiotic 25 resistance gene cassette may be a hygromycin resistance cassette. By way of example, but not by way of limitation, Bardarov, et al., 2002, Microbiol., 148:3007-3017 describes one embodiment of a hygromycin resistance gene cassette.

The term "engineered" is used herein to refer to an 30 organism that has been deliberately genetically altered, modified, or changed, e.g. by disruption of the genome. For example, an "engineered M. tb strain" refers to an M. tb strain that has been deliberately genetically altered, modified, or changed.

The term "corresponding wild-type strain" or "parent wild-type strain" is used herein to refer to the wild-type M. tb strain from which the engineered M. tb strain was derived. As used herein, a wild-type M. tb strain is a strain that has not been engineered to knock out one or more of the ctpV, 40 rv0990c, rv0971c, or rv0348 genes. The engineered M. tb strain may have been modified to knock out more than one of the ctpV, rv0990c, rv0971c, or rv0348 genes.

The term "pathogen" or "infectious agent" is used herein to refer to a specific causative agent of disease or illness in 45 ability of a pathogen to cause disease. a host, such as, for example, a bacterium or virus.

The term "strain" is used herein to refer to a genetic variant of a organism, such as bacteria or virus. Thus, a wild-type M. tb strain is genetically different from a mutant M. tb strain.

The term "attenuated strain" is used herein to refer to a strain with weakened or reduced virulence in comparison to the corresponding wild-type strain.

The term "post-infection lifespan" ("PILS") is used herein to refer to the length of time an organism survives (i.e., lives) 55 after infection with an infectious agent (e.g., an M. tb strain). As used herein, the PILS of an organism infected with a "standard" or "reference" infectious agent (e.g., a wild-type M. tb strain) is 100% when compared to the PILS of an organism infected with a "test" infectious agent (e.g., an 60 engineered mutant strain of the "standard" or "reference" infectious agent). A PILS of greater than 100% indicates the organism infected with the test infectious agent lives longer than the organism infected with the reference infectious agent. A PILS of less than 100% indicates that the organism 65 infected with the test infectious agent lives less long (i.e., dies sooner) than the organism infected with the reference

10

infectious agent. In some embodiments, the "infected organism" is a mouse, and the infectious agent is an M. tb strain. In some embodiments, the "reference" M. tb strain is a wild-type M. tb strain and the "test" infectious agent is an engineered mutant of the wild-type M. tb strain.

The term "average post-infection lifespan" refers to the average time a group of organisms survives post-infection.

In some embodiments, the post-infection lifespan of organisms infected with different infectious agents (e.g., different strains of M. tb) are compared. For example, in some embodiments, the PILS of an organism (e.g., a mouse) infected with an engineered M. tb strain (i.e., "test" strain) is compared to the PILS of an organism (e.g., a mouse) infected with the corresponding wild-type strain of M. tb (i.e., the "reference" strain). In some embodiments, the average post-infection lifespan of organisms infected with different infectious agents (e.g., different strains of M. tb) are compared. For example, in some embodiments, the average PILS of mice infected with an engineered M. tb strain is compared to the average PILS of mice infected with the corresponding wild-type strain of M. tb. In some embodiments, the median post-infection lifespan of organisms infected with different infectious agents (e.g., different strains of M. tb) are compared. For example, in some embodiments, the median PILS of mice infected with an engineered M. tb strain is compared to the median PILS of mice infected with the corresponding wild-type strain of M. th.

By way of example, but not by way of limitation, the median PILS of mice infected with a wild-type M. tb reference strain is 29 weeks. In comparison, mice infected with a mutant M. tb strain, (e.g., $\Delta ctpV)$ have a median PILS of 47 weeks. In this example, the PILS of mice infected with the mutant M. tb is at least 62% greater than the PILS of 35 mice infected with the wild-type M. tb reference strain. Thus, the PILS of the mice infected with the mutant M. tb is 162% of the PILS of mice infected with the wild type M. tb. As another non-limiting example, mice infected with mutant M. tb strain \Deltarv0348 live for at least 40 weeks, while mice infected with the corresponding wild-type M. tb strain have a median survival time of 29 weeks. Accordingly, the PILS of mice infected with the mutant M. tb strain is at least 138% of mice infected with the wild-type strain.

The term "virulence" is used herein to refer to the relative

The term "attenuated virulence" or "reduced virulence" is used herein to refer to a reduced relative ability of a pathogen to cause disease. For example, attenuated virulence or reduced virulence can describe bacteria or viruses that have been weakened so they produce immunity when exposed to a subject, but do not cause disease, or cause a less severe form, duration, onset or later onset of the disease.

The term "pathogenesis" is used herein to refer to the series of events leading up to a disease and the step-by-step development of the disease due to structural and/or functional changes to a cell, tissue, or organ caused by a pathogenic agent (e.g., bacterium, virus, chemical compound etc.).

The term "attenuated pathogenesis" is used herein to refer to a reduction in the number or severity of events leading up to a disease or a slowing of the development of a disease.

The term "adjuvant" is used herein to refer to a substance that enhances the pharmacological effect of a drug or increases the immune response to an antigen. By way of example, but not by way of limitation, adjuvants include mineral salts, e.g., aluminium hydroxide and aluminum or calcium phosphate gels; oil emulsions and surfactant based
formulations, e.g., MF59 (microfluidised detergent stabilized oil-in-water emulsion), QS21 (purified saponin), AS02 [SBAS2] (oil-in-water emulsion+MPL+QS-21), Montanide ISA-51 and ISA-720 (stabilised water-in-oil emulsion); particulate adjuvants, e.g., virosomes (unilamellar liposomal vehicles incorporating influenza haemagglutinin), AS04 ([SBAS4] Al salt with MPL), ISCOMS (structured complex of saponins and lipids), polylactide co-glycolide (PLG); microbial derivatives (natural and synthetic), e.g., monophosphoryl lipid A (MPL), Detox (MPL+M. Phlei cell wall skeleton), AGP [RC-529] (synthetic acylated monosaccharide), DC_Chol (lipoidal immunostimulators able to self organize into liposomes), OM-174 (lipid A derivative), CpG motifs (synthetic oligonucleotides containing immunos- 15 timulatory CpG motifs), modified LT and CT (genetically modified bacterial toxins to provide non-toxic adjuvant effects), endogenous human immunomodulators, e.g., hGM-CSF or hIL-12 (cytokines that can be administered either as protein or plasmid encoded), Immudaptin (C3d tandem 20 array); inert vehicles, such as gold particles.

As described above, the present application provides novel knockout mutants of Mycobacterium tuberculosis ("M. tb") useful in eliciting an immune response in a mammal against M. tb. The following examples are pre- 25 sented to illustrate 1) methods of producing knockout mutants, 2) methods of testing virulence of a knockout, and 3) methods of eliciting an immune response with the mutants. The examples are provided to assist one of ordinary skill in making and using the same. The examples are not 30 intended in any way to otherwise limit the scope of the invention. The section is divided into eight main Examples: Example I provides information regarding the Δ ctpV knockout mutant; Example II provides information regarding the Δrv0384 knockout mutant; Examples III provides informa- 35 tion regarding a $\Delta rv0990c$ knockout mutant; Example IV provides information regarding a $\Delta rv0971c$ knockout mutant; Example V provides information regarding M. tb. infected mice; Example VI provides information regarding mice infected with a Δrv0990c mutant; Example VII pro- 40 vides information regarding mice infected with a Δrv0971c mutant; and Example VIII provides information regarding the use of M. tb mutants to generate an immune response and as vaccines.

Example I: ActpV Knockout Mutant

A. Overview

Many enzymes require a metal cofactor for activity. The metals that serve as cofactors in enzymes required for life 50 are considered biologically active metals. These metals, including iron, copper, zinc, and magnesium, serve as required micronutrients for many diverse cellular organisms, from humans to bacteria. For bacteria that colonize the human body, this can serve as a form of environmental 55 stress, as microbes and host cells struggle for the possession of the same micronutrients.

The most commonly used metal cofactor, iron, has frequently been studied in the context of this struggle. Required by both host cells and bacteria for a number of enzymatic ⁶⁰ activities, including respiration and detoxification, iron is kept bound by host proteins such as transferrin and lactoferrin. Successful human pathogens have developed compounds termed "siderophores" to compete with host proteins for bound iron. These microbes also use iron-specific uptake ⁶⁵ mechanisms and regulators which contribute to iron scavenging and survival within a host.

Another biologically active metal, copper, is also required by both host and bacterial enzymes, including oxidases and superoxide dismutase. The potential role of copper in host/ microbe interactions has not yet been elucidated. Interestingly, studies of copper homeostasis mechanisms in pathogenic organisms have shown that copper export, as opposed to acquisition, seems to be most important for virulence. For example, copper export is required for full virulence of the human pathogens *Psuedomonas aeruginosa* and *Listeria monocytogenes* as well as the plant pathogen *Pseudomonas fluorescens*. Conversely, no copper importers or uptake mechanisms have been identified as required for virulence in any pathogen.

Studies of biometals indicate that although pathogenic bacteria must obtain sufficient amounts of micronutrients, they are also sensitive to metal toxicity. Therefore, an equal balance of metal import and export (homeostasis) must be obtained at levels appropriate for each metal. Presumably, the ability to sense metals in the environment and regulate the expression of homeostasis mechanisms is key to maintaining intracellular metals at appropriate concentrations.

The first copper-binding transcriptional regulator in *Mycobacterium tuberculosis* ("M. tb") was identified, and it has been demonstrated that this important human pathogen has the ability to respond to copper in its intracellular environment. As shown in FIG. 1, this copper-binding regulator, CsoR, is encoded within a region of the M. tb genome previously associated with in vivo survival, an in vivo expressed genomic island ("iVEGI") of M. tb preferentially expressed in murine host during tuberculosis. CsoR has been shown to upregulate the expression of its own operon, the cso operon includes the ctpV gene, which encodes a putative metal transporter previously associated with copper response in M. tb.

Previously, the expression of the ctpV gene was determined to be induced by copper ions via the copper-binding transcriptional regulator CsoR. ctpV was identified as a 40 member of the M. tb whole-genome transcriptional response to copper at both growth-permissive and toxic physiological levels, with highest induction occurring at toxic copper levels. Sequence analysis showed that ctpV has ~70% protein-level similarity to previously characterized copper 45 transporters involved in copper export and import in *Escherichia coli* and *Enterococcus hirae*, respectively. Thus, due to its particularly high induction during exposure to toxic levels of copper, ctpV may encode a copper exporter required for detoxification in the presence of elevated cop-50 per.

In the following example, the role of ctpV in mycobacterial copper response and its relevance to the development of tuberculosis is shown. CtpV is a copper exporter required for copper homeostasis in M. tb. The CtpV copper exporter is also required for the full virulence of the bacteria in a mouse model of infection.

B. Construction of the ctpV Knockout Mutant

A knockout mutant of ctpV, Δ ctpV, was created in the virulent M. tb strain H37Rv by replacing the coding region of ctpV with a hygromycin resistance cassette using homologous recombination. Referring to FIG. **2**, the Δ ctpV mutant was created with homologous recombination via pML21, a derivative of pPR27, which resulted in the deletion of 2.1 kB of the ctpV coding region (represented in black) and the insertion of a 3.5 kB region encoding a hygromycin resistance cassette. The ctpV gene is 2313 base pairs long. About 2.1 kB of the coding sequence of ctpV

(base 102 to 2239) were deleted from the genome of M. tb and replaced by the hygromycin cassette.

Briefly, to construct $\Delta ctpV$, 800 basepair fragments of both the upstream and downstream portion of the gene were amplified by PCR (primers AMT567, AMT568, AMT371, 5 and AMT372 are listed in Table 3). The amplified fragments were cloned into the pGEM-T Easy vector (Promega, Madison, Wis.). The fragments were digested with the flanking restriction enzyme sites (AfIII/XbaI and HindIII/SpeI for upstream and downstream portions, respectively) and 10 ligated into pYUB854. After digestion by NotI and SpeI (Promega), the linearized vector was ligated into pML19, a derivative of pPR27 where a kanamycin resistance cassette has been inserted into the PstI site. The resulting vector was named "pML20".

This vector was electroporated into electrocompetent M. tb using a Gene Pulser II machine (BioRad, Herculese, Calif.), and cells were plated onto Middlebrook 7H10 supplemented with 10% albumin-dextrose-catalase (ADC) and 50 ug/mL hygromycin (Invitrogen, Carlsbad, Calif.). 20 After one month of growth at 32° C., transformants were grown for two weeks with shaking at 32° C. in Middlebrook 7H9 supplemented with 10% ADC and 50 ug/mL hygromycin. These cultures were plated onto Middlebrook 7H10 supplemented with 10% ADC, 2% sucrose, and 50 ug/mL 25 hygromycin and incubated at 39° C. for three weeks. The genomic incorporation of the plasmid was confirmed via the inability of colonies to grow on Middlebrook 7H10 supplemented with 25 ug/mL kanamycin.

The transformant used for experiments, $\Delta ctpV$, was con- 30 firmed via negative PCR for the ctpV coding region and positive PCR for the hygromycin resistance cassette with primers listed in Table 3, AMT885, AMT886, AMT887, and AMT926.

Additionally, Southern blot analysis was performed on 35 Δ ctpV and wild type genomic DNA (5 µg) digested with BamHI (Promega), using probes for the remaining coding region of ctpV or the hygromycin resistance cassette. Referring to FIG. 3, the mutant was confirmed with Southern blots using a membrane constructed from BamHI-digested 40 genomic DNA for WT or Δ ctpV. Incubation with a P-32 labeled probe for the remaining ctpV region (FIG. 3, left) revealed the increased size of the band in Δ ctpV resulting from the loss of two BamHI restriction enzyme sites within the ctpV coding region, as shown in FIG. 2, when it was 45 replaced with HygR, which contains no BamHI sites. Additionally, a probe for the hygromycin resistance cassette (FIG. 3, right) hybridized only to the mutant gDNA.

Because ctpV is the third gene in the 4-gene cso operon, Δ ctpV was tested for possible polar effects on the down- 50 stream gene of unknown function, rv0970. Using reversetranscriptase PCR, the transcription of rv0970 in the mutant strain was confirmed. Referring to FIG. 4, the polarity of the ctpV knockout mutant was addressed using RT-PCR to check for transcription of its downstream gene. In the 55 wild-type strain (left), positive bands show that ctpV and the downstream gene rv0970 are both encoded in the genome and transcribed (able to be amplified from cDNA), with negative amplification from RNA shown as a negative control. In the isogenic mutant $\Delta ctpV$ (right), the ctpV 60 coding region is not present in the genome nor is it transcribed, but the downstream gene rv0970 is unaffected.

C. Construction and Evaluation of a ctpV Complement

A complemented strain was created by cloning the ctpV coding region into an integrative vector (pMV361) contain- 65 ing the constitutive hsp60 promoter and transforming into the Δ ctpV mutant strain. Integration of ctpV into the Δ ctpV

genome to create the complemented strain Δ ctpV:ctpV was confirmed with PCR, and restored gene expression was confirmed with qRT-PCR.

Briefly, for complementation of $\Delta ctpV$, the ctpV coding region was amplified and cloned into the pGEM-T easy vector for sequencing. The pGEM vector was then digested with EcoRI and HindIII (Promega), and the fragment was ligated into pMV361. The vector was sequenced, and then electroporated into electrocompetent $\Delta ctpV$ cells and plated on 7H10 supplemented with 10% ADC with 50 ug/mL hygromycin and 25 ug/mL kanamycin. The complemented strain was confirmed using a forward primer within the pMV361 vector (hsp60) and a reverse primer within the ctpV coding region.

D. Evaluation of $\Delta ctpV$, Complement $\Delta ctpV$:ctpV and Wild-Type M. tb Strain H37Rv

Referring to FIG. 5, expression of ctpV was measured using qRT-PCR, with cDNA created from 30 mL cultures exposed to 500 µM Cu. Data is expressed as fold-change relative to cultures kept copper-free, a condition in which expression from the cso operon is minimal. qRT-PCR did not detect expression of ctpV in the knockout mutant (middle), but expression was restored in the complemented strain (right). The higher level of induction in the complemented strain relative to WT H37Rv (left) is indicative of the increased strength of the hsp60 promoter used for complementation relative to the native cso promoter.

A growth curve in 7H9 media revealed that ActpV and its complement ActpV:ctpV have no generalized growth defects relative to WT. Referring to FIG. 6, growth curves of WT, its isogenic mutant $\Delta ctpV$, and the complemented strain ∆ctpV:ctpV were performed in 7H9+ADC. 7H9 media was prepared using Remel brand 7H9 Middlebrook powder, prepared as described by manufacturer. 10% ADC supplementation consisted of adding 100 mL containing 2 grams glucose, 5 grams BSA fraction V, and 0.85 grams NaCl to 900 mL 7H9 media. Cultures were seeded from stock to OD 0.10 and allowed to grow for 14 days at 37° with shaking, with CFUs taken at 0, 4, 8, and 14 days via plating on 7H10+ADC. The data show an identical growth rate among the three strains. Two biological replicates were performed.

CsoR is induced proportionally to intracellular copper concentration. The ActpV mutant shows increased expression of csoR at 500 µM copper as compared to wild-type, while the Δ ctpV:ctpV mutant shows decreased expression of csoR at 500 µM copper. (See FIG. 35).

The $\Delta ctpV$ mutant and the complemented strain $\Delta ctpV$: ctpV were then used to experimentally characterize the role of ctpV in copper response.

E. ctpV Expression is Required for Optimal Survival in High Copper

To test the role of ctpV in copper transport, copper sensitivity between $\Delta ctpV$ and wild-type H37Rv M. tb ("WT") were compared. The knockout of a copper exporter would be expected to result in increased sensitivity to copper-based toxicity, and this phenotype has been observed in knockouts of previously characterized copper exporters in other organisms. To test the copper sensitivity phenotype of Δ ctpV, growth curves of WT and Δ ctpV in liquid broth cultures supplemented with defined amounts of copper were performed using a range of copper concentrations previously determined to be physiologically relevant.

Growth curves were performed in 30 mL Cu-free Sauton's minimal media+0.05% Tween, prepared using water treated with Chelex (Sigma-Aldrich, St Louis, Mo.), with defined amounts of CuCl₂ added. Glassware was acidwashed (1N nitric acid) to maintain metal-free conditions.

Cultures were seeded to OD 0.1 with bacterial stock washed 2× in Sauton's, and allowed to grow for 14 days at 37° C. with shaking. Colony forming units ("CFUs") were determined at 0, 4, 8, and 14 days post-exposure by plating on Middlebrook 7H10+10% ADC, with 50 ug/mL hygromycin 5 added in the case of the mutant and complemented strains.

Growth at 0 μ M and 50 μ M CuCl₂ were identical among the three strains, as shown in FIG. 7, thus only data for WT at $0 \,\mu\text{M}$ and $50 \,\mu\text{M}$ CuCl₂ are shown in FIG. 8. Referring to FIG. 8, at 500 μ M copper, Δ ctpV displayed an increased 10 copper sensitivity relative to WT, while the complemented strain showed a decreased copper sensitivity. Comparisons of CFUs of $\Delta ctpV$ and WT strains revealed that at toxic levels of copper (500 μ M CuCl₂), the Δ ctpV strain, lacking ctpV, survived for 8 days, while the WT strain survived for 15 14 days.

F. ctpV Expression is Required for Virulence of M. tb

The ctpV gene is part of a 29-gene genomic island called the in-vivo expressed genomic island ("iVEGI") previously shown to be preferentially induced in mice relative to in 20 vitro culture. The ctpV gene may play a role in the survival of M. tb within a host, as experiments have shown that ctpV is a copper exporter, and data indicate that copper homeostasis in bacteria may play a role in pathogenesis, though this had not previously been tested in M. tb.

BALB/c mice were infected with either $\Delta ctpV$ or wildtype M. tb using a low-dose aerosolization protocol. Bacterial survival and mouse lung pathology were measured at short-term as well as long-term time points via the homogenization and plating of infected lung tissue as well as organ 30 histology. Additionally, mice infected with the two strains were monitored over the long-term course of the infection and the survival of the infected mice was recorded.

Briefly, BALB/c mice (Harlan, Indianapolis, Ind.) were infected in a Glas-Col chamber (Glas-Col, LLC, Terra 35 Haute, Ind.) loaded with 10 mL of either Δ ctpV or wildt-type at OD 0.30. Infectious dose of approximately 300 CFU/ animal was confirmed via a 1-day time point. CFUs were determined by homogenizing lung tissue in PBS buffer and plating on Middlebrook 7H10+10% ADC, followed by 40 incubation at 37° C. for one month. Final CFUs were normalized to the weight of the lung tissue used. Sections of lung, liver, and spleen tissue were taken and incubated in formalin prior to sectioning and staining with H&E and AFS. Histopathology slides were examined and scored by a 45 pathologist not associated with the study.

As shown in FIG. 9, a decrease in lung CFUs of $\Delta ctpV$ relative to WT was observed at both short-term and longterm time points. Referring to FIG. 9, the bacterial load of mouse lungs after infection with either wild type (H37Rv) or 50 its isogenic mutant ActpV was determined via homogenization of lungs from infected mice (N=3-5 per time point) in PBS and plating on 7H10+ADC (numbers normalized to grams of lung tissue homogenized) with approximately one-log difference seen between ActpV and WT at 2 weeks 55 and 38 weeks. Mice infected with Δ ctpV lived longer than mice infected with WT, with a 18-week increase in time to death, as shown in FIG. 10. Referring to FIG. 10, the survival of mouse groups (N=10) after infection with WT or ActpV is shown. The median survival time for mice infected 60 delayed copper sensitivity phenotype as shown in FIG. 10. with WT was 29 weeks, versus 47 weeks for mice infected with $\Delta ctpV$.

As shown in FIG. 11, acid-fast stains of histology sections confirm the lower bacterial load of mice infected with $\Delta ctpV$ compared to infection with the wild-type strain at two weeks 65 post infection. As shown in FIG. 12 and FIG. 36 (4 weeks post infection comparison of mouse lung tissue infected with

wild-type, Δ ctpv and the Δ ctpV::ctpv M. tb complement), histopathology revealed lower levels of tissue destruction along the course of infection with $\Delta ctpV$ relative to WT, even at time points where bacterial load was not significantly different between $\Delta ctpV$ and WT. At 8 weeks post infection, lung tissue from mice infected with ActpV displayed granulomatous inflammation, whereas mice infected with H37Rv displayed massive granulomatous inflammation with more lymphocytic infiltration. And by 38 WPI, granuloma formation occupied almost the whole lungs of mice infected with the wild-type strain, compared to only 50% of tissues of mice infected with the ActpV mutant. However, whether wild type or the $\Delta ctpV$ were used for infection, granulomatous lesions included sheets of lymphocytes and aggregates of activated macrophages. Leisons observed in the complemented strain were very similar to those observed in mice infected with the H37Rv strain.

Immunohistochemstry using IFN-y antibodies was performed on lung tissue sections from mice infected with WT, ActpV or ActpV::ctpV M. tb strains. At eight weeks post infection, mice infected with the $\Delta ctpV$ mutant showed decreased IFN- γ expression relative to mice infected with the corresponding wild-type M. tb strain. The IFN-y antibody appears brown in FIG. 34.

Taken together, mouse infection data indicates a role for ctpV in M. tb survival in lungs as well as overall virulence and host mortality.

G. Other Genes are Expressed under High Copper Conditions in the ctpV Knockout

In M. tb, ctpV is very highly expressed at toxic concentrations of copper (500 μ M), and it has been shown that ctpV is required for normal survival at this level of copper. Interestingly, the genome of M. tb encodes a number of genes with high sequence similarity to ctpV. Specifically, ctpV is a metal translocation P-type ATPase, and there are ten other predicted metal-translocating P-type ATPases in the H37Rv genome with significant sequence similarity to ctpV as shown in Table 1. With the exception of ctpV, potential cation prediction is based solely on sequence data. Percent similarity was determined at the protein level using MATCHER. Sequences were obtained from Tuberculist.

TABLE 1

Predicted Metal-Translocating P-type ATPases in the H37Rv Genome with Significant Sequence Similarity to ctpV						
Gene name	Product name	Potential Cation	% similarity to CtpV			
rv0092	CtpA	Copper	65.3			
rv0103c	CtpB	Copper	61.4			
rv3270	CtpC	Unknown	54.7			
rv1469	CtpD	Cadmium	50.4			
rv0908	CtpE	Unknown	44.5			
rv1997	CtpF	Unknown	44.7			
rv1992c	CtpG	Unknown	55.5			
rv0425c	CtpH	Unknown	44.1			
rv0107c	CtpI	Magnesium	44			
rv3743c	CtpJ	Cadmium	49.8			
rv0969	CtpV	Unknown	_			

The presence of redundant proteins is indicated by the The eight-day delay in a phenotypic difference between WT and $\Delta ctpV$ implies that, initially, other mechanisms may be able to compensate for the lack of ctpV, although any such functional complementation is only partial after eight days.

Cultures of ActpV were exposed to 500 µM CuCl₂ for 24 hours and transcript levels of the cells were compared to those of wildtype cultures that had been exposed to the same

conditions, as published previously (see e.g., Ward, et al., J Bacteriol 2008 April; 190(8): 2939-46).

Briefly, cultures of $\Delta ctpV$ were inoculated to OD 0.1 in Sauton's media and allowed to grow shaking at 37° C. to OD 0.6. The cultures were then supplemented with 500 μ M ⁵ CuCl₂ and incubated for three more hours prior to spinning down the cultures and freezing immediately at -80° C.

Briefly, RNA was extracted using a Trizol-based method (Invitrogen, Carlsbad, Calif.), and treated with DNAse I (Ambion, Austin, Tex.) to remove contaminating DNA. cDNA was synthesized from 1 µg total RNA using an Invitrogen SuperScript ds-cDNA synthesis kit in the presence of 250 ng genome-directed primers. cDNA clean up, Cv3 labeling, hybridizations, and washing steps were performed using the NimbleGen gene expression analysis protocol (NimbleGen Systems, Inc., Madison, Wis.). Microar18

ray chips were purchased from NimbleGen Systems, Inc., and they contained nineteen 60-mer probes for each of the 3,989 open reading frames identified in the genome of M. tb H37Rv, with five replicates of the genome printed on each slide (total of 95 probes/gene). Slides were scanned using an Axon GenePix 4000B scanner (Molecular Devices Corporation, Sunnyvale, Calif.), and fluorescence intensity levels normalized to 1000. Significantly changed genes between WT and $\Delta ctpV$ were determined using the EBArrays package in R (R is an open source platform used by Bioconductor, an open source and open development software project). A cutoff value of 0.50 for the probability of differential expression, determined using an LNN model, was used to determine statistically differentially expressed genes.

Ninety-eight genes with significantly different expression levels between $\Delta ctpV$ and WT after exposure to 500 μM $CuCl_2$ were identified and are listed in Table 2.

TABLE 2

Genes with Significantly Different Expression Levels between ActoV and WT after Exposure to 500 µM CuCl ₂					
	ΔetpV500)/			
rv name	wt500	Gene name	Description		
Gene Regulation	-				
rv1221	1.86	sigE	ECF subfamily sigma subunit		
rv1379	1.57	pvrR	regulatory protein - pyrimidine biosynthesis		
rv1398c	2.14	F 5	conserved hypothetical protein		
rv1909c	4.46	furA	ferric uptake regulatory protein		
rv1994c	2.98		transcriptional regulator (MerR family)		
rv3260c	1.81	whiB2	WhiB transcriptional activator homologue		
Transporters	_				
	2.45	- 4 37			
1V0909 m/2308a	-2.45	ctp v	cation transport Airrase		
Membrane/secreted proteins	-2.14	Cysw	surpliate transport system permease protein		
^	-				
rv0451c	-2.83	mmpS4	conserved small membrane protein		
rv0970	-3.07		hypothetical protein		
rv1566c	1.54		putative exported p60 protein homologue		
rv1799	1.52	lppT	probable lipoprotein		
rv1980c	-2.47	mpt64	secreted immunogenic protein Mpb64/Mpt64		
rv1987	1.90		probable secreted protein		
rv2080	2.75	lppJ	lipoprotein		
rv3763	1.86	lpqH	19 kDKD		
Enzymes	-				
rv0247c	-1.72		probable iron-sulphur protein *(succinate dehydrogenase)		
rv0462	-1.73		probable dihydrolipoamide dehydrogenase		
rv1182	-2.21	papA3	PKS-associated protein, unknown function		
rv1185c	-1.78	fadD21	acyl-CoA synthase		
rv1471	1.89	trxB	thioredoxin reductase		
rv1520	1.58		glycosyltransferase		
rv1908c	-1.68	katG	catalase-peroxidase		
rv2196	-1.82	qcrB	cytochrome b component of ubiQ-cytB reductase		
rv2200c	-1.58	ctaC	cytochrome c oxidase chain II		
rv2244	2.00	acpM	acyl carrier protein (meromycolate exten-		
rv2445c	-1.58	ndkA	nucleoside diphosphate kinase		
rv2930	-1.75	fadD26	acyl-CoA synthase		
rv3116	-1.55	moeB	molybdopterin biosynthesis		
rv3117	-1.61	cysA3	thiosulfate sulfurtransferase		
rv3146	-1.62	nuoB	NADH dehydrogenase chain B		
rv3359	1.59		probable oxidoreductase		
rv3377c	-1.68		similar to many cyclases involved in steroid biosynthesis		
rv3824c	-1.80	papA1	PKS-associated protein, unknown function		
Mce proteins	_	- *	* ·		
rv0169	-1 58	mce1	cell invasion protein		
rv0170	-1 87		part of mcel operon		
	1.07		L		

TABLE 2-continued

Genes with Significantly Different Expression Levels between ActpV and WT after Exposure to 500 µM CuCl ₂					
	ΔctpV500	/			
rv name	wt500	Gene name	Description		
rv0171	-1.59		part of mce1 operon		
rv0174	-1.57		part of mce1 operon		
Kibosomai proteins	_				
rv0055	3.29	rpsR	30S ribosomal protein S18		
rv0056	1.75	rplI	50S ribosomal protein L9		
rv0719	-1.65	rpsQ rpIF	50S ribosomal protein L6		
rv1298	2.11	rpmE	50S ribosomal protein L31		
rv2882c	-1.65	frr	ribosome recycling factor		
Protein fate	_				
rv2109c	-2.13	prcA	proteasome [alpha]-type subunit 1		
rv2457c	-1.77	clpX	ATP-dependent Clp protease ATP-binding		
rv2903c	1.83	lenB	subunit ClpX signal peptidase I		
rv2094c	3.74	tatA	tatA subunit tatAB secretion system		
rv3875	2.09	esat6	early secretory antigen target		
Other	_				
rv3841	1.75	bfrB	bacterioferritin		
rv0001	-1.61	dnaA	chromosomal replication initiator protein		
rv1080c Hypothetical proteins	-1.80	greA	transcription elongation factor G		
Typometrear proteins	_				
rv0021c	1.83		conserved hypothetical protein		
rv0140 rv02364	1.54		conserved hypothetical protein		
rv0500B	1.81				
rv0508	1.55		hypothetical protein		
rv0664	-1.52		hypothetical protein		
rv0730	-1.72		conserved hypothetical protein		
rv0740	-1.52		conserved hypothetical protein		
rv0755A	1.90				
rv0/59c rv0991c	1.62		hypothetical protein		
rv1087A	1.51		-51		
rv1134	1.61		hypothetical protein		
rv1334	1.58		conserved hypothetical protein		
rv1532c	1.51		conserved hypothetical protein		
rv1765A	2.35				
rv1783	-2.18		conserved hypothetical protein		
rv1794	-2.07		conserved hypothetical protein		
rv1982c	1.69		conserved hypothetical protein		
rv2269c	1.57		hypothetical protein		
rv2401	1.56		hypothetical protein		
rv2623	-1.58		conserved hypothetical protein		
rv20520	1.55		hypothetical protein		
rv2708c	1.51		conserved hypothetical protein		
rv2804c	1.74		hypothetical protein		
rv2970A	1.69				
rv3022A	-2.33		conserved hypothetical protein		
rv3142c	2.34		hypothetical protein		
rv3221A	1.99				
rv3222c	1.74		conserved hypothetical protein		
rv3288c	-1.90		conserved hypothetical protein		
rv3412	2.24 1.87		conserved hypothetical protein		
rv3492c	-1.57		conserved hypothetical protein		
rv3528c	1.90		hypothetical protein		
rv3614c	-1.65		conserved hypothetical protein		
rv3010c	2.53		conserved hypothetical protein		
rv3658c	1.63		probable transmembrane protein		
rv3686c	2.01		conserved hypothetical protein		
rv3822	-1.52		conserved hypothetical protein		

To confirm the validity of the microarray data, expression levels of nine of the genes identified in the microarray dataset were tested with qRT-PCR.

Briefly, qRT-PCR was performed using a SYBR greenbased protocol. cDNA was synthesized from DNAse-treated 5 RNA, obtained as described above, using SuperScript III (Invitrogen) as directed by the manufacturer, in the presence of 250 ng mycobacterial genome-directed primers. 100 ng cDNA was used as template in a reaction with iTaq SYBR green Supermix with ROX (Bio-Rad Laboratories, Hercules, Calif.) in the presence of gene-specific primers (see Table 3) at a concentration of 200 nM. Cycle conditions were 50° C. for 2 min, 95° C. for 3 min, and 40 cycles of 95° C. for 15 seconds and 60° C. for 30 seconds. Reactions were performed in triplicate on an AB7300 machine (Applied Biosystems, Foster City, Calif.) with fluorescence read at the 60° C. step. Threshold cycle values were normalized to 16S rRNA expression.

TABLE 3

Gene-Specific Primers (SEQ ID NOs: 1-28, respectively, in order of appearance)					
Primer	Sequence	Purpose			
AMT371	ATCACTACTAGTTGAAGACGGTTCGGGGCCAT	ctpV flank cloning			
AMT372	ATCACTAAGCTTATAGGCGTGCACGGCGTGCA	ctpV flank cloning			
AMT567	ATCACTTCTAGAGGGTTCTCCTCGGTCAGCGTG	ctpV flank cloning			
AMT568	ATCACTGGTACCCAGAAACGTCCGCCCCGCTG	ctpV flank cloning			
AMT874	GCGGGTGTGGTTGGCCTTGCCGTT	Internal primer for mutant screening			
AMT875	GCGGCAACGATCGCCGCACCGATG	Internal primer for mutant screening			
AMT926	TGGTGGACCTCGACGACCTGCAGG	ctpV mutant screening			
AMT887	ACGAAGCGCGCGAAGGGATGCTGG	ctpV mutant screening			
AMT885	GGAACTGGCGCAGTTCCTCTGGGG	ctpV mutant screening			
AMT886	TTGACCGCAAAGAAGCGCGCGCGGCG	ctpV mutant screening			
AMT1335	ACCTCGAACATGGACAC	ctpV Forward			
AMT1336	ACCGGCAAACAACTGATAC	ctpV Reverse			
AMT1114	CAATCCAGGGAAATGTCA	esxA Forward			
AMT1115	AGCTTGGTCAGGGACT	esxA Reverse			
AMT1116	TCGTTGGGCAAGTCAT	tatA Forward			
AMT1117	GCTTCCGCTTTGTTCT	tatA Reverse			
AMT1132	AACCCGGTGGCAAACAAC	ctaC Forward			
AMT1133	CGCAGTGGCCCACGAATG	ctaC Reverse			
AMT1168	CCGTCCTGGAAGCAGTGAATG	furA Forward			
AMT1169	AAACGCACGGCACCGAAA	furA Reverse			
AMT1178	GCCGCACAGTTCAACGAAAC	rv1471 Forward			
AMT1179	CGCACCAGGAGGCCCAAT	rv1471 Reverse			
AMT1194	AGCACGATGCCGAAGACCTG	sigE Forward			
AMT1195	TGCCCGGCTGGTAATTCTG	sigE Reverse			
AMT1196	GTCGAGGAACGAAACCATGCAAT	bfrB Forward			
AMT1197	ACCGTGTCTACGCCGGGAAT	bfrB Reverse			
AMT1198	CGCGGCGATGAACGACAT	qcrB Forward			
AMT1199	ACGGCGGCAGAATCACCAT	qcrB Reverse			

The microarray fold-change direction was confirmed by qRT-PCR for all nine genes, as shown in FIG. 13. Referring to FIG. 13, from left to right are: esxA, tatA, ctpV, ctaC, furA, rv1471, sigE, bfrB, and qcrB. qRT-PCR was used to confirm selected genes from the microarray data set, using RNA from the original microarray experiment as the source for cDNA. Direction of induction was reproduced in gRT-PCR data 100% of the time with data shown as fold change of expression in ActpV relative to WT and normalized to 16S expression. Additionally, qRT-PCR of cDNA from $\Delta ctpV$: ctpV cells treated with the same 3-hour exposure to 500 µM copper showed that complementation restored WT-levels of induction for selected genes from the microarray data set.

Because the removal of a copper exporter increases 15 intracellular copper concentration, it was expected that the $\Delta ctpV$ response to toxic copper levels relative to the response of WT would show a transcriptional response of many of the 15 genes previously associated with copper stress in M. tb. In fact, 11/15 of the genes previously 20 associated with toxic copper response were identified as having significantly changed transcript levels between ΔctpV and WT during copper stress. A number of these genes (N=7) showed a change in the direction of induction (e.g., genes upregulated in general copper response were ²⁵ downregulated after deletion of CtpV).

In addition to the overlap with the copper stress dataset, eighty-seven other genes were identified, including functional categories not previously associated with copper 30 response, such as mammalian cell entry ("mce") family proteins, ribosomal proteins, and a number of membrane/ secreted proteins. While these studies have shown that deletion of ctpV invokes a unique response to environmental copper via increased intracellular copper levels, it is appar-35 ent that deletion of ctpV also has other affects on the intracellular environment of the bacterium that cannot easily be attributed to copper concentration alone. Though not wishing to be bound by any particular theory, it is possible that the lack of a membrane protein affecting membrane stability or signaling, or deletion causes indirect affects on other proteins such as regulators responsive to generalized cellular stress.

The whole-genome microarray of Δ ctpV relative to WT at 45 high copper did not reveal induction of any of the genes with high sequence similarity to CtpV (see Table 1). The more sensitive technique of qRT-PCR was then used to more precisely investigate the transcriptional induction of all of 50 the other P-type ATPases in the M. tb genome.

These data revealed that only one other P-type ATPase, ctpG, is induced in the presence of copper, and is particularly induced in the absence of ctpV, as shown in FIG. 14. Referring to FIG. 14, a qRT-PCR survey of the response of 55 all predicated metal-transporting P-type ATPases within the M. tb H37Rv genome to copper was conducted. The transcriptional profile at 500 µM copper in the wildtype strain (gray bars) shows induction of only ctpG and ctpV. In the absence of ctpV (black bars), the induction of ctpG is 60 increased. Data are displayed as fold-change relative to expression at 0 µM Cu, and are normalized to expression of 16S.

A predicted metalloregulatory protein, rv1994c, lies upstream of ctpG, and was identified via microarrays as 65 responsive to general copper stress as well as the absence of ctpV.

Example II: rv0348 Knockout Mutant

A. Overview

Earlier analysis of the chronic stage of tuberculosis in mice identified several unique genes induced during chronic infection, including a novel transcriptional regulator encoded by the rv0348 gene (also known as the "mosR" gene). Transcripts for rv0348 were upregulated ~200 fold after 60 and 140 days of M. tb infection in mice, and the Rv0348 protein was shown to bind to its own promoter. In this Example, an M. tb mutant is generated with an inactivated rv0348 gene to examine the role of this gene in M. tb survival in the murine model following aerosol infection.

B. The Arv0348 Knockout Mutant Shows Attenuated Activity Compared to its Wild-Type Counterpart

In BALB/c mice, the bacilli load of the $\Delta rv0348$ mutant strain was significantly lower compared to the H37Rv and rv0348-complemented strains, indicating a role for rv0348 in controlling mycobacterial virulence.

1. Strains, Media, Plasmids and Statistical Methods

Escherichia coli DH5a and HB101 were used as host cells for cloning purposes in all experiments of this Example. M. tb H37Rv and M. smegmatis mc²155 strains were grown in 7H9 Middlebrook liquid medium (BD Biosciences, Rockville, Md.) and on 7H10 Middlebrook plates supplemented with albumin dextrose catalase ("ADC") and antibiotics, when needed (25 µg/ml kanamycin or 50 µg/ml hygromycin). Protocols for DNA manipulations employed throughout this Example, including PCR, cloning, DNA ligations, and electroporation were performed as described in "Molecular cloning, a laboratory manual," Sambrook, et al., Cold Spring Harbor Laboratory Press, Cold Spring Harbor, N.Y. (1989) or according to manufacturer's recommendations. A list of plasmids and constructs used in this Example is presented in Table 4. Student's T-test implemented in Microsoft Excel was used to assess significance difference among samples at p<0.05 level for the reporter assays and bacterial load counts.

TABLE 4

Plasmids and Constructs used in Experiments of Example 2			
Plasmid	Characteristics		
pYUB854	Cosmid for disruption construct		
pMV361	Integrative mycobacterial shuttle vector. Kan ^R		
M. smeg::	Recombinant M. smegmatis harboring the		
pML21	whole Rv0348 operon under the control of		
	its own promoter in addition to hsp60. Kan^R		
pML23	pMV361 harboring Rv0348 gene. Kan ^R		
pCV77	Replicative shuttle vector with promoterless		
	LacZ transcriptional fusion. Kan ^R		
pML24	pCV77 with hygromycin cassette in		
	opposite direction to LacZ. Kan ^R , Hyg ^R		
pML25	pML24 harboring the promoter region of		
	Rv0347 operon. Kan ^R , Hyg ^R		
pML26	pML24 harboring the promoter region of		
	Rv0167 (mce1 operon). Kan ^R , Hyg ^R		
pML27	pML24 harboring the promoter region of		
	Rv0700 ($rpsJ$). Kan ^R , Hyg ^R		
pML28	pML24 harboring the promoter region of		
	Rv3130c (tgs1). Kan^{R} , Hyg^{R}		
pML29	pML24 harboring the promoter region of		
	hsp60. Kan ^R , Hyg ^R		

The procedures for cloning, overexpression, and purification of M. tb Rv0348 in E. coli are described in Talaat et al., 2007, J. Bacteriol., 189:4265-4274. Total RNA samples were extracted from mycobacterial cultures grown to OD₆₀₀=0.5 or 1.5 using Trizol (Invitrogen, Carlsbad, Calif.) as described in Talaat et al., Proc. Natl. Acad. Sci U.S.A, 2004, 101:4602-4607 and Talaat et al., 2007, J. Bacteriol.,

189:4265-4274. Extracted mycobacterial total RNA samples were treated with DNAse I (Ambion, Austin, Tex.) until no

26

DNA was detected using PCR primers for the 16S rRNA gene. Primers used in Example 2 are listed in Table 5.

TABLE	5
-------	---

Prime	rs used	in	Experiments	of	Exan	nple	2	(SEQ	ID	NOs:	29-94,	respectively,	
			in	or	der	of a	app	earan	ce)				
TD													

Gene ID	sequence	purpose
Rv3130c F1	5'-gggtttctcaaggcagaaga-3'	qRT-PCR
Rv3130c R1	5'-ggatcgtccacccatttg-3'	qRT-PCR
Rv2628 F	5'-aatccgccaccatctatcag-3	qRT-PCR
Rv2628 R	5'-atctcaacggacaggtgctc-3'	qRT-PCR
Rv0700 F1	5'-ggacagaagatccgcatcag-3'	qRT-PCR
Rv0700 R1	5'-cccgcgagtccttgtactta-3'	qRT-PCR
Rv0167 F1	5'-attctttcgcatgtgtgtgc-3'	qRT-PCR
Rv0167 R1	5'-gaagatcaacagcaccgtca-3'	qRT-PCR
Rv0347 F1	5'-agcttgccgatctcaaactc-3'	qRT-PCR
Rv0347 R1	5'-cttctgccggaggttctttc-3	qRT-PCR
Rv0569 F	5'-cgatagatcaaccggaccac-3'	qRT-PCR
Rv0569 R	5'-cattctgctcctccgcagt-3'	qRT-PCR
Rv1996 F	5'-caacaaacgaacctcggaat-3'	qRT-PCR
Rv1996 R	5'-tactcaaatgcccacccttc-3'	qRT-PCR
Rv1997 F	5'-tcaagaatccaaggcagagg-3'	qRT-PCR
Rv1997 R	5'-tgactcgttcacgctcaatc-3'	qRT-PCR
Rv2032 F	5'-gacttggtggagtcgcagtt-3'	qRT-PCR
Rv2032 R	5'-ccaatgaactgtgcggtatg-3'	qRT-PCR
Rv3128c F	5'-gggctcaaagcttctgtcac-3'	qRT-PCR
Rv3128c R	5-tggtggcctagtggtttttc-3'	qRT-PCR
Rv0348A	5'-actagtctacccgggctgggaggagtttcg-3'	Knockout of Rv0348
Rv0348B	5'-aagettgeaaageegtagteegegagetge-3'	Knockout of Rv0348
Rv0348C	5'-tctagatggcgggacatcgcacgcgttgtc-3'	Knockout of Rv0348
Rv0348D	5'-ggtaccaacgggccaacggtgctgtcggag-3'	Knockout of Rv0348
Rv0348 F1	5'-TCGCGGACTACGGCTTTG-3'	qRT-PCR in stress conditions
Rv0348 R1	5'-CCTTGCGCCATTTGGTGATTG-3'	qRT-PCR in stress conditions
Rv0348 F2	5'-atcctctagaatgaccatttcgttct-3'	Cloning of Rv0348 gene in pMAL- c2
Rv0348 R2	5'-gcgcaagcttaccgcttgggtcttat-3	Cloning of Rv0348 gene in pMAL- c3
Rv0348 F3	5 ' - AA <u>GAATTC</u> GTGCCCGGCGCGCGCGAGTTGACG- 3 '	Cloning of Rv0348 operon into pMV361
Rv0348 R3	5 ' - CACCCCGCTC <u>AAGCTT</u> GCCTCGAC - 3 '	Cloning of Rv0348 operon into pMV361
Rv0348 F4	5'-ggg <u>gaattc</u> atgaccatttcgttctctagc-3'	Cloning of Rv0348 gene into pMV361
Rv0348 R4	5 ' - TGG <u>AAGCTT</u> TTACCGCTTGGGTCTTATCGA - 3 '	Cloning of Rv0348 gene into pMV361

TABLE 5-continued

Gene ID	sequence	purpose
Rv0347 F2	5'-cggtctagaAttgagctccctgggatggtg-3	Cloning into pML24
Rv0347 R2	5'-cggaagcttggccgtcacaacattcatgataa-3'	Cloning into pML24
Rv3130c F2	5'-cggaagcttGTAACCGCTGCCCGAAC-3'	Cloning into pML24
Rv3130c R2	5'-cgcggatccCACACCACGCTGAGGATCA-3'	Cloning into pML24
Rv0700 F2	5'-cggtctagaCGGGAAGCTCGCAGGTgg-3'	Cloning into pML24
Rv0700 R2	5'-cggaagcttCTCCCGCGAGTCCTTGTac-3'	Cloning into pML24
Rv0167 F2	5'-cggtctagaCGAAGACCTAGGTGAGTTCCTG-3'	Cloning into pML24
Rv0167 R2	5'-cggaagcttGAGCGTGAAGATCAACAGCA-3'	Cloning into pML24
hsp60	5'-cgctctagacgggtcttgttgtcgttggcgg-3'	Cloning into pML24
hsp60	5'-cggaagcttcattgcgaagtgattcctccgg-3'	Cloning into pML24
Rv0347 F3	5'-ttgtcgtgccgaccgtcgcggg-3'	EMSA
Rv0347 R3	5'-ggagtccatcgcgccagctcct-3'	EMSA
Rv0165c F	5'-tcaacggcagcaccacgtgg-3'	EMSA
Rv0165c R	5'-tgacccgatcgccgaaaccg-3'	EMSA
Rv0823c F	5'-acacagegeeeggaatgega-3'	EMSA
Rv0823c R	5'-ggaagcccgtacgggcaaga-3'	EMSA
Rv1846c F	5'-gtgtaggcaaggtcgcggcg-3'	EMSA
Rv1846c R	5'-ggetgeacgteettgtgtetacaee-3'	EMSA
Rv2160c F	5'-cagetegaaegegagttgge-3'	EMSA
Rv2160c R	5'-aagccatgcctagcgccgac-3'	EMSA
Rv1996 F	5'-gaagacgaggagcaccggcgct-3'	EMSA
Rv1996 R	5'-gtgcgcttgggcgaccaggtac-3'	EMSA
Rv3139 F	5'-TGCCCAGGCTGCCGGGCAACG-3'	EMSA
Rv3139 R	5'-gcgcagtgatcggttcagcgga-3'	EMSA
Rv0145 F	5'-GTCTCTTCGTTGGCCGAGACGCTGT-3'	EMSA
Rv0145 R	accogoogacgacaccaacacc	EMSA
Rv3825c F	5'-ccacttgcacaccgtccgaccg-3	EMSA
Rv3825C R	5'-gaagegteagaetaeeggeeeg-3'	EMSA
Rv3130c_F3	5'-GTAACCGCTGCCCGAAC-3'	EMSA
Rv3130c_R3	5'-CACACCACAGCTGAGGATCA-3'	EMSA
Rv0700_F3	5'-CGGGAAGCTCGCAGGT-3'	EMSA
Rv0700_R3	5'-CTCCCGCGAGTCCTTGT-3'	EMSA
Rv0167_F3	5'-CGAAGACCTAGGTGAGTTCCTG-3'	EMSA
Pv0167 P3	5 - GAGCGTGAAGATCAACAGCA - 3 '	FMSA

2. Construction of the rv0348 Knockout Mutant

The strategy to construct the rv0348 mutant included the insertion of a hygromycin cassette within the coding 65 sequence of the rv0348 gene using a specialized transduction-based protocol. Attempts to delete the whole gene with

the 200 bp flanking sequences failed to yield any mutants. Earlier transposon mutagenesis indicated the rv0347 gene flanking the rv0348 sequence was essential, explaining the failure to delete the whole rv0348 gene where flanking sequences were disrupted. However, following specialized

transduction of the insertion constructs (introducing the hyg^{*r*} sequence at 269 bp after the start of rv0348) to the M. tb H37Rv strain, several transductants were obtained. The coding sequence of rv0348 could not be replaced by hygR sequence so the generated mutant had all the sequence of 5 rv0348 but with hygR inserted at 269 bp after the translation start of rv0348.

A specialized transduction protocol was adopted with a few modifications to inactivate the rv0348 gene using the virulent strain of M. tb H37Rv. Approximately 800 bp- 10 fragments flanking the rv0348 ORF (specifically, flanking the 269 bp) were amplified using standard PCR protocols. Amplicons were cloned into pGEM-T vector (Promega, Madison, Wis.) and sequence verified before ligation into the pYUB845 vector using SpeI and HindIII for left arm and 15 XbaI and Acc65I for right arm to form the Allelic Exchange Substrate ("AES"). Construction of specialized transducing mycobacteriophages and transduction protocols were performed as described in Bardarov et. al., 2002, Microbiol., 148:3007-3017. Following 6 weeks of incubation at 37° C., 20 hygromycin-resistant colonies were selected for further analysis. PCR and Southern blot analyses were used to verify the mutant genotypes as described before (see, Talaat, et al., 2000, Am. J. Vet. Res., 61:125-128 and Wu et al., 2007, J. Bacteriol., 189:7877-7886). PCR, sequencing and South- 25 ern blot analyses of several transductants, shown in FIG. 16, verified the desired genotype ($\Delta rv0348$) in all transductants, and one of them was chosen for the rest of the analyses.

FIG. **15** shows the organization of the rv0348 operon and the strategy for gene disruption. Data in FIG. **16**A show a 30 Southern blot analysis of Sail-digested genomic DNA of the H37Rv WT and Δ rv0348/ Δ rv0348 mutant. Data in FIG. **16**B show PCR analysis of cDNA synthesized from RNA samples purified from H37Rv (lanes 1, 3, 5) or Δ rv0348/ Δ rv0348 mutant (lanes 2, 4, 6). Presence of transcripts of the 35 upstream and downstream genes of the rv0348 gene indicate that the Δ rv0348 mutant is non-polar.

To generate antibodies against purified Rv0348, two adult male New-Zealand White rabbits were inoculated with 125 μ g of the recombinant fusion protein in Fruend's incomplete 40 adjuvant (Sigma, St. Louis, Mo.) using an approved protocol by the Institutional Animal Care and Use Committee. Rabbits were housed individually in cages at 15 to 18° C. and given antibiotic-free food and water ad libdium. Each immunization was administered subcutaneously (12.5 μ g), intra-45 dermally (37.5 μ g), intramuscularly (50 μ g), and intraperitoneally (25 μ g) in accordance with the manufacturer's suggestions. Injections of the antigen-adjuvant mixture were administered every 3 weeks for a total of three immunizations. Antibody titers for seroconverted rabbits were measured by ELISA and immunoblot using recombinant purification tag-specific antibodies.

For immunoblotting, mycobacterial cultures were harvested and lysed by boiling in PBS buffer. Total crude extracts were centrifuged and soluble lysates and insoluble 55 pellets were separated on 12% SDS-PAGE and transferred onto PVDF membrane (Hybond-P, Amersham Biosciences). Membranes were saturated by 5% dried milk and rabbit polyclonal antibody was used as primary antibody at a dilution of ¹/₅₀₀₀ for 2 hrs. Horse raddish peroxidase conjugated to goat anti-rabbit IgG (Pierce Thermo Scientific, Rockford, Ill.) was used as secondary antibody at ¹/₃₀₀₀₀. Membranes were developed by Chemiluminescent kit according to the manufacturer's protocol (Pierce).

Data in FIG. **16**C show a Western blot analysis for 65 different M. tb strains using polyclonal antibodies raised in rabbits against MBP-Rv0348 protein. Pellets from (1) M. tb

H37Rv, (2) $\Delta rv0348$ mutant, (3) $\Delta rv0348$::rv0348 complemented strain, and (4) H37Rv::rv0348 overexpression strain, were subjected to immunoblotting. The level of expression of Rv0348 protein in M. tb H37Rv compared to other constructs was examined in order to determine its expression (or lack of expression) in M. tb bacilli with variable rv0348 constructs. Rv0348 was detectable, but at low levels, when mycobacterial pellets not culture filtrate samples were analyzed using Western blot, indicating intracellular expression of the Rv0348 protein. The blot for soluble fractions was negative (data not shown).

3. Construction and Evaluation of an rv0348 Complement The selected Δ rv0348 mutant was further used to construct the complementation strain where the coding sequence of rv0348 is expressed in-trans using pMV361rv0348 to yield the Δ rv0348::rv0348 construct. Attempts to introduce the whole operon into M. tb were unsuccessful due to several genomic rearrangements (data not shown). As can be seen in FIG. **17**, growth curves for all strains—wild type H37Rv, its isogenic mutant Δ rv0348, complemented strain Δ rv0348::rv0348, and M. tb H37Rv: rv0348—showed no measurable difference during in vitro growth in Middlebrook 7H9 broth. The four M. tb strains were inoculated into Middlebrook 7H9 broth at O.D600 0.02 and cultures were shaken at 37° C. in an incubator for six days. OD was monitored during the incubation time.

For complementation experiments, the coding sequence of the entire rv0348 operon (2.3 kb) or the coding sequence of the rv0348 gene alone (~654 bp) were amplified by PCR. Amplicons were cloned into pGEM-T vector and subsequently verified by DNA sequencing. Vectors were double digested by EcoRI and HindIII restriction enzymes followed by ligating gel-purified inserts into pMV361 to give rise to pML21 (Oprv0348) and pML23 (rv0348) shuttle vectors for the expression of the whole operon or rv0348 gene, respectively. Both plasmids (pML21 and pML23) were independently electroporated into electrocompetent M. smegmatis and M. tb H37Rv cells. Transformants were selected and subsequently analyzed by PCR to verify integration of the delivered sequences into the M. tb genome. Expression of the Rv0348 protein was further examined using immunoblotting as described above.

4. Evaluation of Δ rv0348, Complement Δ rv0348:rv0348 and Wild-Type M. tb strain H37Rv

Three groups (N=40) of 5-week old BALB/c mice were infected with H37Rv, \Deltarv0348 or \Deltarv0348::rv0348 strains and housed in BSL3 environment using an approved protocol from the University of Wisconsin, Institutional Animal Care and Use Committee ("IACUC"). Cultures of M. tb H37Rv, Arv0348 and Arv0348::rv0348 strains were grown to mid-log phase (OD_{600} =1). A total of 10 ml cultures adjusted to OD_{600} =0.3 were suspended in sterile PBS buffer and used for aerosolization using the Glass-Col aerosol chamber (Terra-Haute, Ind.) to generate an infectious dose of 200-400 cfu per mouse. Two mice were sacrificed at 4-6 hours post infection to enumerate the infectious dose by plating on 7H10 Middlebrook plates in the presence of hygromycin and/or kanamycin for the mutant and complemented strains, respectively. Mice (N=5) were sacrificed at different times post infection to remove lungs for plating on Middlebrook 7H10 agar for colony counting. Portions of livers, spleens and lungs were fixed in 10% neutral buffered formalin for at least 2 hrs before sectioning and staining with hematoxylin and eosin ("H&E") stain and Ziehl-Neelsen stain.

Culturing lung tissues at day 1 post infection confirmed that all groups of mice received a comparable infectious dose of each strain (220 CFU/mouse for H37Rv, 350 CFU/ mouse for the $\Delta rv0348$ and, 460 CFU/mouse for the $\Delta rv0348::rv0348$). Murine survival and lung colonization following aerosol infection M. tb with different copies of rv0348 is shown in FIGS. 18-20. FIG. 19 shows survival 5 curves of 3 mice groups (N=10) infected with H37Rv, Δrv0348 and Δrv0348::rv0348. FIG. 18 shows lung CFU/ GM murine lungs following aerosol infection with H37Rv, Δrv0348 and Δrv0348::rv0348. The "*" denotes significant difference at these times (Student's t-Test). FIG. 20 shows 10 histological analysis of lung sections of mice lungs at 2 weeks and at 20 weeks after infection with H37Rv, Δrv0348, and $\Delta rv0348$::rv0348. Note the level of accumulation of inflammatory cells (arrow heads) in H&E stained sections of mice groups.

As shown in FIG. 19, all mice infected with the $\Delta rv0348$ mutant survived the infection up to 40 weeks post infection ("WPI"; end of experiment) with a median survival time ("MST") >40 weeks, while mice infected with the wild type strain, H37Rv began to die at 27 WPI with MST=29 weeks. 20 As shown in FIG. 18, the mycobacterial count for the Δrv0348-infected group was significantly different from other groups, especially at 2, 30, 38 WPI, as at these WPI, the bacterial loads of the mutant strain were significantly lower than the wild type strain. This lower bacterial load of 25 the mutant strain is further demonstrated by data shown in FIG. 21, which shows CFU/g tissue in murine lungs at time of death for H37Rv wild-type strain, which occurred at 37 weeks, and for $\Delta rv0348$ strain, which occurred at 62 weeks.

The difference in CFU counts was mostly observed fol- 30 lowing 30 WPI and later, indicating a critical role for rv0348 in the chronic rather than the early phase of tuberculosis, where the difference was observable in only one data point. Initial colony counts of the complemented strain, Δrv0348:: rv0348 at 2 WPI were similar to those of the wild type 35 H37Rv strain indicating successful complementation of Rv0348. Nonetheless, colonization levels at subsequent times, in addition to its survival curve, indicated only a partial complementation of Rv0348 activity. PCR analysis of the retrieved colonies from mice lungs infected with the 40 RNA using SuperScript III (Invitrogen) as directed by the Δrv0348::rv0348 strain at all times indicted the stability of the complementation construct, even after 30 WPI in mice (data not shown). Failure of complementation after 8 weeks of infection could be explained by the strength of rv0348 operon promoter in comparison to hsp60 promoter used in 45 the complementation construct. LacZ assays in M. smegmatis showed that hsp60 promoter is at least 4 times weaker than the promoter of rv0348 operon (data not shown). Deficiency of in vivo complementation was encountered for several other genes using similar complementation vectors 50 and strategy.

As shown in FIG. 20, histopathological analysis of infected mice tissues showed typical, progressive granulomatous lesions in lungs of mice infected with the wild type or complemented strains where aggregates of foamy mac- 55 rophages were observed by 20 WPI. Granulomas were more visible as the disease progressed where they occupied almost the whole lungs by the time of death (~29 WPI). Conversely, a lower level of macrophage and lymphocyte aggregates were observed in mice infected with the zfrv0348 mutant. 60 Notably, inflammatory lesions were visible in 100% of lung sections of mice infected with H37Rv starting at 20 WPI and later, while lesions were observed in only 50% of lung sections of mice infected with the $\Delta rv0348$ mutant. This level of inflammatory response did not change significantly 65 by the end of the experiment (40 WPI) when $\Delta rv0348$ infected mice were sacrificed. Overall, bacterial loads and

survival curves in addition to histopathological analyses indicated the attenuation of the $\Delta rv0348$ mutant, especially during chronic tuberculosis.

C. rv0348 Function under Variable Stress Conditions

The transcriptional profiles of the isogenic mutant relative to its parental strain, H37Rv, indicated the regulation of several gene groups organized into operons and regulons including those involved in mammalian cell entry (mce1), hypoxia (dosR) and starvation.

The ability of the Rv0348 protein to affect transcription of these genes was further analyzed using a LacZ reporter assay and quantitative, real-time PCR (qRT-PCR).

1. Expression of rv0348 under Variable Stress Conditions Transcripts constituting the rv0348 operon are known to 15 be activated during starvation and extended anaerobic conditions. To examine the role of rv0348 gene in other mycobacterial defenses, cultures of the wild type strain H37Rv and its isogenic mutant, $\Delta rv0348$, were exposed to stress conditions that are thought to be activated during intracellular survival of M. tb. Following exposure to variable stressors, both colony counts and transcriptional profiles of rv0348 transcripts were assayed (for the H37Rv strain only).

Cultures for M. tb H37Rv, H37Rv∆rv0348, complemented strain, Arv0348::rv0348, or H37Rv M. tb:rv0348 were grown to early log phase (OD₆₀₀=0.5) and their colony counts were determined by plating on Middlebrook 7H10 agar plates in order to calculate the viable cells at the beginning of the experiment. Aliquots (10 ml) were subjected to 0.05% SDS treatment (Sodium Dodecyl Sulfate, Sigma) for 4 hrs at 37° C. or to heat shock at 45° C. for 24 hrs in a slow-shaking incubator. To test static growth conditions, 50 ml-aliquots of M. tb constructs were allowed to grow for 2 and 6 months without shaking in closed Falcon tubes. At the designated times, culture aliquots were plated and counted on Middlebrook 7H10 agar. Other aliquots were used for RNA isolation to assess the expression of rv0348 under the examined stress conditions using quantitative, real-time PCR ("qRT-PCR").

For qRT-PCR, cDNA was synthesized from 1 µg of total manufacturer, in the presence of SYBR green and 250 ng of mycobacterial genome-directed primers. SYBR green qRT-PCR was done using gene specific primers (Table 5) at a concentration of 200 nm. The thermocycle conditions were: 95° C. for 3 min, and 40 cycles of 95° C. for 15 S and 60° C. for 30 S. qRT-PCR reactions were performed in triplicates and the threshold cycle values were normalized to levels of 16SrRNA transcripts and fold changes were calculated by $\Delta\Delta C_T$ method.

Transcriptional Analysis was performed as follows. Before DNA microarray hybridizations, double-stranded cDNA (ds-cDNA) was synthesized from 10 ug of total RNA using the SuperScript Double-Stranded cDNA Synthesis Kit (Invitrogen) as directed by the manufacturer, in the presence of 250 ng genome-directed primers. The ds-cDNA was cleaned up and labeled following the NimbleGen gene expression analysis protocol (NimbleGen Systems, Inc., Madison, Wis.) and hybridized to NimbelGen-manufactured microarrays following a protocol we established earlier. In this microarray, each of the 3989 open reading frames ("ORFs") encoded in the genome of M. tb H37Rv strain, was represented by nineteen of 60 mer oligonucleotide probes. Further, the whole genome was represented five times on each chip (i.e. 5 technical replicates/chip) for a total of 95 probes/gene. All hybridizations (3 µg of doublestranded cDNA/Chip) were performed using NimblGen hybridization buffer and commercial hybridization chambers (TeleChem International, Inc., Sunnyvale, Calif.) overnight at 42° C. Following hybridization, washing steps were performed using Nimblegen washes I, II, and III as recommended by the manufacturer. Slides were scanned using an Axon GenePix 4000B scanner (Molecular Devices Corporation, Sunnvvale, Calif.) and fluorescent intensity levels extracted using NimbleScan (NimbleGen) and normalized to a mean value of 1,000. Determination of significantly changed genes was performed using a flexible empirical Bayes model; specifically, the LNN model in the EBArrays package employing an R language (R is an open source platform used by Bioconductor, an open source and open development software project). A cutoff of 0.50 for the probability of differential expression (PDE>0.5) was used to determine significantly changed genes. Statistical enrichment of gene groups within the microarray genes vs. other transcriptoms were calculated using a standard hypergeometric distribution function in Microsoft Excel.

FIG. **22** shows the transcriptional profile of rv0348 in M. ²⁰ tb H37Rv by qRT-PCR of rv0348 transcripts under variable ²⁰ stress conditions, such as high temperature (45° C.), H_2O_2 (10 mM) and SDS (0.05%) treatments, as well as transition to stationary phase (OD₆₀₀=1.5). Fold change was calculated relative to transcripts in untreated cultures of M. tb H37Rv strain (OD₆₀₀=0.5). Error bars represent ±standard ²⁵ deviations from the means (bars). qRT-PCR showed that the transcripts of rv0348 remained unchanged when M. tb cultures were exposed to SDS (0.05%).

The transcriptional profile of rv0348 indicated induction 30 at 45° C. and repression following exposure to high levels of H_2O_2 or during the stationary phase of growth. On the other hand, no difference in colony counts was found when mycobacterial cultures (H37Rv and Δ rv0348) were exposed to any of the examined stressors including culturing under static conditions for 2-6 months at 37° C. As shown in FIG. **23**, different M. tb strains were grown in Middlebrook 7H9

liquid medium to early log phase (OD600=0.5) and their counts were determined. Aliquots of each strains (10 ml) were subjected to different stressor (SDS 0.05%, for 4 hrs) or to heat shock at 45° C. for 24 hours and the CFUs were determined for all strains by plating on Middlebrook 7H10 plates at 37° C.

2. Global Changes in M. tb Transcriptome Triggered by rv0348

It has been suggested that rv0348 plays a role in the transcriptional regulation of M. tb during the transition to the chronic stage in murine lungs. To identify genes under control of rv0348, cultures of both H37Rv and its isogenic mutant, Δ rv0348, were grown in vitro for DNA microarray analysis using a high-sensitivity oligonucleotide microarray platform.

Replicate microarray hybridizations were performed for at least two biological samples of both the wild type and mutant strains and showed a high correlation level (r=0.9). Using a standard protocol for Bayesian statistics, significantly regulated genes with a probability of differential expression (PDE) >0.5 and >±2 fold change between H37Rv and Δ rv0348 mutant were identified. Using these criteria, a significant change in a set of 163 genes (Table 11) was identified between the transcriptomes for H37Rv and the Δ rv0348 (rv0348-regulon).

Table 11 shows a list of the 163 genes whose expression differs in Δ rv0348 as compared to the wild-type M. tb counterpart H37Rv. Functional category code for Table 11: 0 virulence, detoxification, adaptation; 1 lipid metabolism; 2 information pathways; 3 cell wall and cell; processes; 4 stable RNAs; 5 insertion seqs and phages; 6 PE/PPE; 7 intermediary metabolism and respiration; 8 unknown; 9 regulatory proteins; 10 conserved hypotheticals; 16 conserved hypotheticals with an orthologue in *M. bovis*. A partial list of significantly changed genes organized into operons, as determined by an operon prediction algorithm, is listed in Table 6.

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11.1	121	12	6
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ΑL	A List of Mycobacterial Operons under Positive and Negative Control of Rv0348					
No.	Gene-ID	Operon Name*	Putative Function			
		Positive Regula	tion			
1	P ₂ 0167 0177	mcel	Mammalian call entry operon			
2	Rv0684-0685	fus A_tuf	Flongation factor			
3	Rv0700-0710	rns I-rns ()	30S ribosomal protein S10			
4	Rv0718-0723	rpsJ-rplQ	30S ribosomal protein S10			
5	Rv1184c-1185c	Rv1184c-1185c	Conserved hypothetical protein, acvl-CoA synthase			
6	Rv1613-1614	trpA-ltg	Tryptophan synthase α chain, prolipoprotein diacylglyceryl transferase			
7	Rv2391, 2392	nirA-cysH	Probable nitrite reductase/sulphite reductase			
8	Rv2948c-Rv2950c	fadD22-fadD29	acyl-CoA synthase			
9	Rv3148-Rv3154	nuoD-nuoJ	NADH dehvdrogenase chain D-J			
10	Rv3460c**	rpsM-J	30S ribosomal protein S13-L36			
11	Rv3824c-Rv3825c	papA1-pks2	PKS-associated protein, unknown			
		1 1 1	function, polyketide synthase			
12	Rv3921c-Rv3924c	mpA, rpmH	Unknown membrane protein			
		Negative Regula	tion			
13	Rv0823c-Rv0824c	desA1	Transcriptional regulator, ntrB			
			(NifR3/Smm1 family)			
14	Rv1622c, Rv1623c	cydB, appC	Cytochrome d ubiquinol oxidase subunit II			
16	Rv2031c**	hspX	14 kD antigen, heat shock protein Hsp20 family			

TABLE 6-continued						
acterial	Operons under	Positive	and	Negativ		

AL	A List of Mycobacterial Operons under Positive and Negative Control of Rv0348							
No.	Gene-ID	Operon Name*	Putative Function					
17 18	Rv2629-Rv2630 Rv3048c**	Rv2629-Rv2630 nrdG	Hypothetical protein Ribonucleoside-diphosphate small subunit					
19	Rv3053c**	nrdH	Glutaredoxin electron transport					
20	Rv3139-Rv3140	fadE24, fadE23	acyl-CoA dehydrogenase					

*Operon predications are based on earlier analysis.

**Single genes of a larger operon or regulon

the $\Delta rv0348$ mutant (N=98 genes) are suggested to be under the positive control of the rv0348 while repressed genes (N=65) are suggested to be under its negative control. A representative sample of genes that showed transcriptional changes by DNA microarray analysis was verified by qRT- 20 PCR. In all of the examined genes (N=10), there was an agreement of the transcriptional change (either induction or repression) between DNA microarray and qRT-PCR analyses, as shown in Table 7 and FIG. 24.

Induced genes in the H37Rv transcriptome compared to 15 positively-regulated by Rv0348. FIG. 25(A) shows a Venn diagram representing the number of rv0348-positively regulated genes compared to genes induced under nutrient starvation (Betts et al., 2002, Mol. Microbiol., 43:717-31) and those repressed in the phagosome environment (Schnappinger, D. et al., 2003, J. Exp. Med., 198:693-704). Among the rv0348-positively regulated genes are a group of twentynine genes that were repressed during macrophage infection. This profile indicates the ability of M. tb to modulate levels

TABLE 7

Genes	Confirm: qRT-PCR Δrv0348/WT	<u>ation of l</u> SD	Microarrays Data Microarrays Δrv0348/WT	with Real PDE	<u>ih Real-Time qRT-PCR</u> qRT-PCR PDE Δrv0348::rv0348/WT	
Rv0167	-7.69	0.7	-8.9	1.00	-1.38	0.4
Rv0347	54.19	0.9	4.6	1.00	2.02	0.3
Rv0569	42.99	0.3	6.4	1.00	1.22	1.7
Rv0700	-2.13	0.7	-3.5	1.00	-1.03	0.3
Rv1996	32.60	0.4	12.7	1.00	2.89	0.3
Rv1997	565.48	0.3	3.4	1.00	3.23	0.4
Rv2032	169.29	1.2	3.8	0.99	3.23	0.5
Rv2628	448.82	0.2	15.0	1.00	4.05	0.4
Rv3128	853.16	0.9	0.0	0.00	4.05	0.4
Rv3130c	8.34	0.8	4.4	0.99	-1.61	0.6

FIG. 24 shows fold changes of ten genes utilizing RNA from both mutant $\Delta rv0348$ and complemented $\Delta rv0348$:: rv0348 strains relative to H37Rv wild type strain. Both the $\Delta rv0348$ and $\Delta rv0348$::rv0348 are represented by black and $_{45}$ number of phagosome-activated genes (N=33). Among this grey bars, respectively.

Genes involved in survival during stationary and persistent phases (rpoB) of growth as well as those regulating transcription (e.g., rho, rpmE) (TubercuList database) were among genes under positive control of Rv0348. The posi- 50 tively-regulated operons (Table 6) included the mce1 operon (rv0167-rv0177), indicating a role for rv0348 in regulating virulence of M. tb. Other genes induced in the presence of rv0348 included a tryptophan biosynthesis gene (trpA), translation apparatus operon (fusA-tuf) and the ribosomal 55 biosynthesis operon (rv0700-rv0723) (Table 6). Several other regulatory genes were also among the Rv0348-regulon including the hupB (encodes a DNA-binding protein) and rho (transcription termination factor). In E. coli, the expression of the tryptophan operon is regulated by inhibition of 60 ribosomal binding sites. It is noteworthy to mention here that functional orthologues to trp operon regulatory genes are induced by rv0348 (e.g., 50S ribosomal operon, rho gene) indicating the ability of Rv0348 to exert its regulatory role(s) through transcriptional inhibition. Further compara-65 tive analysis to the starvation-induced transcriptome analyzed before identified a set of eighteen genes that are

of gene transcripts to survive the macrophage environment using a rv0348-dependent mechanism.

Rv0348-negatively regulated genes included a significant group is rv3130c which encodes triglyceride synthase (tgs1), a protein that is involved in triglyceride synthesis in M. tb, indicating a role for rv0348 in regulating mycobacterial fatty acid metabolism. A set of the rv0348-negatively regulated genes (N=24) were among the 47 genes responsive to hypoxia (see, FIG. 25(B)) or to the 48 genes responsive to reactive nitrogen intermediates ("RNI") and gradual adaptation to low levels of oxygen. Additionally, a list of thirtythree genes that were activated during anaerobic growth of M. tb were also found among the rv0348-negatively regulated genes in this study. FIG. 25(B) shows a Venn diagram representing the number of rv0348-negatively regulated genes compared to genes induced under hypoxia (Park, H. D. et al., 2003, Mol. Microbiol., 48:833-43) and anaerobic conditions (Muttucumaru, D. G. N. et al., 2004, Tuberculosis, 84:239-46). Previously, a significant level of overlap existed between the hypoxia and RNI regulons and were shown to be under the two-component regulator, dosR. Transcripts for the dosR regulator did not change in the present analysis, indicating an additional and/or alternative role(s) for the set of twenty-four genes in the pathobiology of M. tb. However, the activation of the acr gene is usually

considered a strong indication of the activation of the dosR regulon. The acr gene was previously confirmed to contribute to M. tb survival in macrophages, hence its inclusion under negative control of rv0348 indicates a potential role for rv0348 in down-regulating genes involved in hypoxia, in 5 stages when they are not needed. Finally, hypergeometric distribution analysis of the Rv0348-dependent genes and each of the compared transcriptomes indicated the significant association between the rv0348-induced transcriptome and starvation, phagosome survival, hypoxia and anaerobic 10 conditions (p<0.001), as shown in Table 8.

TABLE 8

Analysis of Groups Overrepresented in the Transcriptome of <i>Mycobacterium tuberculosis</i> as Determined by Hypergeometric Distribution					
Category	# in rv0348 Transcriptome	# in Conditions	P-value		
Starvation	16	114	9.0E-06		
Low in Phagosome	27	127	3.2E-13		
Hypoxia	24	48	0.0E+00		
Anaerobic	33	231	6.3E-11		

Overall, the presented analyses show the previously 25 undiscovered, yet broad and far reaching potential regulatory roles exerted by the rv0348 in M. th survival strategies.

3. rv0348 Expression in M. smegmatis Model of Hypoxia The study of rv0348 expression under hypoxic conditions in M. smeg::pML21 was performed using the Wayne model 30 of hypoxia in M. tb, which has proven equally useful in studies of *M. smegmatis*. Briefly, a single colony of *M*. smeg::pML21 (see, EXAMPLE II section B.3 for construction) harboring the rv0348 operon was grown with shaking at 37° C. to an OD_{600} of 1.0 in Dubos Tween Albumin 35 medium (BD Biosciences) supplemented with kanamycin (30 µg/ml). This culture was used to inoculate 6×30 ml screw-capped tubes containing stir bars to an OD_{600} of 0.1 in Dubos media containing methylene blue (1.5 µg/ml) to serve as an indicator of oxygen levels. Three tubes were used 40 as aerobic controls with loose caps, a head space ratio ("HSR") of 1.5, and were stirred at 200 rpm. The remaining 3 tubes were used for the anaerobic cultures with tightened, parafilm-sealed caps, an HSR of 0.5, and were stirred at 120 rpm. The color of the tubes was monitored and aerobic/ 45 anaerobic tubes were taken for analysis when the methylene blue first showed signs of fading (day 1) and after the anaerobic cultures became completely colorless (day 6 and 7). An aliquot (100 μ l) of each sample was plated for colony counts while the rest was used for total RNA extraction and 50 qRT-PCR as described above. The whole experiment was repeated 3 times.

Using the Wayne model of hypoxia in M. tb, transcripts of rv0348 operon were modestly induced under anaerobic conditions indicating the rv0348 operon's involvement in 55 hypoxic responses. Since large number of the dormancy regulon genes were suggested to be controlled by rv0348, it is possible that rv0348 could be involved in mycobacterial hypoxic responses. To test this hypothesis, an in vitro model of hypoxia where the influence of hypoxia and anaerobic 60 conditions on rv0348 operon could be studied in a recombinant strain *M. smegmatis* (*M. smeg*::pML21) was developed that was shown to express Rv0348, as shown in FIG. **20**(A). FIG. **20** shows the transcriptional regulation of Rv0348-dependent genes in presence or absence of the 65 rv0348 operon. Referring to FIG. **20**, the * denotes significant change in a Student's t-Test (p<0.001). FIG. **20**(A)

shows a Western blot analysis of the recombinant strain of *M. smegmatis* mc²155 expressing Rv0348 protein. FIG. **20**(B) shows the survival curve of *M. smeg*::pML21 under aerobic and anaerobic conditions (left scale) and fold change in rv0348 transcripts as measured by qRT-PCR (right scale).

Construction of LacZ vectors and β-galactosidase assays were performed as follows. The DNA fragment corresponding to the putative promoter regions of rv3130c, rv0167, rv0700, rv0347 and hsp60 genes were cloned by PCR using 10 gene-specific primers (Table 5). The different promoters were cloned into pML24 shuttle vector (a derivative of pCV77 vector where a hygromycin cassette was cloned into a SpeI site). *M. smegmatis* was first electroporated by pML21 and positive clones were selected and verified by 15 PCR and Western blot to ensure the expression of Rv0348 protein. Recombinant *M. smegmatis* were electroporated with a different shuttle vector (pML24 derivative) and incubated on selective LB plates supplemented with 5-bromo-4-chloro-3-indoyl-β-D-galactopyranoside

20 (X-Gal). All recombinant *M. smegmatis* developed blue color on plates except the negative control (pML24). Assessment of β-galactosidase activity in different constructs was performed in sonicated extracts of *M. smegmatis* strains using a β-galactosidase assay kit (Stratagene, Cedar Creek, 25 Tex.) according to the manufacturer protocol. Experiments were carried out in triplicate and repeated twice from independent cultures with different amounts of soluble fraction proteins. β-galactosidase was expressed as Miller units/ mg of soluble lysate. FIG. 26(C) shows Lac-Z repression for constructs for rv0347. FIG. 26(E) shows Lac-Z repression for constructs of rv0700. FIG. 26(F) shows Lac-Z induction for constructs of rv0167.

BLAST analysis indicated that the rv0348 operon is absent from the genome of *M. smegmatis*, allowing for the expression of Rv0348 and assessment of its function(s) in the rapidly growing *M. smegmatis*. Using a modified version of the Wayne model of hypoxia, it was found that aerobic cultures of *M. smeg*::pML21 grew to a higher density than the anaerobic cultures, as expected (see, FIG. 26(B)). Interestingly, transcripts of rv0348 were significantly up-regulated in the cultures grown under hypoxic conditions (at day 1) with a more profound induction when cultures reach anaerobic phase by day 6 of incubation. This dramatic increase in rv0348 transcripts strongly supports the hypothesis that rv0348 participates in M. tb response to anaerobic stress, in addition to its role in M. tb survival during infection. Currently, experiments are underway to examine the survival of H37RvArv0348 mutant under anaerobic environment.

4. Rv0348 binding to New Promoter Regions

It has been shown that rv0348 encodes a transcriptional regulator that binds to its own promoter. Electrophoresis mobility shift assay ("EMSA") assays were performed using the predicted regulatory sequences of ten genes that changed their transcriptional profile based on presence/absence of intact rv0348 gene to examine the ability of Rv0348 to regulate other genes. For EMSA assays, the Rv0348 protein was purified as detailed in Talaat et al., 2007, J. Bacteriol. 189:4265-4274. Probes were generated using standard PCR amplification protocols and primers designed by Primer3 v. 0.4.0 by providing the upstream probable regulatory sequences of selected genes. Potential promoter regions of several selected genes were amplified by PCR and endlabelled by radioactive P32. The different probes were allowed to bind to recombinant MBP-Rv0348 and subsequently run on 4% native polyacrylamide gel. The gel was

then dried and exposed to Kodak film. As shown in FIG. 27, the presence of Rv0348 did not impact the migration pattern of DNA fragments representing any of the ten putative promoters indicating an indirect regulatory function for Rv0348. Only when the positive control was used (upstream 5 region of the rv0348 operon), a retardation of the DNA migration was noticeable. It is possible that other regulatory elements are needed to amplify the regulatory role(s) of rv0348.

5. Rv0348 Regulatory Functions

Because of the lack of a direct binding of Rv0348 to any of the examined genes with differential gene expression profile, the LacZ reporter gene was employed to examine the regulatory role of Rv0348. For this purpose, the generated M. smeg::rv0348 (M. smeg::pML21) construct was used to 15 examine the transcriptional regulation of a selected list of genes that belong to rv0348-regulon. A verified clone of the M. smeg::rv0348 was electroporated with derivatives of the pML24 plasmid, listed in Table 4, where the putative promoter regions of several genes were cloned upstream of a 20 promoterless reporter gene (lacZ).

Screening of transformants showed that all constructs formed blue colonies on plates supplemented with X-Gal except when a promoterless Lac-Z vector was used for transformation (see FIG. 28). Nonetheless, quantitative 25 analysis of β -galactosidase activity of each construct in the presence/absence of the rv0348 operon showed significant differences among constructs depending on presence of the rv0348 operon.

In all examined promoters, a significant change in the 30 expression level of LacZ was found between constructs where the rv0348 operon was present compared to those without. Both the repression of rv0347 (promoter for rv0348) and rv3130c promoters and the induction of rv0167 (promoter for mce1) were in agreement with the negative 35 and positive regulation by Rv0348, respectively, as indicated by DNA microarrays. However, in the case of rv0700 (promoter for ribosomal protein operon), the LacZ assay indicated its repression despite evidence that it is under positive control of Rv0348, indicating the presence of other 40 Δ rv0990c. regulatory mechanisms, besides rv0348, that control rv0700 in M. smegmatis. Interestingly, the LacZ reporter technology was able to show differential regulation for mce1, rv3130c and rv0700 genes in M. smegmatis expressing Rv0348, despite the inability of Rv0348 to bind to their putative 45 promoter regions indicating an alternative strategy for gene regulation exerted by Rv0348.

To further confirm the regulatory role of rv0348, qRT-PCR was employed to estimate the transcript levels of regulated genes in the complemented strain, H37Rv 50 Δrv0348::rv0348, compared to the mutant strain H37Rv $\Delta rv0348$ (see FIG. 24). Such analysis was intended to test the ability of rv0348 expression in trans to maintain the functional role(s) played by rv0348 and provide an additional confirmation of the regulatory role of Rv0348. In all 55 examined genes, the induction/repression levels of transcripts in the $\Delta rv0348$ were consistent with DNA microarray analysis. However, transcripts in the complemented strain for the ten examined genes were restored to the wild type level (± 1) confirming the regulatory role for the rv0348 gene 60 and the success of the complementation for in vitro cultures. Overall, both the reporter assay and quantitative PCR analysis supported a regulatory role for the Rv0348 as a transcriptional factor.

It has been shown that rv0348 encodes a transcriptional 65 regulator with both inducer and repressor activities that are used to regulate key mycobacterial responses to stressors

such as starvation and low oxygen tensions. Based on the presented analyses, a model was generated that delineates possible pathways that can be utilized by Rv0348 to explain its role in establishing chronic tuberculosis. Though not wishing to be bound by any particular theory, in this model, as depicted in FIG. 40 (a schematic depicting several scenarios in which rv0348 can play a role in M. tb survival strategies), Rv0348 can bind to its own promoter in order to maintain a low level of expression especially during log phase culture or under in vitro growth, in general. During certain stressors (e.g., high O⁻ level), the expression of Rv0348 will be even lower (see FIG. 26(B)) which will relieve its repression of other genes such as hypoxia- and phagosome-responsive genes.

During other stressors (e.g., high temp or in vivo growth), the rv0348 is induced (see FIG. 22), most likely through the activity of other transcriptional regulators (e.g. SigC) which share a transcriptional binding sites upstream of rv0348 operon. Such binding could prevent the binding of Rv0348 to its promoter, and hence, its own expression will be induced which in turn could activate genes involved in starvation and invasion among the rv0348-regulon (see, FIG. 25(A)). Under all of these scenarios (relieve of hypoxia gene repression or induction of starvation genes), the general outcome of the induction of the rv0348-regulon is the fitness of M. tb to persist under variable host microenvironments.

Example III: rv0990c Knockout Mutant

A. Overview

The rv0990c gene is the central gene of an operon of three genes (rv0989c-0991c) located in the iVEGI (see FIG. 1). Bioinformatics analysis suggested that rv0990c could be a DNA-binding protein. To investigate the role of rv0990c in the regulatory pathways and pathogenesis of M. tb, the coding sequence of rv0990c was deleted using a phagemediated delivery technique. The animal data obtained (e.g., cfu count, histopathology, and survival curves) following aerosol infection confirmed the attenuation phenotype of

B. Construction of Δrv0990c Knockout Mutant

A knockout mutant of rv0990c, Δ rv0990c, was prepared using the virulent M. tb strain H37Rv. The rv0990c gene is 657 base pairs. 490 base pairs of the coding sequence of rv0990c (from 70-560) were deleted from the genome of M. tb and replaced by the hygromycin cassette using the same phage delivery technique employed to disrupt the rv0348 gene and generate the knockout mutant. Briefly, ~800 basepair fragments of both the upstream and downstream portion of the rv0990c gene were amplified by PCR and cloned into the pGEM-T Easy vector (Promega, Madison, Wis.). The fragments were then digested at the flanking restriction enzyme sites and ligated into pYUB854. The restriction sites used were Spel/HindIII and Xbal/KpnI for left flank and right flank respectively.

As described for the rv0348 knockout, the pYUB845 construct was used to form specialized transduction mycobateriophages. Transduction protocols were performed as described in Bardarov et. al., 2002, Microbiol., 148:3007-3017. Following 6 weeks of incubation at 37° C., hygromycin-resistant colonies were selected for further analysis.

Confirmation of the mutant genotype was performed as described previously for the ctpV and the rv0348 knockouts, using PCR and Southern blot analyses. (See also, Talaat, et al., 2000, Am. J. Vet. Res. 61:125-128 and Wu et al., 2007, J. Bacteriol. 189:7877-7886). Primers used to generate and test this mutant are shown in Table 9.

TABLE 9	9
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Gene-Specific Primers for Construction of Arv0990c Mutant (SEQ ID NOs: 95-102, respectively, in order of appearance)						
Primer	Sequence	Purpose				
AMT533	ATCACTACTAGTGATAGCGTAGCGGAGTCACC	Rv0990c flank cloning				
AMT534	ATCACTAAGCTTAGTGACCGGGTCGTTTTGGT	Rv0990c flank cloning				
AMT535	ATCACTTCTAGAGGTCCAGTCCGGGCGCAAAA	Rv0990c flank cloning				
AMT536	ATCACTGGTACCGAACCTTGGCTGCCGGAAGC	Rv0990c flank cloning				
AMT926	TGGTGGACCTCGACGACCTGCAGG	Rv0990c mutant screening				
AMT899	GTGGACAGCTTGGCCAAGGTCGGC	Rv0990c mutant screening				
AMT900	GCACGCTGGGGACTGCTCGAAC	Rv0990c mutant screening				
AMT885	GGAACTGGCGCAGTTCCTCTGGGG	Rv0990c mutant screening				

65

C. Construction of the rv0990c Complement

One of rv0990c mutants was electroporated with a copy of rv0990c gene cloned under the control of hsp60 promoter in pMV361. The transformants were verified by PCR for the 25 construct stability M. tb. One of the complemented strains

replaced by a hygromycin cassette using the same phage delivery technique described above for the rv0990v knockout. The mutants were verified by PCR and Southern blot techniques. The restriction sites were SpeI/HindIII and XbaI/KpnI for left and right arm respectively. Primers used to generate and test this mutant are in Table 10:

TABLE 10

Gene (SEQ	Gene-Specific Primers for Construction of Arv0971c Mutant (SEQ ID NOs: 103-110, respectively, in order of appearance)						
Primer	Sequence	Purpose					
AMT563	ATCACTACTAGTCAACTCACTGCGGTTACGCC	Rv0971c flank cloning					
AMT564	ATCACTAAGCTTATGCTGGCCTTCCTGCAGAA	Rv0971c flank cloning					
AMT565	ATCACTTCTAGAGCGGTTGTGCGGAGAGTTCA	Rv0971c flank cloning					
AMT566	ATCACTGGTACCGACTGGATCATCAAGGGCCA	Rv0971c flank cloning					
AMT885	GGAACTGGCGCAGTTCCTCTGGGG	Rv0971c mutant screening					
AMT897	GTTCTCCTCGGTCAGCGTGGTGAC	Rv0971c mutant screening					
AMT926	TGGTGGACCTCGACGACCTGCAGG	Rv0971c mutant screening					
AMT898	AAGATCACCACCGCGCGTC	Rv0971c mutant screening					

was used to infect a group of BALB/c mice to confirm the observed attenuation phenotype of the mutant.

Example IV: rv0971c Knockout Mutant

A. Overview

The rv0971c gene is the last gene of an operon of six genes located in to the iVEGI of M. tb. (See FIG. 1). 55 Although, the exact function of rv0971c is largely unknown, it was annotated as a crotonase in the Tuberculist, and the operon is believed to play a crucial role in lipid metabolism (biosynthesis and degradation). The unique location of the operon in the M. tb pathogenicity island suggested a role in 60 mycobacterial virulence. Attempts to delete the whole operon from the genome of M. tb were unsuccessful. Instead, the rv0971c gene was deleted and virulence of the mutant was studied in an animal model.

B. Construction of the rv0971c Knockout Mutant

The rv0971c gene is 810 base pairs. 674 base pairs of the coding sequence of rv0971c (66-740) were deleted and

C. Construction of the rv0971c Complement

One of the verified mutants was electroporated with a ⁵⁰ functional copy of rv0971c under hsp60 promotor control, in the integrative shuttle vector pMV361. The complementation study is in progress.

Example V: Evaluation of Wild-Type M. Tb Strain H37Rv and M. Tb Knockout Mutants

BALB/c mice can be infected with an M. tb knockout mutant (e.g., $\Delta rv0990c$ and/or $\Delta rv0971c$) or corresponding wild-type M. tb using a low-dose aerosolization protocol. Bacterial survival and mouse lung pathology can be measured at short-term as well as long-term time points via the homogenization and plating of infected lung tissue as well as organ histology. Additionally, mice infected with the M. tb strains can be monitored over the long-term course of the infection and the survival of the infected mice can be recorded.

Briefly, BALB/c mice (Harlan, Indianapolis, Ind.) can be infected in a Glas-Col chamber (Glas-Col, LLC, Terra

Haute, Ind.) loaded with 10 mL of an M. tb knockout mutant such as $\Delta rv0990c$ and/or $\Delta rv0971c$, or the corresponding wildt-type M. tb strain at OD 0.30. Infectious dose of approximately 300 CFU/animal can be confirmed via a 5 1-day time point. CFUs can be determined at different time points (e.g., 2 weeks, 4 weeks, and 38 weeks, etc.) by homogenizing lung tissue in PBS buffer and plating on Middlebrook 7H10+10% ADC, followed by incubation at 37° C. for one month. Final CFUs can be normalized to the 10weight of the lung tissue used. Sections of lung, liver, and spleen tissue can be taken and incubated in formalin prior to sectioning and staining with H&E and AFS. Histopathology slides can be examined and scored by a pathologist not associated with the study.

Example VI: A 0990c Infected Mice

Three groups of mice were infected with 40990c M. tb knockout mutant as describe above in Example V. The $_{20}$ progression of the disease was monitored in the three groups of infected mice by cfu count and survival curves. As shown in FIG. **29**, a decrease in CFUs of a Δ rv0990c knockout mutant (derived from M. tb strain H37RV) relative to the corresponding WT H37Rv strain was observed at both 25 short-term and long-term time points. Referring to FIG. **29**, the bacterial load of mice after infection with either wild-type (H37Rv) or its isogenic mutant Δ rv0990c was determined at 2, 4, 8, 30 and 38 weeks.

Mice infected with $\Delta rv0990c$ lived longer than mice ³⁰ infected with the wild-type H37Rv strain, resulting in an increase in time to death, as shown in FIG. **30**. Referring to FIG. **30**, the survival of mouse groups after infection with WT or $\Delta rv0990c$ is shown.

Example VII: A 0971c Infected Mice

Two groups of mice were infected with wild-type and $\Delta rv0971c$ with aerosol challenge as described above in Example V, and the cfu count and survival were monitored ⁴⁰ in the two groups. As shown in FIG. **29**, a decrease in lung CFUs of a $\Delta rv0971c$ knockout mutant (derived from M. tb strain H37Rv) relative to the corresponding H37Rv WT strain was observed at both short-term and long-term time points. Referring to FIG. **29**, the bacterial load infection with ⁴⁵ either wild type (H37Rv) or its isogenic mutant $\Delta rv0971c$ was determined at 2, 4, 8, 30 and 38 weeks.

Mice infected with $\Delta rv0971c$ lived longer than mice infected with WT, as shown in FIG. **30**. Referring to FIG. **30**, the survival of mouse groups after infection with WT or 50 $\Delta rv0971c$ is shown.

Example VIII: Knockout Mutants Used to Generate an Immune Response in Mammals and as Vaccines

Live attenuated mutants can be used as vaccines candidates against tuberculosis. Additionally, genetic vaccines based on the targeted genes can be used to develop a genetic immunization protocol that can elicit protection against tuberculosis.

In a typical immunization experiment, hosts (e.g. mice or non-human primates) will be immunized with the attenuated mutants. At 4 weeks post infection, sera or organ tissues can be collected from inoculated animals to evaluate the generated immune responses. Both humoral and cellular-based 65 assays can be used to evaluate the host responses to immunization.

Although humoral and cellular assays can estimate the level of immunity generated following vaccination, it will not provide estimate of the level of protection offered by each vaccine construct. To estimate the protective power of vaccine candidates, immunized animals can be challenged by aerosolization of the virulent strain of *M. tuberculosis*. The readout of such assays includes animal survival curves, the level of organ colonization with the virulent strain of *M. tuberculosis* as well as immunological and histopathological responses elicited by challenge.

A. Vaccination and challenge of guinea pigs: Female Dunkin-Hartley guinea pigs (350-450 g) free of infection can be used. Four groups of ten guinea pigs can be immunized with 75 μ l of a 5×10⁴ CFU live knockout mutant 15 formulation subcutaneously in the nape of the neck. Group I can be immunized with the Δ ctpV mutant; Group II can be immunized with the Arv0348 mutant; Group III can be immunized with the $\Delta rv0990c$ mutant, and Group IV can be immunized with the $\Delta rv0971c$ mutant. A control groups of 10 guinea pigs can be vaccinated with a 5×10^4 CFU live BCG Pasteur formulation, and a control group of 10 guinea pigs can be injected with saline. Five weeks after vaccination, all but two guinea pigs (the controls) from each group can be challenged aerogenically with a live suspension of M. tb strain H37Rv to achieve an inhaled retained dose in the lungs of approximately 300 organisms.

B. Vaccination and challenge of guinea pigs: Female Dunkin-Hartley guinea pigs (350-450 g) free of infection can be used. Four groups of ten guinea pigs can be immunized with 75 μ l of a 5×10⁴ CFU live knockout mutant formulation subcutaneously in the nape of the neck. Group I can be immunized with the Δ ctpV mutant; Group II can be immunized with the Arv0348 mutant; Group III can be immunized with the $\Delta rv0990c$ mutant, and Group IV can be 35 immunized with the $\Delta rv0971c$ mutant. A control groups of 10 guinea pigs can be vaccinated with a $5{\times}10^4~{\rm \widetilde{CFU}}$ live BCG Pasteur formulation, and a control group of 10 guinea pigs can be injected with saline. Five weeks after vaccination, the guinea pigs can vaccinated as described above, but with 50% of the CFUs. Five weeks after the second vaccination, all but two guinea pigs (the controls) from each group can be challenged aerogenically with a live suspension of M. tb strain H37Rv to achieve an inhaled retained dose in the lungs of approximately 300 organisms.

C. Testing for an immune response in vaccinated guinea pigs: Prior to exposure to the infectious M. tb strain H37Rv., a blood sample can be taken from each of the guinea pigs, including vaccinated and saline-injected, and the presence or absence of antibodies directed to M. tb can be determined by methods known in the art.

D. Post mortem examination of guinea pigs: Guinea pigs can be sacrificed according to institutional protocol after 20 weeks. Tissues of interest (e.g., lung, spleen, etc.) can be harvested immediately after death and analyzed for M. tb colonization.

E. Bacterial enumeration: CFUs can be determined by homogenizing lung tissue in PBS buffer and plating on Middlebrook 7H10+10% ADC, followed by incubation at 37° C. for one month. Final CFUs can be normalized to the
weight of the lung tissue used. Sections of lung, liver, and spleen tissue can be taken and incubated in formalin prior to sectioning and staining with H&E and AFS. Histopathology slides can be examined and scored by a pathologist not associated with the study.

F. Results: Guinea pigs from Groups I-IV and control guinea pigs vaccinated with BCG Pasteur formulation are expected to have developed antibodies directed to M. tb. Additionally, guinea pigs from these groups are expected to live longer and have fewer CFUs in organs and tissues tested, post infection, as compared to guinea pigs injected with saline. Additionally, further challenges of vaccinated guinea pigs with infectious M. tb strains is expected to result ⁵ in less sever symptoms. For example, re-challenged guinea pigs are expected to exhibit an increased post-infection life span and fewer CFUs in lung, liver and spleen than nonvaccinated guinea pigs. Similar results are expected with the "boosted" guinea pigs described in section VIII.B.

In contrast, no or very low titer antibodies directed to M. tb are expected in the saline-injected guinea pigs. Moreover, subjects in this test group are expected to die due to the M. tb infection at about 38 weeks post infection.

Example IX: ActpV Infected Mice

Three groups of mice were infected with $\Delta ctpV$ M. tb knockout mutant as described above in Example V. BALB/c mice (Harlan Laboratories, Inc., Indianapolis, Ind., USA) 20 were infected in a Glas-Col chamber (Glas-Col, LLC, Terra Haute, Ind., USA) loaded with 10 ml of either ActpV or wildtype bacteria at OD_{600} 0.30. Infectious dose of approximately 300 CFU/animal was confirmed via a 1-day timepoint. CFUs were determined by homogenizing lung tissue 25 in PBS buffer and plating on Middlebrook 7H10+10% ADC, followed by incubation at 37° C. for one month. For the survival curve, animals were monitored daily by animal care staff not associated with the study. As specified in our animal protocol, mice were sacrificed after being identified by our 30 animal care staff as morbidly ill, using criteria such as haunched posture, extreme weight loss, and slow or pained movements. Sections of lung, liver, and spleen tissue were taken and incubated in formalin prior to sectioning and staining with hematoxylin and eosin (H&E) and acid-fast 35 staining (AFS). Histopathology slides were examined and scored by a pathologist not associated with the study. For immunohistochemistry, the primary antibody, rabbit antiinterferon gamma (Invitrogen), was diluted 1:1000 in Van Gogh Yellow antibody diluent (Biocare Medical, Concord, 40 Calif., USA) and incubated for one hour. Negative control slides received only diluent in lieu of antibody. Primary antibody was detected using biotinylated goat anti-rabbit IgG secondary antibody (Biocare Medical) and Streptavidin-horseradish peroxidase (Biocare Medical). Staining was 45 visualized with DAB+(diaminobenzidine) (Dako, Glostrup, Denmark) and counterstained with CAT hematoxylin (Biocare Medical) mixed 1:1 with distilled water.

The ctpV gene is part of a 29-gene genomic island previously shown to be preferentially induced in mice 50 relative to in vitro culture (termed the in vivo expressed genomic island, iVEGI). This suggested that ctpV might play a role specific to the in vivo lifestyle of Mtb. In addition, experiments showed that CtpV is a copper exporter, and data suggest that copper homeostasis in bac- 55 teria may play a role in pathogenesis, although this had never been tested in Mtb. To investigate this hypothesis, groups of BALB/c mice (n=30-40) were infected with H37Rv, ActpV, or ActpV::ctpV using a low-dose aerosolization protocol. Bacterial colony counts from mouse lung 60 tissue over the course of the infection revealed that, overall, bacterial survival between the three strains over the course of infection was similar, and differences in colonization levels did not reach statistical significance at any time point (FIG. 37).

FIG. **37** shows bacterial colonization of mouse lungs after aerosol infection with either wild-type H37Rv, its isogenic

mutant ΔctpV, or the complemented strain ΔctpV::ctpV. CFUs were determined via homogenization of lungs from infected mice (N=3-5 per time point) in PBS and plating on 7H10+ADC, with hygromycin added in the case of the
mutant and complemented strain. CFUs were normalized to grams of lung tissue homogenized. Colonization levels between the three strains did not display a statistically significant difference over the course of the infection. The experiment was performed twice, with a representative 10 experiment shown.

Survival of mouse groups after aerosol infection with H37Rv, ActpV, or ActpV::ctpV is shown in FIG. 38. Survival is displayed as the time from infection (week 0) until the time declared morbid by animal care staff. Morbid mice were subsequently euthanized, with tuberculosis determined as the cause of illness via necropsy. A log-rank statistical test was used to analyze survival of mice groups. Survival of mice infected with H37Rv was significantly different from those infection with $\Delta ctpV$ (p-value=0.002), and those infected with survival was ∆ctpV::ctpV strain (p-value=0.02). Experiment was performed once with 10 mice/group.

In contrast to the similarity in bacterial load of the mice infected with H37Rv, Δ ctpV, and Δ ctpV::ctpV, the mice infected with Δ ctpV lived significantly longer than mice infected with wild type, with 16-week increase in time to death of mice infected with Δ ctpV versus mice infected with H37Rv (FIG. **38** shows survival curves of three mice groups infected with H37Rv wild-type strain, Δ ctpV strain, and Δ ctpV::ctpV strain). In fact, the median survival time for mice infected with Δ ctpV and 42 weeks for mice infected with Δ ctpV::ctpV. As determined by a log-rank statistical test (Ref), survival was significantly different between the H37Rv and Δ ctpV infection (p-value=0.002), and survival was also significantly different between the H37Rv and Δ ctpV::ctpV infection (p-value=0.02).

FIG. 39 shows histological (A-F) and immunohistochemisty (G-L) analysis of lung sections of mice lungs at 8 or 38 weeks post infection with wild-type ("WT") M. tb and $\Delta ctpV$ and $\Delta ctpV::ctpV$. Hematoxylin and eosin (H&E) stained mouse lung tissue (40× magnification) throughout the infection show increased lung damage of the mice infected with H37Rv and ActpV::ctpV relative to mice infected with $\Delta ctpV$ FIG. 39 A-F shows representative images at 8 and 38 weeks post-infection. Inset images (1000× magnification) show the Mtb bacilli (arrow heads) which were visible in lung tissue starting from 8 weeks forward. Immunohistochemisty of infected lung tissue at variable times of infection is shown in FIG. 39G-L. Lung tissue was sectioned and stained with antibody for mouse IFN- γ , which appears brown in the images (40× magnification). Inset images show 200x magnification of lesions displaying IFN-y expression.

Despite carrying similar levels of bacteria throughout the infection, histology staining of the infected mouse tissue revealed consistently lower levels of tissue damage in mice infected with Δ ctpV versus the wild-type and complemented strains. For example, at 8 weeks post-infection, lung tissue from mice infected with Δ ctpV displayed granulomatous inflammation, whereas mice infected with H37Rv displayed massive granulomatous inflammation with more lymphocytic infiltration (FIG. **39** A-F). By 38 weeks post-infection, granulomas became more developed (presence of giant cells) and occupied almost the whole lungs of mice infected with H37Rv, compared to only 50% of tissues of mice infected with the Δ ctpV mutant. Lesions observed in the

complemented strain were very similar to those observed in mice infected with H37Rv strain. Overall, animal survival and histopathological data indicated the attenuation of the Δ ctpV mutant compared to other tested strains.

Lung pathology in tuberculosis is thought to be caused 5 mainly by the host immune response. In order to investigate a possible mechanism for the decreased lung pathology and increased survival time of mice infected with Δ ctpV relative to H37Rv and Δ ctpV::ctpV, the lung sections were stained with an antibody against mouse interferon- γ , a key cytokine 10 known to be highly expressed during tuberculosis infection. As expected, no indication of IFN- γ expression was seen at

48

2 weeks post infection, prior to the start of the adaptive immune response (data not shown). However, by 8 weeks post infection, mice infected with H37Rv show significant IFN- γ expression, localized in areas of lung tissue damage, yet mice infected with Δ ctpV showed only small amounts of IFN- γ expression (FIG. **39**G-L). Mice infected with Δ ctpV: ctpV showed an intermediate level of IFN- γ expression. Interestingly, even at the 38 week time point where mice infected with Δ ctpV display large amounts of tissue damage, there was still little expression of IFN- γ relative to mice infected with H37Rv.

TABLE 11

No.	Gene_ID	Product	Function_Class	Foldchange (Mutant/WT)	GG_PDE	Functional category
	Positive Re	gulation	_			
1 2	Rv0006 Rv0007	gyrA	DNA gyrase subunit A conserved hypothetical	-2.5 -2.0	0.92 0.49	2 3
3	Rv0058	dnaB	protein DNA helicase (contains	-2.4	0.88	2
4	Rv0108c		hypothetical protein	-2.4	0.87	16.6
5	Rv0145		conserved hypothetical protein	-2.7	0.97	10.5
6	Rv0166	fadD5	acyl-CoA synthase	-4.2	1.00	1
7	Rv0167	yrbE1A	part of mce1 operon	-8.9	1.00	0
8	Rv0168	yrbE1B	part of mcel operon	-2.0	0.50	0
9	Rv0169	mcel	part of mcel operon, cell invasion protein	-5.1	1.00	0
10	KV0170 Dr/0171	mce1B mee1C	part of meel operon	-7.2	1.00	0
11	KV01/1 Dr/0172	mceIC mee1D	part of meel operon	-13.3	1.00	0
12	RV0172 Pr/0172	IncerD	part of meet operon	-3.0	1.00	0
13	RV0175 Rv0174	ipr K	part of meet operon	-3.0	1.00	0
15	Rv0174 Rv0175	meen	conserved hypothetical	-2.0	0.55	3
16	Rv0176		conserved hypothetical protein (mce1)	-2.2	0.69	3
17	Rv0177		conserved hypothetical protein (mce1)	-4.0	1.00	10.5
18	Rv0249c		probable membrane anchor protein	-2.2	0.71	7
19	Rv0364		conserved hypothetical protein	-2.2	0.74	3
20	Rv0430		hypothetical protein	-3.7	1.00	10.5
21	Rv0469	umaA1	unknown mycolic acid	-2.3	0.52	1
			methyltransferase			
22	Rv0635		conserved hypothetical protein	-3.1	0.99	10.5
23	Rv0636		hypothetical protein	-2.6	0.85	7
24	Rv0637		conserved hypothetical protein	-2.2	0.69	10.5
25	Rv0642c	mmaA4	methoxymycolic acid synthase 4	-2.1	0.41	1
26	Rv0667	rpoB	[beta] subunit of RNA polymerase	-2.4	0.91	2
27	Rv0684	fusA	elongation factor G	-2.7	0.98	2
28	Rv0685	tuf	elongation factor EF-Tu	-3.7	1.00	2
29	Rv0700	rpsJ	30S ribosomal protein S10	-3.5	1.00	2
30	Rv0701	rplC	50S ribosomal protein L3	-4.7	1.00	2
31	Rv0703	rplW	50S ribosomal protein L23	-4.1	1.00	2
32	Rv0704	rplB	50S ribosomal protein L2	-10.1	1.00	2
33	Rv0705	rpsS	30S ribosomal protein S19	-9.5	1.00	2
34	Rv0708	rplP	50S ribosomal protein L16	-2.4	0.66	2
35	Rv0709	rpmC	50S ribosomal protein L29	-4.2	1.00	2
36	Rv0710	rpsO	30S ribosomal protein S17	-6.2	1.00	2
37	Rv0718	rosH	30S ribosomal protein S8	-3.0	0.99	2
38	Rv0719	mIF	50S ribosomal protein L6	-5.0	1.00	2
39	Rv0721	rpsE	30S ribosomal protein S5	-2.4	0.91	2
40	Rv0723	rplO	50S ribosomal protein L15	-2.1	0.58	2
41	Rv0988	-1.2	conserved hypothetical protein	-2.1	0.65	3
42	Rv1182	papA3	PKS-associated protein, unknown function	-5.3	1.00	1

TABLE 11-continued

No.	Gene_ID	Product	Function_Class	Foldchange (Mutant/WT)	GG_PDE	Functional category
43	Rv1183	mmpL10	conserved large membrane	-2.6	0.96	3
44	Rv1184c		conserved hypothetical	-3.4	1.00	3
45	Rv1185c	fadD21	acyl-CoA synthase	-21	0.49	1
46	Rv1198	Tadi D2 T	conserved hypothetical	-2.0	0.03	3
47	Rv1297	rho	transcription termination	-2.4	0.82	2
48	Rv1298	rpmE	50S ribosomal protein L31	-2.0	0.33	2
49	Rv1535	-	hypothetical protein	-2.1	0.58	16.6
50	Rv1613	trpA	tryptophan synthase [alpha] chain	-2.5	0.92	7
51	Rv1614	lgt	prolipoprotein diacylglyceryl transferase	-4.6	1.00	3
52	Rv1643	rplT	50S ribosomal protein L20	-2.5	0.93	2
53	Rv1794		conserved hypothetical	-2.0	0.46	10.5
54	Rv1810		protein conserved hypothetical	-4.4	1.00	10.5
55	Rv1826	gcvH	protein glycine cleavage system H	-2.5	0.92	7
56	Rv1883c		protein conserved hypothetical	-2.4	0.70	10.5
			protein			
57	Rv1886c	fbpB	antigen 85B, mycolyltransferase	-2.3	0.80	1
58	Rv2067c		conserved hypothetical protein	-2.1	0.60	10.5
59	Rv2080	lppJ	lipoprotein	-2.7	0.98	3
60	Rv2147c		hypothetical protein	-2.2	0.22	10.5
61	Rv2190c		putative p60 homologue	-3.1	1.00	0
62	Rv2391	nirA	probable nitrite reductase/sulphite	-3.5	1.00	7
63	Rv2392	cysH	3'-phosphoadenylylsulfate (PAPS) reductase	-3.5	1.00	7
64	Rv2441c	rpmA	50S ribosomal protein L27	-2.2	0.65	2
65	Rv2840c	1	conserved hypothetical protein	-2.3	0.72	10.5
66	Rv2928	tesA	thioesterase	-2.0	0.53	1
67	Rv2948c	fadD22	acyl-CoA synthase	-2.8	0.98	1
68	Rv2949c		hypothetical protein	-16.1	1.00	10.5
69	Rv2950c	fadD29	acyl-CoA synthase	-3.2	1.00	1
70	Rv2959c		some similarity to methyltransferases	-2.2	0.67	7
71	Rv2986c	hupB	DNA-binding protein II	-2.4	0.89	2
72	Rv3135	PPE50	PPE-family protein	-2.0	0.55	6
73	Rv3148	nuoD	NADH dehydrogenase chain D	-2.4	0.87	7
74	Rv3152	nuoH	NADH dehydrogenase chain H	-2.2	0.64	7
75	Rv3153	nuoI	NADH dehydrogenase chain I	-3.6	1.00	7
76	Rv3154	nuoJ	NADH dehydrogenase chain J	-2.5	0.88	7
77	Rv3377c		similar to many cyclases involved in steroid	-2.2	0.73	7
70	Dx131560	lO	DIOSYNTHESIS		1.00	2
78 79	Rv3450c Rv3457c	rpoA	[alpha] subunit of RNA	-2.1	0.59	2
80	Rv3460a	rnsM	30S ribosomal protein \$12	_27	0.96	2
81	Rv3461c	romI	50S ribosomal protein L36	-2.5	0.78	2
82	Rv3477	PE31	PE-family protein	-4.8	1.00	- 6
83	Rv3478	PPE60	PPE-family protein	-4.1	1.00	6
84	Rv3487c	lipF	probable esterase	-4.4	1.00	7
85	Rv3600c	-	conserved hypothetical protein	-2.1	0.63	10.5
86 87	Rv3680 Rv3686c		probable anion transporter conserved hypothetical	-2.3 -3.2	$0.80 \\ 1.00$	3 10.5
88	Rv3763	lpqH	protein 19 KD lipoprotein antigen	-3.2	0.99	3
89	Rv3783	rfbD	integral	-2.5	0.94	3
			protein, ABC-2 SUBFAMILY			

No. Gene_ID	Product	Function_Class	Foldchange (Mutant/WT)	GG_PDE	Functional category
90 Rv3806c		possible integral membrane	-2.1	0.62	3
91 Rv3822		conserved hypothetical	-2.6	0.97	10.5
92 Rv3823c	mmpL8	conserved large membrane	-4.0	1.00	3
93 Rv3824c	papA1	PKS-associated protein,	-3.7	1.00	1
94 Rv3825c 95 Rv3921c	pk52	polyketide synthase unknown membrane	-2.2 -4.5	$\begin{array}{c} 0.70 \\ 1.00 \end{array}$	1 3
96 Rv3922c 97 Rv3923c	rnpA	possible hemolysin ribonuclease P protein component	-4.7 -2.4	$\begin{array}{c} 1.00 \\ 0.88 \end{array}$	0 2
98 Rv3924c Negative R	rpmH egulation	50S ribosomal protein L34	-3.0	0.99	2
		—			
99 Rv0079 100 Rv0129c	fbpC2	hypothetical protein antigen 85C,	3.7 2.7	1.00 0.53	16.6 1
		mycolytransferase			
101 Rv0188		putative methyltransferase	6.4	1.00	3
102 Rv0211	pckA	phosphoenolpyruvate carboxykinase	3.8	1.00	7
103 Rv0233	nrdB	ribonucleoside-diphosphate reductase B2	3.0	0.97	2
104 Rv0276		conserved hypothetical protein	2.2	0.51	10.5
105 Rv0341		conserved hypothetical	5.6	1.00	3
106 Rv0347		conserved hypothetical	4.6	1.00	3
107 Rv0569		conserved hypothetical	6.4	1.00	10.5
108 Rv0570	nrdZ	ribonucleotide reductase,	2.7	0.67	2
100 Pr/05720		burgethetical protain	2.1	0.01	16.6
109 Rv0677c	mmnS5	conserved small membrane	2.1	0.01	3
110 1000770	mmpss	protein	2.1	0.25	5
111 Rv0805		conserved hypothetical	2.8	0.92	10.5
112 Rv0823c	ntrB	transcriptional regulator, ntrB (NifR 3/Smm1 family)	2.6	0.53	9
113 Rv0824c	desA1	acvl-[ACP] desaturase	2.7	0.17	1
114 Rv0885		unknown transmembrane	3.0	0.98	10
115 Rv0967		conserved hypothetical	2.2	0.43	10.5
116 Rv0968		conserved hypothetical	2.0	0.27	10.5
117 Rv1303		conserved hypothetical	2.3	0.45	3
118 Rv1304	atpB	ATP synthase a chain	2.4	0.64	7
119 Rv1332		putative transcriptional regulator	2.0	0.18	9
120 Rv1461		conserved hypothetical protein	2.1	0.10	10.5
121 Rv1577c		phiRV1 possible prohead	2.4	0.65	5
122 Rv1622c	cydB	cytochrome d ubiquinol	12.1	1.00	7
123 Rv1623c	appC	cytochrome bd-II oxidase subunit I	7.5	1.00	7
124 Rv1733c		possible membrane protein	2.8	0.77	3
125 Rv1737c	narK2	nitrite extrusion protein	2.2	0.12	3
126 Rv1738		conserved hypothetical	2.9	0.17	10.5
127 Rv1813c		conserved hypothetical	9.6	1.00	10.5
128 Rv1846c		putative transcriptional	2.4	0.70	9
129 Rv1894c		some similarity to	2.2	0.44	10.5
130 Rv1955		hypothetical protein	25	0.79	16.6
131 Rv1995		conserved hypothetical	12.7	1.00	10.5
132 Rv1997	ctpF	protein probable cation transport ATPase	3.4	1.00	3

No. Gene_ID	Product	Function_Class	Foldchange (Mutant/WT)	GG_PDE	Functional category
133 Rv2031c	hspX	14 kD antigen, heat shock	2.5	0.04	2
134 Rv2032	acg	conserved hypothetical	3.8	0.99	10.5
135 Rv2160c		hypothetical regulatory	2.4	0.66	9
136 Rv2193	ctaE	cytochrome c oxidase polypeptide III	2.3	0.04	7
137 Rv2280		similar to D-lactate	2.2	0.30	7
138 Rv2495c	pdhC	dihydrolipoamide acetyltransferase	2.1	0.31	7
139 Rv2497c	pdhA	pyruvate dehydrogenase E1 component [alpha] subunit	2.5	0.70	7
140 Rv2557		conserved hypothetical protein	4.6	1.00	16.5
141 Rv2623		conserved hypothetical protein	7.1	1.00	10.5
142 Rv2624c		conserved hypothetical protein	4.3	1.00	10.5
143 Rv2625c		conserved hypothetical protein	5.8	1.00	3
144 Rv2626c		conserved hypothetical protein	5.1	1.00	10.5
145 Rv2627c		conserved hypothetical protein	11.5	1.00	10.5
146 Rv2628		hypothetical protein	15.0	1.00	16.6
147 Rv2629		hypothetical protein	4.0	1.00	10.5
148 Rv2630		hypothetical protein	2.0	0.27	16.6
149 Rv2780	ald	L-alanine dehvdrogenase	8.0	1.00	7
150 Rv2846c	efnA	putative efflux protein	2.4	0.47	3
151 Rv3048c	nrdG	ribonucleoside-diphosphate small subunit	2.5	0.77	2
152 Rv3053c	nrdH	glutaredoxin electron transport component of NrdEF	2.2	0.16	2
153 Rv3127		conserved hypothetical protein	5.3	1.00	10.5
154 Rv3129		conserved hypothetical protein	7.2	1.00	10.5
155 Rv3130c		conserved hypothetical protein	4.4	0.99	10.5
156 Rv3131		conserved hypothetical	3.5	0.93	10.5
157 Rv3139	fadE24	acyl-CoA dehydrogenase	3.7	1.00	1
158 Rv3140	fadE23	acyl-CoA dehydrogenase	8.8	1.00	1
150 Dv2020-	1801523	aimilar to various	0.0	1.00	7
139 KV3230C		oxygenases	2.1	0.89	1
160 Rv3675		hypothetical protein	2.6	0.76	3
161 D-2041	h fD	hastan afamitin	2.0	1.00	5
101 KV3841		bacterioierritin	0.2	1.00	/
102 Kv3842c	gipQi	glycerophosphoryl diester phosphodiesterase	2.3	0.26	/
163 Rv3854c	ethA	probable monooxygenase	2.8	0.91	7

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64

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66

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70

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FEATURE:		
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76

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77

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79

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80

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US 10,786,559 B2

84

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US 10,786,559 B2

85

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88

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90

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15

What is claimed is:

1. An immunogenic composition comprising a pharmaceutically acceptable carrier and an engineered attenuated *Mycobacterium tuberculosis* strain whose genome comprises a knockout mutation of gene rv0348.

2. A method of stimulating an immune response comprising administering to a mammal an immunogenic composition according to claim **1**.

3. The immunogenic composition of claim **1**, wherein the $_{10}$ knockout mutation is an insertion of a heterologous sequence into the rv0348 gene.

4. The immunogenic composition of claim **1**, wherein the knockout mutation is a deletion of a portion of the rv0348 gene.

5. The immunogenic composition of claim **4**, wherein the knockout mutation is a deletion of at least 10% of the rv0348 gene.

6. The immunogenic composition of claim **5**, wherein the knockout mutation is a deletion of at least 20% of the rv0348 gene.

7. The immunogenic composition of claim 6, wherein the knockout mutation is a deletion of at least 30% of the rv0348 gene.

8. The immunogenic composition of claim **1**, wherein the knockout mutation is an engineered non-function copy of the wild-type rv0348 gene.

9. The immunogenic composition of claim 1, wherein the rv0348 gene is silent.

10. The immunogenic composition of claim **1**, wherein the knockout mutation is a null-mutation and the rv0348 gene expresses a non-functional protein.

11. The immunogenic composition of claim **1**, wherein the composition additionally comprises an adjuvant.

12. The immunogenic composition of claim **11**, wherein the adjuvant is Fruend's incomplete adjuvant.

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