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Recombinant Mycobacterium as a vaccine

Description

5 The invention relates to a recombinant Mycobacterium cell for use as a vaccine.

Every year, up to 2 million people die from tuberculosis (TB) (1). The only available vaccine against TB is *Mycobacterium bovis* Bacillus Calmette-Guérin (BCG), which was used in humans for the first time in 1921 (2). To date, 4 billion doses of BCG have been administered, rendering it the most widely used human vaccine worldwide (3). Yet, we are still far from having achieved eradication of TB. BCG vaccination prevents tuberculous meningitis and miliary TB in infants (4). However, protection against other forms of TB, notably pulmonary TB in adolescents and adults is inconclusive as emphasized by a meta-analysis, which revealed protective efficacies ranging from 0–80% in adults (5). Therefore, new vaccines against TB are urgently needed. Currently, new vaccination strategies against TB in clinical trials include recombinant BCG to replace canonical BCG as well as subunit vaccines and non-replicating viral vector-based vaccines to booster BCG prime (6) (7).

The identification of immunologic mechanisms underlying protection can facilitate rational design of novel vaccination strategies for TB prevention. Moreover, this strategy could reveal biomarkers indicative for protective immunity that could reveal surrogate endpoints of clinical outcome in clinical TB vaccine efficacy trials, and thus reduce their duration as well as facilitate testing of larger numbers of vaccine candidates in parallel trials. Observational studies focusing on newly infected, healthy contacts of TB patients and on BCG-vaccinated infants have been initiated to define such biomarkers (8). Despite extensive research on the immune response to TB, the fundamental elements of protective memory have yet to be elucidated. After BCG vaccination, antigen-specific memory CD4 T cells are difficult to

detect due to the paucity of immunodominant antigens. Currently, the most widely used biomarkers are based on elevated frequencies of CD4 T cells producing IFN γ . Increasing evidence questions the value of IFN γ as correlate of protection in TB (9,10). Undoubtedly IFN γ does play a crucial role in defense against MTB (11), but determination of IFN γ alone can no longer be considered as a reliable marker of protective immunity.

A recombinant BCG strain expressing a phagolysosomal escape domain is described in WO 99/10496 , the content of which is herein incorporated by reference. The phagolysosomal escape domain enables the strain to escape from the phagosome of infected host cells by perforating the membrane of the phagosome. In order to provide an acidic phagosomal pH for optimal phagolysosomal escape activity, a urease-deficient recombinant strain was developed. This strain is disclosed in WO2004/094469, the content of which is herein incorporated.

A recombinant $\Delta ureC$ Hly⁺ rBCG (rBCG) strain expressing membrane-perforating listeriolysin (Hly) of *Listeria monocytogenes* and devoid of urease C induces superior protection against aerogenic challenge with MTB as compared to parental BCG (pBCG) in a preclinical model (12). This vaccine construct has successfully proven safety and immunogenicity in a phase I clinical trial (US 61/384,375), the content of which is herein incorporated by reference.

In the present study, it is shown that rBCG and pBCG induce marked Th1 immune responses, whilst only rBCG elicits a profound Th17 response in addition. It was also observed earlier recruitment of antigen-specific T lymphocytes to the lung upon MTB infection of rBCG-vaccinated mice. These T cells produced abundant Th1 cytokines after restimulation. Superior protective efficacy of rBCG was apparently dependent on IL17. Elevated IL17 production after rBCG, but not pBCG vaccination, was also detected in healthy volunteers during a phase I clinical trial. Our findings identify a general immunologic pathway as a marker for improved vaccination

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strategies against TB and other diseases.

A subject-matter of the present invention is a recombinant Mycobacterium cell which comprises a recombinant nucleic acid molecule encoding a fusion polypeptide comprising:

(a) a domain capable of eliciting an immune response, and

(b) a phagolysosomal escape domain

for use as vaccine for generating a Th17 immune response.

A further aspect of the present invention is a method for generating a Th17 immune response in a subject in need thereof, comprising administering to said subject a recombinant nucleic acid molecule encoding a fusion polypeptide comprising:

(a) a domain capable of eliciting an immune response, and

(b) a phagolysosomal escape domain.

In a preferred embodiment, the vaccine is a live recombinant Mycobacterium cell which comprises a recombinant nucleic acid molecule encoding a fusion polypeptide comprising (a) a domain capable of eliciting an immune response and (b) a phagolysosomal escape domain. The domain capable of eliciting an immune response is preferably an immunogenic peptide or polypeptide from a pathogen or an immunogenic fragment thereof. In a further embodiment the vaccine is a vaccine based on an inactivated whole pathogen cell or cell fraction.

The Mycobacterium cell is preferably an *M. bovis* cell, an *M. tuberculosis* cell, particularly an attenuated *M. tuberculosis* cell or other Mycobacteria, e.g. *M. microti*, *M. smegmatis*, *M. canettii*, *M. marinum* or *M. fortuitum*. More preferably, the cell is a recombinant *M. bovis* (BCG) cell, particularly a recombinant *M. bovis* cell from strain Danish subtype Prague (43). In an especially preferred embodiment, the vaccine is a recombinant urease-deficient Mycobacterium cell. In an especially preferred embodiment the ureC sequence of the Mycobacterium cell is inactivated (Δ Urec), e.g. by constructing

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a suicide vector containing a ureC gene disrupted by a selection marker gene, transforming the target cell with the vector and screening for selection marker-positive cells having a urease negative phenotype. Most preferably, the cell is recombinant BCG strain Danish subtype Prague characterized as rBCG
5 Δ Urec :: Hly⁺ :: Hyg⁺.

The domain capable of eliciting an immune response is preferably selected from immunogenic peptides or polypeptides from *M. bovis*, *M. tuberculosis* or *M. leprae* or from immunogenic fragments thereof having a length of at least 6,
10 preferably at least 8 amino acids, more preferably at least 9 amino acids and e.g. up to 20 amino acids. Specific examples for suitable antigens are Ag85B (p30) from *M. tuberculosis*, Ag85B (α -antigen) from *M. bovis* BCG, Ag85A from *M. tuberculosis* and ESAT-6 from *M. tuberculosis* and fragments thereof. In other embodiments, the domain capable of eliciting an immune response is
15 selected from non-Mycobacterium polypeptides.

The vaccine of the present invention is suitable for generating a Th17 immune response in a mammalian, e.g. human subject. The vaccine is preferably administered to a human subject in a dose of about $1-10 \times 10^5$, preferably about
20 $2-8 \times 10^5$ cells. The vaccine is preferably administered as a single dose, e.g. by injection. Subcutaneous injection is preferred. Further it is preferred to administer the vaccine without adjuvant.

The vaccine is preferably a vaccine against mycobacterial infections, such as
25 leprosy or tuberculosis, particularly pulmonary mycobacterial infections, more particularly pulmonary tuberculosis. Further, the vaccine may be a vaccine against bladder cancer, or an autoimmune disorder, e.g. an autoimmune skin disorder such as neurodermitis or psoriasis.

30 The vaccine may be for generating a Th17 immune response in a Mycobacterium-naïve subject, e.g. a human who has not been pre-exposed to an immunogenic Mycobacterium challenge or a human who has not been preimmunized with a Mycobacterium-based vaccine, e.g. BCG. Examples of

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such subjects are, e.g., newborns or children, e.g. up to 8 years, e.g. in areas endemic for mycobacterial infections, such as tuberculosis, or persons at risk in non-endemic areas. Alternatively, the vaccine may be administered to a subject, e.g. a human who has been pre-exposed to an immunogenic
5 Mycobacterium challenge or a human who has been preimmunized with BCG.

In an especially preferred embodiment, the vaccine is used for generating a combined Th17 and Th1 immune response.

10 According to the invention, a Th17 immune response is generated in a vaccinated subject. Determination of the Th17 immune response is preferably carried out in a biological sample derived from said subject, wherein said sample comprises immune cells, particularly T cells and/or NK cells, more particularly antigen-specific T cells such as CD4 T cells. The sample may be a
15 body fluid or tissue sample, e.g. a blood, serum or plasma sample or a sample from lung or spleen. Methods for collecting samples are well known in the art.

For a determination of the Th17 immune response it is preferred to restimulate the immune cells present in the sample in the subject to be analyzed with an
20 immunogen and determining cytokine expression from said cells. The cells to be analyzed are preferably antigen-specific T cells, more preferably CD4 T cells. The immunogen for the restimulation corresponds to the immunogen present in the vaccine (the efficacy of which is to be determined). The immunogen may be present either in a form identical to the form present in the
25 vaccine or in a different form. For example, when the vaccine comprises an immunogenic polypeptide, the immunogen in the restimulation step may comprise an immunogenic fragment thereof or vice versa. Preferably, the immunogen used for the restimulation step is a purified polypeptide or peptide. In order to test the efficacy of tuberculosis vaccines, particularly a live
30 tuberculosis vaccine as described above, the immunogen may be advantageously a mycobacterial antigen, e.g. selected from PPD "Purified Protein Derivative", which is a glycerol extract of mycobacteria or Ag85A and Ag85B, as well as other mycobacterial antigens and immunogenic fragments

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thereof (such as described above).

Determination of the Th17 response according to the invention may comprise determining cells associated with the Th17 response, e.g. IL-17 producing
5 cells, by means of surface markers and cytokines present in and/or secreted by said cells. Examples of surface markers are CD4, CD8, IL-23R, CCR4 and/or CCR6. Examples of cytokines present in and/or secreted by such cells are IL-17, IL-21, IL-22, IL-23, IFN- γ and combinations thereof. Preferably, the cytokine is IL-17. Such cells may be determined by cytological methods, e.g.
10 by cell sorting techniques using immunological detection reagents such as antibodies specific for cell-surface markers and/or cytokines, which may carry a labelling, e.g. a fluorescence group.

More preferably, cells associated with a Th17 immune response are e.g. CD4
15 T cells producing and optionally secreting IL-17.

In a further embodiment the determination of the Th17 immune response comprises determining a cytokine secreted from Th17 immune response associated cells, e.g. IL-17. The cytokine may be determined by immunological
20 methods using appropriate antibodies, e.g. antibodies directed against IL-17.

In a preferred embodiment, a combined Th17 and Th1 immune response is generated. A Th1 immune response may be determined by determining cells associated with the Th1 response by means of surface markers and cytokines
25 present in and/or secreted by said cells. Examples of surface markers are CD4, CD8, CCR5 and CD62^{low}. Examples of cytokines present in and/or secreted by such cells are IFN- γ , IL-22, and IL-23 and combinations thereof. Such cells may be determined by cytological methods, e.g. by cell sorting techniques using immunological detection reagents such as antibodies specific
30 for cell surface markers and/or cytokines, which may carry a labelling, e.g. a fluorescence group.

In a further embodiment, determination of the Th1 immune response

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comprises determining a cytokine secreted from Th1 immune response-associated cells, e.g. IFN- γ , IL-22 and/or IL-23. The cytokine may be determined by immunological methods using appropriate antibodies, e.g. antibodies directed against IFN- γ , IL-22 and/or IL-23.

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Preferably, the Th17 and optionally Th1 immune response is determined at a suitable time after vaccination. For example, the immune response may be determined 20-50 days, particularly 25-35 days after vaccination.

10 Further, the invention is described in more detail by the following Figures and Examples.

Figure Legends

15 **Figure 1: MTB burden in WT mice.** S.c. immunization protects against infection with MTB 90 days p.i. (A). Bacterial burden is comparable between vaccinated and non-vaccinated groups day 7 p.i. (B). CFU determination in lung and spleen after aerosol infection with 400 CFU MTB. The cardiac lung lobe (approx. 71/10th of the whole organ) or half a spleen was homogenized; 20 the remaining material was used for *in vitro* restimulation assays. Statistical significance determined by Mann-Whitney test with two-tailed P values. *, P < 0.05; **, P < 0.01. Data are representative of three experiments with similar results.

25 **Figure 2: Superior cytokine induction after rBCG over pBCG vaccination.** Responses in lung (A) and spleen (B) 83 days after s.c. vaccination with rBCG or pBCG. A total of 2.5×10^5 (lung) or 2×10^6 cells (spleen) were restimulated with PPD for 20 hours and supernatants analyzed by multiplex assays. Cytokine concentrations are depicted as means $\pm$ SEM of four independent 30 experiments with three replicates each. Background cytokine production from medium controls was subtracted. ANOVA and Bonferroni Multiple Comparison Test were applied for statistical analysis. *, P < 0.05; **, P < 0.01.

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Figure 3: Vaccination with rBCG accelerates recruitment of antigen-specific T cells to the lung upon aerosol infection with MTB. Cytokine secretion by lung cells 7 days after aerosol infection with 200-400 CFU MTB. A total of 2×10^5 cells were stimulated with PPD for 20 hours and supernatants analyzed by multiplex assay (A). Cytokine concentrations are depicted as mean $\pm$ SEM of two independent experiments with three replicates each. Background cytokine production from medium controls was subtracted. Cells restimulated with PPD for 6 hours in the presence of Brefeldin A were analyzed by multicolor flow cytometry (B). Frequencies of responding CD4 T cells are depicted as means $\pm$ SEM of three independent experiments with three replicates each. ANOVA and Bonferroni Multiple Comparison Test were applied for statistical analysis. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Figure 4 Vaccination with rBCG increases PPD-specific responses in the spleen upon aerosol infection with MTB. Cytokine secretion by spleen cells 7 days after aerosol infection with 200-400 CFU MTB. A total of 2×10^6 cells were restimulated with PPD for 20 hours and supernatants analyzed by multiplex assays (A). Cytokine concentrations are depicted as means $\pm$ SEM of four independent experiments with three replicates each. Background cytokine production from medium controls was subtracted. Cells restimulated with PPD for 6 hours in the presence of Brefeldin A were analyzed by multicolor flow cytometry (B). Frequencies of responding CD4 T cells are depicted as mean $\pm$ SEM of three independent experiments with three replicates each. ANOVA and Bonferroni Multiple Comparison Test were applied for statistical analysis. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.#

Figure 5: Vaccination with pBCG or rBCG does not lead to significant changes in Treg cell populations. Treg cells in the spleen after s.c. immunization with rBCG or pBCG. Black bars represent CD25⁺FoxP3⁺ and white bars CD25⁻FoxP3⁺ cells. Frequencies of CD4 T cells and CD8 Treg cells 83 days after immunization (A and B) as well as 7 days (C and D) or 90 days (E and F) after aerosol infection with 200-400 CFU MTB. Three mice per group, depicted as mean $\pm$ SEM. Data are representative of three

independent experiments with similar results.

Figure 6: Frequencies of cytokine producing CD8 T cells in the lung after vaccination and subsequent aerosol infection with MTB. Cytokine secretion 7 days after aerosol infection with 200-400 CFU MTB. Cells restimulated with PPD for 6 hours in the presence of Brefeldin A were analyzed by multicolor flow cytometry. Frequencies of responding CD8 T cells are depicted as mean $\pm$ SEM of two independent experiments with three replicates each. ANOVA and Bonferroni Multiple Comparison Test were applied for statistical analysis.

Figure 7: Frequencies of cytokine producing CD8 T cells in the spleen after vaccination and subsequent aerosol infection with MTB. Cytokine secretion 7 days after aerosol infection with 200-400 CFU MTB. Cells restimulated with PPD for 6 hours in the presence of Brefeldin A were analyzed by multicolor flow cytometry. Frequencies of responding CD8 T cells are depicted as mean $\pm$ SEM of four independent experiments with three replicates each. ANOVA and Bonferroni Multiple Comparison Test were applied for statistical analysis. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Figure 8: Immune responses in the lung during persistent MTB infection in rBCG-vaccinated mice. Cytokine secretion by lung cells 90 days after aerosol infection with 200-400 CFU MTB. Cells were restimulated with PPD for 20 hours and supernatants analyzed by multiplex assays (A). Cytokine concentrations are depicted as means $\pm$ SEM of two independent experiments with three replicates each. Background cytokine production from medium controls was subtracted. Cells restimulated with PPD for 6 hours in the presence of Brefeldin A were analyzed by multicolor flow cytometry (B). Frequencies of responding CD4 T cells are depicted as mean $\pm$ SEM of two independent experiments with three replicates each. ANOVA and Bonferroni Multiple Comparison Test were applied for statistical analysis. *, $P < 0.05$; **, $P < 0.01$.

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Figure 9: Frequencies of cytokine producing CD8 T cells after vaccination and subsequent aerosol infection with MTB. Cytokine secretion by cells isolated from the lung 90 days after aerosol infection with 200-400 CFU MTB. Cells restimulated with PPD for 6 hours in the presence of Brefeldin A were analyzed by multicolor flow cytometry. Frequencies of responding CD8 T cells are depicted as mean $\pm$ SEM of two independent experiments with three replicates each. ANOVA and Bonferroni Multiple Comparison Test were applied for statistical analysis. *, $P < 0.05$.

Figure 10: Vaccination induces IL22 but not IL21 production. IL21 (A) and IL22 (B) secretion by cells from spleens (2×10^6 cells) or lungs (2×10^5 cells) of mice 83 days after vaccination and subsequent aerosol infection with 200-400 CFU MTB. IL21 concentrations measured from three samples per group, mean $\pm$ SEM depicted. For IL22 samples from one group were pooled. Data are representative of two (day 83 post vaccination) and five (day 7 p.i.) similar experiments. Cells were restimulated with PPD for 20 hours and supernatants analyzed by ELISA.

Figure 11: rBCG causes increased recruitment of $\gamma\delta$ T cells and NK cells without significantly altering APC populations. Cells recruited to the peritoneal cavity upon administration of 10^6 CFU of rBCG or pBCG i.p. Analysis of cell populations in peritoneal lavage fluid by flow cytometry. APC recruited to the peritoneum 5 hours (upper panel) and 6 days (lower panel) after i.p. administration of rBCG or pBCG (A). ICS of T cell populations 5 hours after injection (B). Cells were stimulated with α CD3/ α CD28 antibodies for 18 hours in the presence of Brefeldin A. ICS of T cell populations 6 days after administration (C). Cells were restimulated with PPD for 18 hours in the presence of Brefeldin A. Data presented as summary of three independent experiments with five mice per group. Horizontal line indicates median. ANOVA and Bonferroni Multiple Comparison Test were applied for statistical analysis. *, $P < 0.05$; **, $P < 0.01$. Cytokines and chemokines detected in peritoneal lavage fluid analyzed by multiplex assay (D) depicted as mean concentrations $\pm$ SEM.

Figure 12: rBCG induces IL17 in human PBMCs from healthy volunteers of a phase I clinical trial. IL17 production by human PBMCs isolated from healthy human volunteers of a phase I clinical study. A total of 5×10^5 cells isolated 29 days post vaccination with rBCG or pBCG, were restimulated with PPD for 20 hours and supernatants analyzed by multiplex assay. Statistical significance determined by Mann-Whitney test with one-tailed P value and Welch's correction. *, $P < 0.05$; $n=3$ for pBCG and $n=7$ for rBCG.

Example

Materials and Methods

Mice

Female BALB/c mice were bred at the Bundesinstitut für Risikobewertung (BfR) in Berlin. Mice were 6–8 weeks of age at the beginning of the experiments and kept under specific pathogen-free (SPF) conditions. Animal experiments were conducted with the approval of the Landesamt für Gesundheit und Soziales (LAGeSo, Berlin, Germany).

Bacteria

The MTB H37Rv and the pBCG and rBCG strains used were described previously (12). Bacteria were grown in Middlebrook 7H9 broth supplemented with glycerol, 0.05% Tween 80 and ADC. Mid-logarithmic cultures were harvested and stored at -80°C until use. All stocks were titrated prior to use. Single cell bacterial suspensions were obtained by repeated transfer through a syringe with a 27G needle.

Vaccination and MTB infection

pBCG or rBCG (10^6 CFU) were administered subcutaneously (s.c.) in close proximity to the tail base. Aerogenic infection of mice with MTB was performed using a Glas-Col inhalation exposure system. Bacterial burdens were assessed by mechanical disruption of aseptically removed organs in

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PBS 0.5% v/v Tween 80 and plating serial dilutions onto Middlebrook 7H11 agar plates supplemented with OADC. After 3 weeks, MTB colonies were counted. Statistical significance of results was determined by Mann-Whitney test with two-tailed p-values for non-parametric data using GraphPad Prism 5.0.

Cell isolation, stimulations and flow cytometry

Cells were purified as previously described (42). Experimental groups comprised five mice. Two spleens or lungs were pooled and one sample processed individually, resulting in three samples per group of five mice for subsequent stimulations. Cells were stimulated with 50 µg/ml PPD (SSI, Copenhagen, Denmark) for 20 hours for cytokine analysis by multiplex assay or for 6 hours in the presence of 25 µg/ml Brefeldin A for intracellular cytokine staining (ICS). The following antibodies were used: CD4 (RM4-5), IFNγ (XMG-1.2), IL2 (JES6-5H4), Ly6G/C (RB6-8C5), CD11b (M1/70), γδ-TCR (GL-3), FoxP3 staining set and CD49b (cloneDX5) all eBioscience. CD8α (YTS169), TNF-α (XT22), CD16/CD32 (2.4G2), F4/80 (CI:A3-1) and CD11c (N418) were purified from hybridoma supernatants and fluorescently labeled in house. IL-17 (TC11-18H10) was obtained from BD Biosciences. Cells were analyzed using a FACSCanto II or LSRII flow cytometer and FACSDiva software (BD Biosciences). Cytokines were measured using the Bio-Plex Mouse Th1/Th2, IL17 and IL6 bead-based immunoassays from Bio-Rad according to manufacturer's instructions. IL21 and IL22 were measured by ELISA from R&D systems. Human IL17 was detected with a Milliplex 42-plex assay from Millipore.

Peritoneal lavage

pBCG or rBCG were freshly prepared from mid-logarithmic cultures. Bacteria were washed three times with PBS and concentration determined by measuring optical density at 580 nm. Administration of 10⁶ CFU was performed intraperitoneally. Recruited cells were obtained from the peritoneal cavity 5 hours or 6 days later by injection of 5 ml PBS and analyzed by flow cytometry. Cytokines and chemokines in lavage fluid were

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determined using the Bio-Plex Mouse Cytokine 23-plex kit from Bio-Rad.

Results

5 Th1/Th17 responses after rBCG and pBCG vaccination

In an attempt to elucidate immune mechanisms relevant to TB vaccine efficacy, we compared immune responses to rBCG and pBCG in mice. Superior protective efficacy of rBCG had been originally determined after i.v. immunization (12). Here we show that s.c. administration of rBCG induced
10 comparable levels of protection and retained its superior efficacy over pBCG (Figure 1A). Next, we analyzed long-term memory responses in lungs and spleens of mice 83 days after s.c. vaccination with rBCG or pBCG. Cells were restimulated with PPD and supernatants analyzed by multiplex assays for cytokines. Immunization with rBCG induced significantly higher cytokine
15 production by cells isolated from the lung as compared to pBCG (Figure 2A). These included IFN γ , IL2, IL6, and GM-CSF. In contrast, type 2 cytokines IL4, IL5 and IL10 were not increased above background levels (data not shown). Intriguingly, approximately 3-fold higher IL17 concentrations were produced by lung cells from rBCG-vaccinated mice. Note that only few cells
20 could be isolated from the lungs of uninfected mice. Consequently, overall cytokine concentrations were lower than in spleen where 10-fold higher cell densities per well could be used for stimulation (Figure 2B). In spleens, both vaccines elicited equally strong Th1 responses as reflected by comparable concentrations of IL2, IL6, IFN γ and GM-CSF. Yet, spleen cells from rBCG-
25 vaccinated mice produced significantly more IL17 upon restimulation with PPD as compared to pBCG-vaccinated animals. Thus, immunization with rBCG, but not pBCG, induced concomitant and strong Th1 and Th17 responses in lungs and spleens, which were sustained for prolonged periods of time.

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Accelerated recruitment of MTB-specific T cells upon infection with virulent MTB in rBCG-vaccinated mice

Th17 cells have been linked to improved immune surveillance (13). We

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compared antigen-specific T cell responses in vaccinated animals upon aerosol infection with virulent MTB, in lungs and spleens 7 days post infection. Marked IFN γ , IL17, IL2 and GM-CSF production by lung cells from rBCG-vaccinated mice was detected 20 hours after restimulation with PPD (Figure 3A) or Ag85A peptides (data not shown). In contrast, these cytokines were barely secreted by cells from pBCG-vaccinated mice. In non-vaccinated animals infected with MTB, cytokine production was below detection limit, in agreement with previous reports that MTB-specific T cells do not appear before 3 weeks after MTB infection (13). The type 2 cytokines IL4, IL5 and IL10 were not detected and TNF α , IL12p70 and IL6 were only barely above background levels at this early timepoint post MTB challenge (data not shown).

We determined cytokine production by lung T cells by flow cytometry 7 days after MTB infection (Figure 3B). Cells were stimulated with PPD for 6 hours followed by intracellular cytokine staining for IL2, IL17, IFN γ and TNF α . In non-vaccinated controls a small proportion of CD4 T cells produced IL2, TNF α or IFN γ . In vaccinated mice, CD4 T cells secreted IL2, IFN γ , TNF α and also IL17. Frequencies of single cytokine producing cells were highest, albeit not significant, in the rBCG group. In vaccinated animals we detected multifunctional T cells implicated in protective immunity (14). Multiple cytokine-producing T cells were predominantly IL2⁺TNF α ⁺ double producers and significantly increased upon rBCG vaccination. Triple-producer cells were almost exclusively IL2⁺IFN γ ⁺TNF α ⁺ and slightly increased in rBCG compared to pBCG-vaccinated mice. Also, IL2⁺TNF α ⁺IFN γ ⁺IL17⁺ quadruple-positive cells exclusively appeared in the rBCG group albeit at very low frequencies.

In principle, splenic T cells produced similar cytokine patterns as pulmonary T cells (Figure 4). IL2 and GM-CSF production was significantly higher in the rBCG-vaccinated animals as compared to the pBCG group and below detection level in non-vaccinated controls, even though in non-vaccinated controls, a small percentage of CD4 T cells produced IFN γ . In sum,

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vaccination with either pBCG or rBCG induced CD4 T cells secreting IFN γ and TNF α with higher frequencies of single and multi-producers in rBCG-vaccinated mice as compared to the pBCG group.

5 At 7 days p.i. CD4 T cells were the main cytokine producers; CD8 cytokine producers were detected with lower frequencies in the lung (Figure 6) and spleen (Figure 7) albeit with similar patterns. It is of note that significantly higher frequencies of TNF α - single producing CD8 T cells were detected in the rBCG group.

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Differential cytokine production and frequencies of producer cells were not due to different bacterial burdens at this early timepoint after infection, as confirmed by comparable colony forming unit (CFU) numbers in lungs and spleens (Figure 1B). Total numbers of Treg cells increased upon infection to a comparable degree in the two vaccinated groups (Figure 5).

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Vaccination with rBCG confers potent immune responses during persistent infection

We analyzed MTB-specific immune responses 90 days p.i. when lung bacterial burdens were approximately 10-fold lower in rBCG-immunized animals as compared to the pBCG group and 100-fold lower as compared to the non-vaccinated control group. Cells from lungs of vaccinated mice and untreated controls were restimulated with PPD for 20 hours and cytokine concentrations measured by multiplex assays (Figure 8A). Cytokines detected upon restimulation were predominantly of type 1. However, we could not detect differences in IFN γ or IL17 between the vaccinated groups during persistent infection. In contrast, amounts of IL2, IL6, GM-CSF and TNF α were higher in rBCG-vaccinated mice. In all groups, IL4 and IL5 were below detection limit and some IL12p70 and IL10 were measured (data not shown). Additionally, analysis of lung cells by multicolor flow cytometry revealed predominantly cytokine-producing CD4 T cells during persistent infection (Figure 8B). CD4 T cells secreting only IFN γ were detected in all groups with similar frequencies. Upon vaccination, CD4 T cells producing

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IL2, IFN γ , TNF α or IL17 in different combinations could be detected as well. Intriguingly, frequencies of responding CD4 T cells did not differ significantly between rBCG and pBCG vaccination despite higher concentrations of IL2 and TNF α in supernatants. We assume that both vaccines increased
5 frequencies of antigen-specific CD4 T cells in the lung during persistent MTB infection with rBCG-induced T cells becoming more potent cytokine producers. CD8 T cells almost exclusively secreted IFN γ with comparable frequencies in all groups whereas significantly higher single TNF α -producing CD8 T cells were detected in the rBCG group. Multifunctional CD8 T cells
10 appeared barely above background (Figure 9).

Vaccination causes IL22 but not IL21 production

Th17 cells can produce additional effector cytokines such as IL21 (15) and IL22 (16). IL22-producing cells have been identified in TB patients, but these
15 seem distinct from IL17-producing cells (17). We did not detect IL21 after stimulation with PPD of spleen or lung cells from vaccinated and subsequently MTB-infected mice (Figure 10A). IL22 was produced at elevated concentrations by splenocytes stimulated with PPD for 20 hours (Figure 10B) in rBCG-immunized mice but did not further increase early after
20 infection with MTB. IL22 production by lung cells was only observed in the rBCG-vaccinated group and declined after aerosol MTB infection.

Intraperitoneal rBCG causes increased recruitment of $\gamma\delta$ T cells and NK cells without significantly altering APC populations

We wanted to define the mechanisms underlying preferential Th17 cell
25 induction after immunization with rBCG. To this end, rBCG and pBCG were administered i.p., immigrant cells isolated from the peritoneal cavity 5 hours or 6 days after administration and analyzed by flow cytometry (Figure 11A). Neutrophils (defined as Gr1^{HI}, CD11b^{HI}, MHCII⁻, CD11c⁻) rapidly entered the peritoneal cavity and remained elevated at day 6 p.i. in pBCG and rBCG
30 groups to the same extent. Frequencies of resident peritoneal macrophages (defined as CD11b^{HI}, F4/80^{HI}, Gr1⁻, MHCII^{HI}, CD11c⁻) and dendritic cells (CD11c⁺, CD11b^{LO}, Gr1⁻) remained unchanged at low percentages. In sum,

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no significant differences were detectable between rBCG and pBCG groups. Peritoneal cells harvested 5 hours after vaccination were subjected to polyclonal stimulation (Figure 11B) with α CD3/ α CD28 antibodies. Frequencies of CD4 T cells and NK cells were comparable between all groups as were IFN γ and IL17 production. Six days after administration, these cells increased numerically and reached highest frequencies in the rBCG group (Figure 11C). PPD was used for re-stimulation of cells at the 6 day timepoint. CD4 T cells did not produce appreciable amounts of IFN γ or IL17, whilst a substantial proportion of NK cells produced IFN γ after rBCG administration. $\gamma\delta$ T cells have been identified as a major source of early IL17 in TB (18). Increased, albeit not significant, proportions of $\gamma\delta$ T cells producing IFN γ were identified 5 hours post-injection with rBCG. This cell population further increased and markedly higher frequencies of $\gamma\delta$ T cells producing IL17 were detected in the rBCG group 6 days after injection. CD8 T cells were not detected in the peritoneum in any of the groups. We analyzed cytokines and chemokines present in the peritoneal cavity by multiplex assay of peritoneal lavage fluid (Figure 11D). MCP-1, MIP1 α , G-CSF and KC were rapidly increased upon injection; levels of Eotaxin remained unchanged and IL12p40 was detected in higher concentrations after 6 days. IL12p70, IFN γ , IL1 α , IL2, IL3, IL4, IL5, IL10, IL17, GM-CSF, and TNF α concentrations were below detection limit whereas IL1 β , IL6, IL9, IL13, MIP1 β and RANTES could be measured but production was comparable between rBCG and pBCG. Thus, rBCG and pBCG induced recruitment of APC as well as chemokine and cytokine production at the site of administration to a similar extent. Intriguingly, proportions of $\gamma\delta$ T cells secreting IL17 and NK cells producing IFN γ were most abundant after rBCG administration.

Vaccination with rBCG generates IL17-producing cells in humans

Last, we analyzed PBMCs from healthy human volunteers of a phase I clinical trial to interrogate whether IL17 production was increased in rBCG-vaccinated study participants. Blood from volunteers was taken 29 days after immunization with rBCG or pBCG and PBMCs isolated and frozen. PBMCs

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were thawed and rested over night, followed by 20-hour restimulation with PPD. Cytokine production was analyzed by multiplex assays. IL17 production was exclusively detected in PBMCs from study participants immunized with rBCG (Figure 12). Note that a limited number of samples
5 was available.

Discussion

The identification of immune markers of protection is crucial for rational
10 design of novel TB vaccines. These markers could also establish the basis for definition of surrogate markers to predict endpoints of clinical outcome in TB vaccine efficacy trials and thus provide guidelines for improvement of current vaccine candidates. The importance of key cytokines which activate macrophage antimycobacterial capacities including IFN γ (21) and TNF α
15 (22), and the necessity for IL2 in the expansion of memory cells (23) are well established and thus commonly used to monitor TB vaccine trials.

In an attempt to identify biomarkers of vaccine efficacy, we compared long-term memory immune responses elicited by rBCG proven to confer superior
20 protection over its parental strain, pBCG. Responses differed in both quantitative and qualitative terms. We detected increased abundance of type 1 cytokines as well as IL17 following vaccination with rBCG in the lung (Figure 2A). Analysis of vaccine-induced immune responses in lung is obviously not feasible in the context of clinical trials. Therefore, we also
25 analyzed systemic long-term memory responses (Figure 2B). Intriguingly, comparable concentrations of type-1 directing cytokines were detected in the pBCG and rBCG groups. In contrast, IL17 production by splenocytes was significantly elevated upon rBCG vaccination. Thus, we conclude that IL17, rather than IFN γ or IL2 qualifies as a marker of superior protection induced
30 by rBCG.

Th17 cells contribute to antimicrobial defense by attracting and activating neutrophils (24) which are among the first cells to be recruited in response to

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IL17. It has been shown that IL17 is dispensable during primary MTB infection (25,26), but gains importance in memory responses (13). In addition, recent reports on the expression of CCR6 on human Th17 cells (27,28) point to a positive feedback loop, because CCR6 is the receptor for CCL20 produced by neutrophils (29) and CCL20-CCR6 has been implicated in immunopathogenesis of TB (30). Thus, Th17 cells could facilitate accelerated recruitment of antigen-specific memory T cells to the sites of bacterial residence. By analyzing vaccine-induced immune responses 7 days after aerosol infection with MTB, we show that vaccination with rBCG indeed lead to accelerated recruitment of effector cells to the sites of bacterial replication. We observed increased frequencies of antigen-specific CD4 T cells and elevated production of IL2, IL17, IFN γ and GM-CSF by lung (Figure 3) and spleen cells (Figure 4).

Multifunctional CD4 T cells co-producing IL2, IFN γ and TNF α were first implicated in successful vaccination strategies against *Leishmania major* (14) and later also against MTB (31). Recently, these polyfunctional CD4 T cells were also detected in clinical TB vaccine trials (32,33). We detected polyfunctional CD4 T cells upon rBCG and pBCG vaccination and subsequent infection (Figure 3 and 4); however the composition of cytokines (IL2, IL17, IFN γ and TNF α) in double- and triple-producers varied considerably between experiments as well as individual animals. If multifunctional cells were a true correlate of protection, then their overall frequencies, which were higher in the rBCG group, rather than their composition, seem most relevant.

Why did rBCG induce a Th17 response? Immunization with rBCG and pBCG caused recruitment of APC as well as chemokine and cytokine producers to a similar extent. Intriguingly, proportions of $\gamma\delta$ T cells secreting IL17 and NK cells producing IFN γ were highly abundant after rBCG vaccination. This is consistent with reports showing that IL17 can be rapidly produced by $\gamma\delta$ T cells (34,18) as well as NKT cells (35). NK cells, which were also increased upon vaccination with rBCG, are an important source of early IFN γ . We have

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already shown that different molecular components released from rBCG reside in the cytosol of infected macrophages (12). Nod-2 is an important cytosolic PRR and its engagement has been linked to the development of Th17 memory T cell responses (19).

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Apoptosis induced during bacterial infection induces Th17 cells (36). We have obtained evidence that rBCG induces increased apoptosis compared to pBCG (12), which could further contribute to increased development of Th17 cells. Activation of inflammasomes could also contribute to Th17 memory responses via production of IL1 β (37). NLRP3 for example has been found to sense the presence of listeriolysin through changes in ATP levels (38). Thus, induction of Th17 cells upon rBCG vaccination might require a complex interplay of intracellular stimuli and increased apoptosis.

15 Th17 cells are considered instrumental in inflammatory and autoimmune diseases such as collagen-induced arthritis (39), EAE (40, 39) and allergic airway hypersensitivity (41,39) rather than being beneficial for successful vaccination. This pathogenic role is usually associated with development of a profound IL21-mediated inflammatory response. We never detected IL21 after vaccination and subsequent MTB infection above background levels in any experiment (Figure 10A). In addition, we never observed signs for autoimmunity or excessive inflammation at the site of injection upon vaccination with rBCG nor in the lung up to 200 days post MTB infection.

25 In a first attempt to compare data from experimental TB in mice with human data, we analyzed cytokine profiles of frozen PBMCs from a phase I clinical trial with rBCG and pBCG. In a limited number of samples we detected IL17 production after rBCG, but not pBCG, vaccination. Th17 cells have been detected in peripheral blood of MTB-infected humans (17). Recently, IL17-producing CD4 T cells have been reported in adolescents vaccinated with a TB vaccine candidate composed of modified vaccinia virus Ankara expressing Ag85A (33). Responses peaked between days 7 and 28 post vaccination and declined thereafter. This is in line with our data showing

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elevated IL17 production at day 29 post vaccination in the rBCG group (Figure 12). Thus, it is tempting to propose IL17 as a correlate of protection in TB vaccine trials.

5 In summary, we show that vaccination with rBCG leads to preferential generation of Th17 cells, likely dependent on intracellular recognition of bacterial components by Nod-2. These Th17 cells in turn accelerate recruitment of antigen-specific T cells to the lung. Ultimately, this cascade of events results in earlier containment of MTB and hence, to superior
10 protection by rBCG as compared to pBCG. We detect IL17 production exclusively by PBMC from rBCG-vaccinated volunteers in a successfully completed phase I clinical trial. Since IL17 seems instrumental for accelerated recruitment of antigen-specific T cells to the sites of MTB replication, future TB vaccines should be tailored to concomitantly induce
15 balanced Th1 and Th17 responses.

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CLAIMS

1. A recombinant *Mycobacterium bovis* Bacillus Calmette-Guérin (BCG) cell from strain Danish subtype Prague derived from the parental strain *Mycobacterium bovis* TMC1025PCG Prague (ATCC35742), which is a urease-deficient cell and which comprises a recombinant nucleic acid molecule encoding a fusion polypeptide comprising:
 - (a) a domain from a Mycobacterium polypeptide, which is antigen (Ag) 85B or Ag85A or a fragment thereof, capable of eliciting an immune response, and
 - (b) a Listeria phagolysosomal escape domainfor use as vaccine against tuberculosis for generating a Th17 immune response.
2. The cell of claim 1 for the use of claim 1, wherein the domain capable of eliciting an immune response is selected from immunogenic peptides or polypeptides from *M. bovis* or *M. tuberculosis*.
3. The cell of any one of claims 1 or 2 for the use of claim 1 for generating a Th17 immune response in a mammalian, e.g. human subject.
4. The cell of any one of claims 1-3 for the use of claim 1 for generating a Th17 immune response in a Mycobacterium-naïve subject or a subject pre-exposed to Mycobacterium challenge.
5. The cell of any one of claims 1-4 for the use as a vaccine for generating a Th17 and further for generating a Th1 immune response.
6. Use of a recombinant *Mycobacterium bovis* (BCG) cell from strain Danish subtype Prague derived from the parental strain *Mycobacterium bovis* TMC1025BCG Prague (ATCC35742), which is a urease-deficient cell, in the manufacture of a vaccine against tuberculosis which comprises a recombinant nucleic acid molecule encoding a fusion polypeptide comprising:
 - (a) a domain from a Mycobacterium polypeptide, which is antigen (Ag) 85B or Ag85A or a fragment thereof, capable of eliciting an immune response, and
 - (b) a Listeria phagolysosomalfor generating a Th17 immune response in a subject in need thereof.