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Protection against Tuberculosis with Homologous or Heterologous Protein/Vector Vaccine Approaches Is Not Dependent on CD8+ T Cells

Susan L. Baldwin,* Lance K. Ching,* Samuel O. Pine,† Magdalini Moutaftsi,* Elyse Lucas,* Aarthry Vallur,* Mark T. Orr,* Sylvie Bertholet,‡ Steven G. Reed,*§ and Rhea N. Coler*¶

Considerable effort has been directed to develop Mycobacterium tuberculosis vaccines to boost bacille Calmette-Guérin or for those who cannot be immunized with bacille Calmette-Guérin. We hypothesized that CD4+ and CD8+ T cell responses with a heterologous prime/boost vaccine approach could induce long-lived vaccine efficacy against M. tuberculosis in C57BL/6 mice. We produced an adenovirus vector expressing ID93 (Ad5-ID93) for induction of CD8 T cells. Ad5-ID93 generates ID93-specific CD8+ T cell responses and induces protection against M. tuberculosis. When Ad5-ID93 is administered in a prime-boost strategy with ID93/GLA-SE, both CD4+ and CD8+ T cells are generated and provide protection against M. tuberculosis. In a MHC class I−deficient mouse model, all groups including the Ad5-ID93 group elicited an Ag-specific CD4+ T cell response and significantly fewer Ag-specific CD8+ T cells, but were still protected against M. tuberculosis, suggesting that CD4+ Th1 T cells could compensate for the loss of CD8+ T cells. Lastly, the order of the heterologous immunizations was critical. Long-lived vaccine protection was observed only when Ad5-ID93 was given as the boost following an ID93/GLA-SE prime. The homologous ID93/GLA-SE prime/boost regimen also induced long-lived protection. One of the correlates of protection between these two approaches was an increase in the total number of ID93-specific IFN-γ-producing CD4+ T cells 6 mo following the last immunization. Our findings provide insight into the development of vaccines not only for tuberculosis, but other diseases requiring T cell immunity. The Journal of Immunology, 2013, 191: 000–000.

Tuberculosis (TB) is the most common cause of infectious disease-related mortality worldwide. One in three people are currently infected with Mycobacterium tuberculosis (1). Although the incidence rate of TB has declined by 2.2% between 2010 and 2011, there were ~8.7 million new cases in 2011, and 1.4 million deaths associated with TB during this time (2). In addition, there has been an increase in multiple drug-resistant TB in 2011 (630,000 cases), and 84 countries have reported extensively drug-resistant TB cases (2). Bacille Calmette-Guérin (BCG) is the only approved vaccine against M. tuberculosis and has been shown to reduce the risk of serious childhood forms of TB. BCG efficacy, however, wanes over time and is not effective against pulmonary disease in adults (3). The absence of a robust, protective vaccine underscores the need to develop a long-lasting and effective vaccine for the prevention of TB.

Our laboratory has developed a novel TB vaccine known as ID93/glucopyranosyl lipid adjuvant (GLA)-stable emulsion (SE), which is currently in Phase I human clinical trials. ID93 is a fusion protein comprising four M. tuberculosis proteins, as follows: Rv2608 (PE/PPE family), Rv3619, Rv3620 (EsX family of virulence factors), Rv1813 (upregulated during latency) (4, 5). When combined with the synthetic TLR4 adjuvant, GLA-SE, ID93 boosts the BCG vaccine and prolongs survival in guinea pigs (5). GLA-SE is a hexa-acylated lipid A derivative shown previously to have multifunctional immunomodulatory activity similar to monophosphoryl lipid A (MPL) on murine cells, but is more potent on a molar basis on human dendritic cells and PBMCs (6). In the absence of a BCG prime, ID93/GLA-SE is also effective as a prophylactic vaccine, capable of reducing lung bacterial burden in the mouse model and reducing lung pathology and improving survival in the guinea pig model of M. tuberculosis infection (7).

Correlates of cellular immune protection against M. tuberculosis are poorly defined. The prevalent belief is that Th1 CD4+ T lymphocytes are critical, but a role for mouse, nonhuman primate, and human CD8+ T cell responses in defense against M. tuberculosis has also been reported (8–14). Viral vaccine vectors such as adenoviral or modified vaccinia Ankara (MVA) expression vectors have been widely used to generate both CD4+ and CD8+ T cell responses against M. tuberculosis (15–25) and other pathogens (26–28). Human clinical trials have been completed with MVA85A, a vaccine developed against TB, in several age groups, including adults and infants (19, 20, 29). The first Phase IIb safety and efficacy trial to use a TB vaccine made to boost
CBG was recently described, in which CBG-immunized infants were boosted with MVA85A (30). Although the outcome of the trial resulted in lack of significant efficacy against M. tuberculosis with this vaccine strategy in CBG-primed infants, it may still prove to be effective in adults, against pulmonary TB (30). Other human clinical trials that have been completed with adenoviral vector vaccines include vaccines against both HIV (31) and malaria (32, 33), in addition to those using MVA vaccines against several infectious diseases such as HIV (34, 35), malaria (36), influenza (37), and smallpox (38). The AdS-vectored Plasmidum falciparum vaccine encoding the 3D7 circumsporozoite protein (NMRC-MV. AD-PIC) approach resulted in primarily CD8 T cell responses, but did not induce sterile protection in human volunteers (33). Some HIV adenoviral vaccine approaches have involved a DNA prime/adenoviral boost regimen that augments both HIV-1 CD4+ and CD8 T cells and humoral immune responses (39-41).

We hypothesize that, by inducing both CD4+ and CD8 T cell responses with a heterologous prime/boost vaccine approach through use of the ID93/GLA-SE subunit vaccine and an adenoviral vector expressing the ID93 protein, we can provide protection against primary M. tuberculosis infection and long-lived memory capable of clearing M. tuberculosis. To test this hypothesis, we developed an adenovirus type 5 vector expressing ID93 (Ad5-ID93), produced as a proof-of-principle vaccine for the generation of Ag-specific CD8 T cells, which could be used alone or as part of a heterologous prime/boost strategy in combination with ID93/GLA-SE. We previously demonstrated that the ID93/GLA-SE subunit vaccine induces a potent CD4+ Th1 cell response that effectively provides protection against M. tuberculosis (5, 7). In this work, we show the outcome of Ad5-ID93 immunization when given as a homologous prime/boost regimen or when administered as part of a heterologous prime/boost strategy with ID93/GLA-SE. We also look mechanistically at the requirement of ID93-specific CD8 T cells in a MHC class I–deficient mouse model that has diminished levels of CD8 T cells. This work sheds additional insight into the development of new TB vaccines and will foster a new appreciation for novel prime/boost strategies against M. tuberculosis and similar pathogens that require the generation of potent Ag-specific Th1 CD4+ T cells.

Materials and Methods

ID93

ID93 is a recombinant fusion protein incorporating four M. tuberculosis Ags, as follows: Rv2608, Rv3620, Rv1813, and Rv3619 (5).

Recombinant adenovirus serotype 5 expressing ID93 (Ad5-ID93)

DNA encoding ID93 was inserted into an adenoviral type 5 vector with a CMV promoter (Viraquest, North Liberty, IA). Replication-deficient recombinant adenovirus clones expressing either no Ag (Ad5-null) or full-length ID93 (Ad5-ID93) were constructed. Adenoviral stocks were amplified, purified by CsCl gradient, and dialyzed to remove the cesium. Virus preps were quantitated by plaque assay.

Cell culture

AD-293 cells are human embryonic kidney cells transformed with shared adenovirus type 5 DNA (E1 region) with an increased adenovirus phenotype. Cells were grown in DMEM (Invitrogen) with 10% heat-inactivated FBS and penicillin (100 U/ml) and streptomycin (100 μg/ml) at 37°C and 5% CO2.

Transgene expression of Ad5-ID93 (Western blot) transgene expression verification

AD-293 cells were infected with Ad5-ID93. Cells were harvested 72 h later and pelleted by centrifugation (15,000 relative centrifugal force, 5 min). The washed pellet was resuspended in 1 ml PBS, and 100 μl cell suspension was combined with 20 μl 6× buffer (0.375 M Tris, 12% NaDodSO4, 0.45 M DTT, 60% glycerol, 0.03% bromphenol blue) and then boiled for 5 min prior to gel electrophoresis (Tris-glycine gel; Invitrogen, Grand Island, NY). After separation, proteins were transferred to nitrocellulose and probed with a purified mAb raised against recombinant ID93 (1:50,000 dilution), followed by HRP-conjugated goat anti-mouse Ab (Jackson ImmunoResearch Laboratories; 1:10,000 dilution). Blots were developed using ECL detection reagent (GE Healthcare, Piscataway, NJ) and imaged by exposing to Kodak Blue XB-1 film (Perkin Elmer, Waltham, MA).

Glucopyranosyl lipid adjuvant

The synthetic TLR-4 agonist, GLA, was bulk manufactured by Avanti Polar Lipids (Alabaster, AL) and formulated at the Infectious Disease Research Institute (IDRI) in an oil-in-water SE.

Identification of MHC I– and MHC II–restricted ID93 epitopes

Splenocytes from mice immunized with either ID93/GLA-SE or Ad5-ID93 were stimulated with a 15-mer peptide library spanning ID93. To identify minimal CD8 T cell epitopes, sequences of positive 15-mer peptides were used to predict the MHC I–restricted T cell epitopes using a consensus prediction algorithm on the Immune Epitope Database (http://www.immuneepitope.org/). The sequence of the MHC class I–restricted 8-mer epitope, included in Rv2608, is VTNLHTAIM, whereas the two MHC class II 15–mer–restricted epitopes from the Rv2608 and Rv3619 proteins (in the ID93 fusion protein) are NFALVPPEVNSARIF and FQFYIEQANAHGQKV, respectively.

Animals

Female C57BL/6 mice (5–7 wk old) were purchased from Charles River Laboratories (Wilmington, MA). For studies using MHC class I–deficient mice, female C57BL/6 mice (7–9 wk old) and age-matched H2Kb–/– mice (42, 43) were purchased from Taconic (Hudson, NY). Animals were housed at the IDRI animal facility under specific pathogen-free conditions. All procedures were performed in accordance with the regulations and guidelines of the IDRI institutional animal care and use committee.

Immunization and murine protection model

Mice (n = 10/group) were immunized two to three times, 3 wk apart. A recombinant replication-deficient adenovirus serotype 5 containing either no Ag (Ad5-null) or the ID93 Ag (Ad5-ID93) was administered intramuscularly (i.m.) in the hind footpad. A dose of 5 × 109 virus particles in 30 μl 20 μM HEPES plus 3% sucrose, and in the left hind footpad at the same dose and volume for the second immunization. Groups also receiving one or more injections of recombinant ID93 (0.5 μg) in the presence or absence of 5 μg GLA-SE were inoculated i.m. Saline controls were immunized i.m. two or three times, 3 wk apart. Vaccine control mice immunized with the BCG (Pasteur strain; Sanofi Pasteur) vaccine were given a single i.d. dose of 5 × 106 CFU at the base of the tail. We have previously shown that mice given adenovirus alone (GLA-SE) provide similar results to the saline control group, neither of which are protective against M. tuberculosis; thus, we have not included an adenovirus-alone group in these experiments (5).

ID93 Ab ELISA

Serum was collected from immunized mice on day 56 (2 wk after the last immunization), and ID93-specific endpoint titers for IgG1, IgG2c, and total IgG were performed, as previously described (5, 7). Plates were read at 450 nm with a reference filter set at 570 nm using a Versamax microplate reader (Molecular Devices, Sunnyvale, CA). Reciprocal dilutions corresponding to endpoint titers were determined utilizing Soft Max Pro5 software (San Diego, CA) with a 0.1 absorbance cutoff.

Cytokine ELISPOTs

IFN-γ and IL-5 ELISPOTs were performed on fresh splenocytes harvested 1 wk following the final immunization (n = 3 mice/group), as previously described (7). Splenocytes (2 × 106 cells/well) were stimulated with either media, Con A (0.75 μg/ml), or ID93 protein (10 μg/ml). To determine whether cytokine-producing cells were induced from CD4+ or CD8 T cells, stimulations were also performed with ID93-specific 15-mer CD4+ peptides or an ID93-specific 8-mer CD8+ peptide. Spots were counted on an automated ELISPOT reader (C.T.L. Seri3A Analyzer; Cellular Technology, Cleveland, OH) and analyzed with ImmunSpot software (C.T.L. Analyzer).

Flow cytometry (intracellular cytokine staining)

Splenocytes from three mice per group were isolated 1 wk following the final immunization for evaluation of effector T cell responses. Splenocytes
were also harvested 6 mo following the final immunization for evaluation of memory T cell responses. Cells were plated at $2 \times 10^6$ cells/well in 96-well U-bottom plates and restimulated with either media (negative control), PMA plus ionomycin (1 µg/ml each; as a positive control), ID93 (10 µg/ml), or a pool of the two 15-mer peptides containing 1-5A-restricted epitopes (1 µg/ml each) and a H-2D-restricted 8-mer peptide (1 µg/ml). In some cases, fluorochrome-conjugated anti-CD107a (clone eBio1d4b) was added (1:200) at the time of stimulation. GolgiPlug (eBioscience, San Diego, CA) was added after 2 h at 1 µg/ml and incubated with cells for 8 h at 37°C. Cells were surface stained with fluorochrome-conjugated mAbs to CD4 (clone RM4-5), CD8 (clone 53-6.7), and CD44 (clone IM7) (eBioscience) in PBS with 20% normal mouse serum (Phenix Research Products, Candler, NC). Cells were fixed and permeabilized for 20 min at room temperature using Cytofix/Cytoperm (BD Biosciences, San Jose, CA), according to the manufacturer’s instructions, and stained intracellularly for 15 min at room temperature with fluorochrome-conjugated mAbs to IFN-γ (clone XMGI.2), TNF (clone MP6-XT22), and IL-2 (clone JES6-5H4) (eBioscience). Cells were washed twice with BD Perm/Wash buffer $1 \times$ (BD Biosciences) and resuspended in PBS with 1% BSA prior to collection on a modified 3-laser BD LSRII or Fortessa flow cytometer (BD Biosciences). Lungs (loaded with 1.25, 2.5, or 5 mg/ml each; as a positive control), ID93 (10 µg/ml), or a pool of the two 15-mer peptides containing I-A b–restricted epitopes (1 µg/ml each) and a H-2D-restricted 8-mer peptide (1 µg/ml) was included at 1 and 2 ng as a control for the lysates (loaded with 1.25, 2.5, or 5 µl lysate) from Ad5-ID93–infected cells. A recombinant adenovirus clone expressing no Ag (Ad5-null) was also constructed.

We first tested the Ad5-ID93 vector to ensure that the vector properly expressed the ID93 fusion protein. Expression of ID93 in Ad5-ID93–infected 293 cells was verified by Western blot (Fig. 1A). Purified ID93 was included at 1 and 2 ng as a control for the lysates (loaded with 1.25, 2.5, or 5 µl lysate) from Ad5-ID93–infected cells.

Next, we determined whether the expressed ID93 protein from the Ad5-ID93 vaccine elicited immune responses in vivo, by measuring Ab responses following immunization with either Ad5-ID93, ID93/GLA-SE, or heterologous prime/boost immunizations with both the subunit and adenovector vaccine vectors. Two weeks after the final immunization, significant levels of anti-ID93 IgG titers (5 mice/group), including IgG1, IgG2c, and total IgG 2 wk after the last immunization. Results are shown as averages ± SD and are representative of two separate experiments. *$p < 0.05$ compared with saline, **$p < 0.05$ compared with ID93 immunization.

**FIGURE 1.** (A) Expression of ID93 by Western blot from an adenoviral vector (subtype 5) with an ID93 fusion protein gene insert. Different amounts of lysates (1.25, 2.5, and 5 µl) from Ad5-ID93–infected AD-293 cells were added to the wells, as indicated. Purified ID93 protein was also included as a positive control at 1 and 2 ng. (B) ID93–specific endpoint Ab titers (5 mice/group), including IgG1, IgG2c, and total IgG 2 wk after the last immunization. The Journal of Immunology 3

Ad5-ID93 was constructed to determine whether ID93-specific CD8+ T cells generated from this vaccine alone, or in a heterologous prime/boost regimen with our candidate subunit vaccine (ID93/GLA-SE), could effectively induce protective immune responses against M. tuberculosis. The Ad5-ID93 expression vector was constructed by inserting DNA for the ID93 fusion protein into an adenoviral type 5 vector with a CMV promoter. A recombinant adenovirus clone expressing no Ag (Ad5-null) was also constructed.

Aerosol M. tuberculosis infection

Mice were aerogenically challenged with a low-dose aerosol of M. tuberculosis H37Rv (ATCC 35718; American Type Culture Collection, Manassas, VA) 6 wk, or 6 mo, after the final immunization ($n = 7$ mice/group), as previously described (7). All operations were performed under biosafety level-3 conditions.

Bacterial burden (CFUs)

To assess bacterial burden, tissues were homogenized through a 45 µm cell strainer and serially diluted 5-fold in 0.1% Tween 80, PBS. Bacterial burden was assessed by plating these dilutions onto Middlebrook 7H11 agar (Molecular Toxicology, Boone, NC) and counting colonies after 2–3 wk of incubation at 37°C with 5% CO2. Protective efficacy promoted by the vaccine was compared with the protective levels afforded when only saline was administered. Reductions in bacterial burden in the lungs are calculated as follows: MeanLog$_{10}$ CFU$_{saline} - $MeanLog$_{10}$ CFU$_{vaccine}$.

**Results**

**ID93 expression by the Ad5-ID93 expression vector**

Ad5-ID93 was constructed to determine whether ID93-specific CD8+ T cells generated from this vaccine alone, or in a heterologous prime/boost regimen with our candidate subunit vaccine (ID93/GLA-SE), could effectively induce protective immune responses against M. tuberculosis. The Ad5-ID93 expression vector was constructed by inserting DNA for the ID93 fusion protein into an adenoviral type 5 vector with a CMV promoter. A recombinant adenovirus clone expressing no Ag (Ad5-null) was also constructed.

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**FIGURE 1.** (A) Expression of ID93 by Western blot from an adenoviral vector (subtype 5) with an ID93 fusion protein gene insert. Different amounts of lysates (1.25, 2.5, and 5 µl) from Ad5-ID93–infected AD-293 cells were added to the wells, as indicated. Purified ID93 protein was also included as a positive control at 1 and 2 ng. (B) ID93–specific endpoint Ab titers (5 mice/group), including IgG1, IgG2c, and total IgG 2 wk after the last immunization. Results are shown as averages ± SD and are representative of two separate experiments. *$p < 0.05$ compared with saline, **$p < 0.05$ compared with ID93 immunization.
Abs were detected in the serum of all Ad5-ID93– and ID93/GLA-SE–immunized but not saline-, BCG-, or Ad5-null–injected animals (Fig. 1B). ID93-specific IgG1 and IgG2c Ab titers were also measured (Fig. 1B). As with ID93/GLA-SE, all Ad5-ID93 vaccine regimens induced greater ID93-specific IgG2c responses compared with either the saline or unadjuvanted ID93-injected groups, indicative of a Th1-biased response.

Immunogenicity: Ad5-ID93, ID93/GLA-SE, and heterologous prime/boost regimens

Mice were inoculated twice with Ad5-ID93 (×2), 3 wk apart. A separate group of animals received a single injection of Ad5-ID93 in a prime-boost regimen with recombinant ID93 protein plus GLA-SE, formulated in an oil-in-water emulsion (ID93/GLA-SE). Ad5-ID93 was tested either as the priming agent (Ad5-ID93→ID93/GLA-SE) or as a boost (ID93/GLA-SE→Ad5-ID93). Responses were compared with a subunit vaccine regimen with ID93/GLA-SE, administered i.m. either two or three times, 3 wk apart, as indicated.

Ag-specific T cell cytokine responses to ID93, CD4 peptide pools, or the CD8 peptide were examined by ELISPOT assay (Supplemental Fig. 1). Splenocytes (n = 3 mice/group) were harvested 1 wk following the last immunization and stimulated ex vivo with either media, ID93, a CD4 peptide pool (CD4pp), or CD8 peptide (CD8pp). These ID93 peptides comprise dominant MHC I-restricted and MHC II-restricted epitopes identified in IFN-γ ELISPOT and ICS assays.

All vaccines including ID93/GLA-SE and/or Ad5-ID93 generated higher frequencies of ID93-specific cells producing IFN-γ compared with saline-treated controls or to unadjuvanted ID93 (Supplemental Fig. 1). Only regimens incorporating the ID93/GLA-SE vaccine elicited strong IFN-γ CD4+ T cell responses by ELISPOT following stimulation with the MHC II-restricted epitope (CD4pp), whereas only ID93/GLA-SE, followed by Ad5-ID93, or two injections of Ad5-ID93 elicited a significant IFN-γ response following stimulation with the MHC I-restricted epitope (CD8pp) (Supplemental Fig. 1). Without adjuvant, ID93 elicited an IL-5 response following stimulation with either the ID93 protein or the MHC II-restricted epitope (Supplemental Fig. 1).

Intracellular cytokine staining

Expression of IFN-γ, TNF, and IL-2 cytokines by splenic CD4/CD44high and CD8/CD44high T cells from C57BL/6 mice was measured 1 wk after the last immunization and determined by ICS following restimulation with ID93 (Fig. 2A–D). A high proportion of Ag-experienced (CD44high) CD4+ T cells secreting IFN-γ (>10%), TNF (>10%), or IL-2 (>10%) was observed for all mice receiving a regimen with an ID93/GLA-SE arm compared with saline-injected mice (Fig. 2A). Consistent with our ELISPOT data, all Ad5-ID93 containing immunization strategies generated CD8+ T cells producing IFN-γ (>10%), TNF (>10%), in addition to IL-2 (>5% for Ad5-ID93 prime/ID93/GLA-SE boost and Ad5-ID93 [×2]) (Fig. 2B). CD107a, which is found on the surface of degranulating cells, adds a functional parameter of Ag-stimulated CD8+ T cells; anti-CD107a–stained CD8+ T cells represent Ag-specific cytotoxic effector cells (44). Significant percentages of CD107a-stained CD8+ T cells were observed in animals immunized at least once with Ad5-ID93 (Fig. 2B). Polyfunctional CD4+ T cells producing IFN-γ, IL-2, and TNF (all >5%) were detected in groups that received at least one injection of ID93/GLA-SE, but were not detected to significant levels for mice inoculated with unadjuvanted ID93, or BCG (Fig. 2C). The greatest proportion of 3+ and 2+ cytokines (pie charts; Fig. 2C) secreted from CD4+ T cells was observed in the ID93/GLA-SE group, followed by equal responses in the heterologous prime/boost groups, and lastly the Ad5-ID93 group; the order of the prime/boost regimen did not matter with respect to the proportion of triple, double, or single cytokines. Polyfunctional CD107a+CD8+ T cells, producing IFN-γ, IL-2, and TNF (>5% frequency), were observed only in the Ad5-ID93 (×2) group and the group that received a prime with Ad5-ID93, followed by a boost with ID93/GLA-SE (Fig. 2D), although all groups that were given at least one Ad5-ID93 immunization had significant levels of polyfunctional C107a+CD8+ T cells producing IFN-γ and TNF (>5% frequencies) (Fig. 2D), including the ID93/GLA-SE prime/Ad5-ID93 boost regimen. No significant percentages of single cytokines from CD8/CD44high splenocytes were observed except in the group given Ad5-ID93 (×2), where ∼1.4% single IFN-γ-producing CD8+ T cells were induced (data not shown). When absolute numbers of ID93-specific IFN-γ–producing T cells were determined, the ID93/GLA-SE–immunized group induced significantly higher IFN-γ–secreting CD4+ T cells (Fig. 2E). Alternatively, all of the Ad5-ID93–containing immunization regimens induced significantly higher numbers of IFN-γ–secreting CD8+ T cells compared with saline (Fig. 2E). Similar numbers of IFN-γ–producing effector CD8+ T cells 1 wk after the last immunization were observed regardless of the order of immunization. Ad5-ID93 (×2) induced statistically greater numbers of IFN-γ–secreting CD8+ T cells compared with the heterologous prime/boost approaches (Fig. 2E).

Short-term protection against M. tuberculosis with ID93/GLA-SE, Ad5-ID93, or heterologous prime/boost approaches with ID93/GLA-SE and Ad5-ID93

Protective efficacy of the Ad5-ID93 vaccine was assessed by enumerating bacterial burden in the lungs 6 wk following a low-dose aerosol challenge with M. tuberculosis H37Rv in four independent studies (Fig. 3 shows the results of one experiment; Table I shows the results of three additional protection studies). As expected, bacterial burden in the lungs of BCG-immunized mice was reduced significantly compared with saline-treated controls (p < 0.05). Reduction of M. tuberculosis burden in the lung was observed in C57BL/6 mice that were immunized with two (Table I) or three doses of recombinant ID93/GLA-SE (p < 0.05), compared with the saline control group (Table I, Fig. 3). Protection against M. tuberculosis was also observed in the lungs of mice following either a homologous Ad5-ID93 prime/boost (Table I, Fig. 3) or a heterologous prime/boost regimen with ID93/GLA-SE and Ad5-ID93 compared with saline, regardless of whether the subunit vaccine was given as the prime or the boost (Fig. 3). Mice immunized twice with the Ad5-null vector (Table I, Fig. 3), or immunized with the ID93 protein alone (Fig. 3), did not provide statistically significant protection against challenge with M. tuberculosis.

Ag-specific CD8+ T lymphocytes in either ID93/GLA-SE or Ad5-ID93–containing immunization strategies are not required for protection against M. tuberculosis

MHC class I–deficient mouse model. We next measured responses to immunization in a MHC class I–deficient mouse model to determine whether the Ad5-ID93 vaccine strategies required a CD8+ T cell response to elicit protection against M. tuberculosis. Homozygous H-2Kb and H-2Db double-targeted mutation mice are devoid of class Ia cell surface molecules and exhibit a reduction in the total number of CD8aβ− peripheral lymphocytes (43). We first measured the total number of CD4+ and CD8+ T cells in the wild-type C57BL/6 mice versus the MHC class I–deficient mice (Supplemental Fig. 2). In addition, the H2Kb−/−/Db−/− mice compensated
FIGURE 2. ID93-specific Th1 and/or CD8 cytokine responses from C57BL/6 mice immunized with ID93/GLA-SE and/or Ad5-ID93. Splenocytes were harvested from three mice/group, 1 wk following the final immunization. Cells were stimulated with ID93 for 12 h in the presence of GolgiStop. ID93-specific cells were identified by CD3 and either CD4 or CD8, and were further gated on CD44<sup>high</sup>-expressing cells. The average percent frequency of each cell type ± SEM is shown, and results are representative of two independent studies. (A) ID93-specific CD4<sup>+</sup>/CD44<sup>high</sup> T cells expressing IFN-γ, TNF, or IL-2; (B) CD107a<sup>+</sup>/CD8<sup>+</sup> T cells and CD8<sup>+</sup>/CD44<sup>high</sup> T cells expressing IFN-γ, TNF, IL-2; (C) polyfunctional cytokine-expressing CD4<sup>+</sup>/CD44<sup>high</sup> T cells plus pie charts representing total triple, double, and single cytokines; (D) polyfunctional cytokine-expressing CD8<sup>+</sup>/CD44<sup>high</sup>/CD107a<sup>+</sup> T cells and pie charts representing quadruple-, triple-, double-, and single-stained cells; and (E) absolute numbers of IFN-γ-producing CD4<sup>+</sup> or CD8<sup>+</sup> T cells ± SD (n = 3 mice/group). *p < 0.05 compared with saline, #p < 0.05 versus Ad5-ID93 (2×).
for the loss of CD8+ T cells with approximately twice as many CD4+ T cells in the spleen (Supplemental Fig. 2).

To determine the outcome of the immune response in the class I–deficient mice following immunization with the Ad5-ID93 virus candidates, we characterized the recall response to either ID93 or ID93 peptides. Similar to responses observed in C57BL/6 mice, the class I–deficient mice elicited robust CD4+ T cell responses directed to ID93 by ELISPOT in all mice that were immunized at least once with ID93/GLA-SE (Supplemental Fig. 3). In contrast to the wild-type mice, there were no significant ID93-specific CD8+ T cell responses in any of the Ad5-ID93–immunized groups, as indicated by the lack of responses to the CD8-specific peptide stimulation (Supplemental Fig. 3), whereas IL-5 responses were unchanged compared with the responses seen in wild-type mice (Supplemental Fig. 3). By flow cytometric analysis, significant frequencies of CD4+/CD4+ T cell responses expressing IFN-γ, TNF, or IL-2, and polyfunctional responses in which all three cytokines are expressed, were observed in mice immunized with ID93/GLA-SE (Fig. 4A, 4C). Significant levels of IL-2 from CD4+ T cells were produced from mice given a heterologous prime/boost with ID93/GLA-SE, followed by Ad5-ID93 (Fig. 4A, 4C). Significant levels of IL-2 from CD4+ T cells were observed in mice immunized with Ad5-ID93 (data not shown). Absolute numbers of ID93-specific IFN-γ–producing CD4+ or CD8+ T cells were also determined in the MHC class I–deficient mice. Animals immunized with the ID93/GLA-SE regimen and those that received an ID93/GLA-SE prime followed by an Ad5-ID93 boost induced significant numbers of IFN-γ–secreting CD4+ T cells compared with the saline control (Fig. 4D). A more dramatic decrease in IFN-γ–producing CD8+ T cells in the MHC class I–deficient mice was observed in the groups given Ad5-ID93 (mice given Ad5-ID93 twice had an 11.4-fold decrease in ID93-specific IFN-γ–secreting CD8+ T cells compared with wild-type mice; ID93/GLA-SE followed by an Ad5-ID93 boost had an 8.68-fold reduction in these CD8+ T cells, and a 12.35-fold decrease was observed in mice immunized with Ad5-ID93, followed by ID93/GLA-SE) (Fig. 4D compared with Fig. 2D).

Next, we examined the contribution of CD8+ T lymphocytes to Ad5-ID93–induced vaccine protection against M. tuberculosis challenge. Protective efficacy of each immunization strategy was evaluated 6 wk after challenge in H-2Kb–Dβ1–/– knockout mice. Immunization of H-2Kb–/–/Dβ1–/– mice with Ad5-ID93 (either homologous or heterologous immunization with ID93/GLA-SE) and ID93/GLA-SE immunization results in significant bacterial burden reduction in the lungs of the M. tuberculosis–infected mice (Fig. 5). Protection in the H-2Kb–/–/Dβ1–/– knockout mice was not impaired by the significant reduction of Ag-specific CD8+ T cells, suggesting that the CD4+ T cell responses in these immunized animals may compensate for the lack of Ag-specific CD8 T cells.

### Table I. Protection with ID93/GLA-SE or Ad5-ID93 in C57BL/6 mice against infection with M. tuberculosis

<table>
<thead>
<tr>
<th>Groups</th>
<th>Treatment</th>
<th>Log10 Protection in the Lungs versus Saline</th>
<th>p Value versus Saline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>Log</strong>&lt;sub&gt;10&lt;/sub&gt;</td>
<td>SD</td>
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<tr>
<td><strong>Experiment 1</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Saline</td>
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<td>0.15</td>
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<tr>
<td>2</td>
<td>BCG</td>
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<td>0.20</td>
</tr>
<tr>
<td>3</td>
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<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>ID93/GLA-SE (5 μg), i.m. (2×)</td>
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<td>0.23</td>
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<td>5</td>
<td>ID93/GLA-SE (5 μg), i.m. (3×)</td>
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<td>0.24</td>
</tr>
<tr>
<td>6</td>
<td>ID93/GLA-SE. i.m.–Ad5-ID93 i.d. footpad (5 × 10^8 vp)</td>
<td>6.24</td>
<td>0.16</td>
</tr>
<tr>
<td>7</td>
<td>Ad5-ID93 i.d. footpad (5 × 10^8 vp)–ID93/GLA-SE, i.m.</td>
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<td>0.21</td>
</tr>
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<td><strong>Experiment 2</strong></td>
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<tr>
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<td><strong>Experiment 3</strong></td>
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<td>BCG</td>
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</tr>
<tr>
<td>3</td>
<td>Ad5-ID93 (5 × 10^8 vp) i.d. footpad (2×)</td>
<td>5.46</td>
<td>0.12</td>
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</table>
Long-lived protection with ID93/GLA-SE or heterologous prime/boost approach with ID93/GLA-SE prime and Ad5-ID93 boost

We next determined which immunization approach(es) would provide durable, long-lived vaccine efficacy, defined as protection against *M. tuberculosis* 6 mo following the last immunization. Immune responses were also measured 6 mo following immunization to determine the profile of immune responses required for long-term vaccine protection against *M. tuberculosis*. The importance of the order of the heterologous prime/boost immuni-
zation strategy was apparent in the responses measured 6 mo following immunization. The subunit vaccine mainly induced a CD4⁺ T cell response and no significant levels of CD8⁺ T cells (Fig. 6A, 6B). An increased frequency of long-lived IFN-γ-secreting T cells was observed only from the splenocytes of animals previously immunized with the ID93/GLA-SE subunit vaccine (Fig. 6A). Significant frequencies of polyfunctional CD4⁺ T cells (>0.5%) were also observed within the ID93/GLA-SE group compared with saline, including cells secreting triple IFN-γ, TNF, and IL-2, or double IFN-γ and TNF cytokines (Fig. 6C). Although not significant, there were greater proportions of 3⁺ and 2⁺ cytokine-producing cells (indicated in the pie charts) in the protein prime/vector boost group compared with the other two Ad5-ID93 vaccine strategies. No significant levels of IFN-γ, IL-2, or TNF-secreting CD44high/CD8⁺ T cells were observed in any of the immunized groups 6 mo postimmunization (Fig. 6B) compared with saline. However, there were slightly enhanced polyfunctional CD8⁺ T cell responses (>0.1%) expressing IFN-γ and TNF observed in the group given the subunit ID93/GLA-SE vaccine, followed by a heterologous Ad5-ID93 boost, with more proportions of double, triple, and quadruple cytokine-expressing cells in this group (shown in the Fig. 6D pie charts) compared with the other groups. For single cytokine-expressing CD8⁺ T cells, only the Ad5-ID93 prime followed by ID93/GLA-SE boost induced significant levels of single IFN-γ–producing CD8⁺ T cells (~0.6%, data not shown); none of the groups induced significant levels of single cytokine CD8⁺ T cells producing either TNF or IL-2 (data not shown). Absolute numbers of IFN-γ-secreting CD4⁺ and CD8⁺ T cells were also analyzed. Significant numbers of IFN-γ–secreting CD4⁺ T cells were elicited in groups given the ID93/GLA-SE subunit vaccine, when mice were immunized with the protein prime/adenovirus boost strategy (Fig. 6E). None of the vaccine strategies elicited significant absolute numbers of IFN-γ–secreting CD8⁺ T cells (Fig. 6E), although the total CD8⁺ T cells were elevated in the protein prime/vector boost-immunized mice. T cell responses within the lungs were also assessed in mice that were challenged with M. tuberculosis 6 mo after the last immunization. ICS was performed on lungs harvested 6 wk after M. tuberculosis challenge (Supplemental Fig. 4). Similar to responses seen in the spleen, the lungs of animals immunized with ID93/GLA-SE showed significant frequencies of IFN-γ–secreting CD4⁺ T cells.

Increased levels of TNF from CD4⁺ T cells were also seen in the ID93/GLA-SE group, and in the two heterologous prime/boost groups (Supplemental Fig. 4A). The highest frequency of IFN-γ/TNF polyfunctional CD4⁺ T cells was observed in the ID93/GLA-SE and in the ID93/GLA-SE prime/Ad5-ID93 boost groups (Supplemental Fig. 4C). There were no significant Ag-specific CD8⁺ T cell responses in the lungs with any of the immunized groups, although all Ad5-ID93–containing vaccines had increased CD107α responses (Supplemental Fig. 4B, 4D).

Next, we measured the efficacy of the vaccine strategies against M. tuberculosis 6 mo after immunization in C57BL/6 mice. Mice administered with either two injections of the subunit vaccine (ID93/GLA-SE) or a prime/boost with ID93/GLA-SE followed by Ad5-ID93 significantly reduced the M. tuberculosis bacterial burden in the lung compared with mice injected with saline (Fig. 7). There was a clear benefit, therefore, of the protein prime followed by a vector boost, compared with the reciprocal approach in which the vector was given first followed by a protein boost.

Discussion

Our previous work has demonstrated that IDRI’s lead vaccine candidate ID93 combined with GLA-SE protects mice and guinea pigs against M. tuberculosis infection when administered as a prophylactic vaccine in the presence or absence of BCG priming (5, 7). Protection in these studies is mediated in large part by the induction of polyfunctional, Ag-specific CD4⁺ T cell responses (5, 7). In this study, we constructed a recombinant adenovirus vector expressing the ID93 Ag to determine whether the generation of ID93-specific CD8⁺ T cells elicited by the Ad5-ID93 vaccine (using either a homologous or heterologous prime/boost approach with the ID93 subunit vaccine) could provide short- or long-lived protection against M. tuberculosis. We also wanted to address whether the addition of an Ag-specific CD8⁺ T cell response elicited by the Ad5-ID93 vaccine, combined with CD4⁺ T cell–mediated protection elicited by ID93/GLA, could further boost and enhance protective responses against M. tuberculosis. The current vaccine against TB, BCG, loses its efficacy over time and fails to protect against adult pulmonary TB. A recent hypothesis regarding the reasons for lack of BCG protection in adults is the failure to generate significant numbers of long-lasting central memory T cells, including CD8 central memory T cells (45). Strategies to increase BCG efficacy have included ways to increase CD8 T cell responses, such as designing Mycobacterium bovis BCG mutants that secrete lipoarabinomannan to promote increased MHC class I presentation (46, 47). Generating additional BCG mutants (48, 49), overexpressing M. tuberculosis proteins from recombinant M. bovis BCG (50, 51), or delivering BCG to different target tissues, such as the lymph node (52), have also shown promise for increasing BCG potency.

We show that the recombinant adenovirus vector expressing the ID93 Ag (Ad5-ID93) generated ID93-specific CD8⁺ T cells. When Ad5-ID93 is given twice in a prime/boost regimen, or when it is given as a heterologous prime/boost with an ID93/GLA-SE vaccine, all of these strategies provided short-lived vaccine protection following challenge with M. tuberculosis in the murine model. In MHC class I–deficient mice, lacking significant levels of Ag-specific CD8⁺ T cells, the Ad5-ID93–containing vaccines, as well as the ID93/GLA-SE subunit vaccine, still provided significant levels of short-lived vaccine protection against M. tuberculosis. CD8⁺ cytotoxic T responses play key protective roles by killing virally infected cells within the lung following infection with viruses such as influenza (53, 54); however, the protective role of CD8⁺ T cells in M. tuberculosis is less understood. Our
FIGURE 6. Enhanced CD4+ or CD8+ T cell cytokine responses from C57BL/6 mice 6 mo after the last immunization. Mice were immunized twice, 3 wk apart. ICS was performed, as described in the legend for Fig. 2. (A) Percent frequency of CD4+/CD44high T cells producing IFN-γ, TNF, or IL-2; (B) percent frequency of CD8+/CD44high T cells expressing IFN-γ, TNF, or IL-2; (C) percent frequency of polyfunctional cytokine-expressing ID93-specific CD4+/CD44+ T cells and pie charts representing CD4+ T cells expressing 3+, 2+, or 1+ (triple, double, or single) cytokines; (D) percent frequency of polyfunctional cytokine-expressing CD8+/CD44+ T cells and pie charts representing CD8+ T cells expressing 4+, 3+, 2+, or 1+ stained cells. Quadruple-stained cells are represented by CD107a-positive, triple cytokine–expressing cells; (E) the absolute numbers of IFN-γ–producing CD4+ or CD8+ T cells ± SD 6 mo following immunization (n = 3 mice/group). This long-lived vaccine immunogenicity study was performed once. *p < 0.05 compared with the saline control group.
data suggest that the CD4+ T cell responses may have compensated for the absence of Ag-specific CD8+ T cells in the MHC class I–deficient mice. Bennekov et al. (15) showed that their adenoviral vector vaccine expressing Ag85B and ESAT-6 induced a strong ESAT-6–specific CD8+ T cell response, but failed to provide protection. When the authors adjuvanted the adenovirus vaccine with MPL and dimethyl dioctadecyl ammonium, a dominant Ag85B–specific CD4+ T cell response was elicited, which led to a protective response against \textit{M. tuberculosis}. We show that in MHC class I–deficient mice, reduced numbers of CD8+ T cells are elicited compared with wild-type mice as expected; however, a small, but significant number of effector CD8+ T cells expressing IFN-γ was still induced in Ad5-ID93–immunized mice. In addition, a significant percentage of CD4+ T cells producing IFN-γ and IL-2 was induced with the Ad5-ID93 vaccine. Polyfunctional CD4+ T cell responses were also observed in the heterologous prime/boost approaches. The ID93/GLA-SE and Ad5-ID93 approaches provided protection in the lungs in both the wild-type and MHC class I–deficient mice, showing the importance of CD4+ T cell responses with these ID93 vaccines.

The homologous Ad5-ID93 vaccine was able to provide short-lived protection (6 wk after the last immunization) in C57BL/6 mice, but the predominant Ag-specific CD8+ T lymphocytes generated in these mice were inadequate for providing long-lived vaccine-mediated protection against \textit{M. tuberculosis}. The order of the heterologous prime and boost was critical; the only effective heterologous regimen that provided long-lived protection against \textit{M. tuberculosis} was the protein prime/vector boost approach. Bouillet et al. (55) have also shown that the order of heterologous immunizations can lead to enhanced immunity over other regimens; memory T cells and both IgG1 and IgG2a Ab responses are increased in BALB/c mice when a recombinant malaria protein combined with Montanide ISA720 adjuvant was included as a prime, and an adenoviral vector vaccine given as a boost. In our study, the ID93/GLA-SE subunit vaccine was also capable of providing long-lasting protection, 6 mo following immunization. Our data also show that durable CD4+ Th1 cells secreting IFN-γ were generated in the groups that provided long-lived protective immunity. Six months after the boost immunization, both the ID93/GLA-SE subunit vaccine and the subunit prime/adenovirus boost vaccine strategies elicited significant frequencies of ID93–specific polyfunctional CD4+ T cells, including IFN-γ and TNF double-positive CD4+ T cells. At this timepoint, the ID93/GLA-SE prime/Ad5-ID93 boost approach also elicited polyfunctional CD8+ T cells producing double cytokines: IFN-γ/TNF and IFN-γ/IL-2, which were enhanced compared with what was observed with the homologous Ad5-ID93–immunized group, which failed to provide long-lived protection. Although we showed that Ag-specific CD4+ T cells can compensate for CD8+ T cell generation in the MHC class I–deficient mice, the combined CD4+ and CD8+ T cell responses elicited by the heterologous protein prime/vector boost approach could have contributed to the long-lived vaccine protection in the wild-type mice. Interestingly, both of the protective vaccines induced significant numbers of Ag-specific IFN-γ–producing CD4+ T cells, providing a clue into a potential correlate of long-lived protection. The importance of the order in which heterologous TB vaccines are given has recently been reported (56). A recombinant TB protein (rMT1721) combined with GLA, followed by a plasmid DNA vaccine expressing the same Ag, induced a more robust immune response, including the generation of both Ag-specific CD4+ and CD8+ T cells, compared with the opposite immunization strategy in which CD8+ T cells were undetectable; however, the authors did not measure protection as a measure of efficacy following this regimen (56). Many others, however, have included the vector first, followed by a protein boost in heterologous prime/boost approaches. One such notable example is the HIV Thai trial (RV144), in which the vaccine strategy elicited 31% protective efficacy against HIV. In this case, a recombinant canarypox vector vaccine was given as a prime, followed by an adjuvanted subunit vaccine boost (57). In rhesus macaques, a promising combination of an adenovirus serotype 35 (Ad35) vector encoding circumsporozoite protein (Ad35.CS), followed by boosting with the RTS,S/AS02A (an MPL/TLR4 ligand-containing adjuvant) subunit vaccine, induced long-lived Th1 T cell responses and Ab responses (58). Unlike these prime/boost strategies, our results show enhanced protection when the subunit vaccine is given first, followed by the adenoviral vector boost.

We believe that immune responses measured 6 mo after immunization, just prior to infection, could shed light into which memory T cell responses are important for the generation of long-lived vaccine efficacy. Notably, the ID93/GLA-SE group was the only group that had a significant polyfunctional CD4+ T cell response at this timepoint, whereas the heterologous ID93/GLA-SE prime/Ad5-ID93 boost approach, which also resulted in long-lived protection against \textit{M. tuberculosis}, induced significant polyfunctional CD8+ T cells. Both successful vaccine strategies, however, maintained significant numbers of IFN-γ–producing ID93–specific CD4+ T cells, suggesting that this may represent at least one of the factors that led to long-lived, durable vaccine efficacy. These Th1 memory CD4+ T cells, seen 6 mo after the last immunization with the protein prime/vector boost strategy, may have provided help for the maintenance of the double cytokine (IFN-γ and TNF)–secreting Ag-specific CD8+ T cells, a hypothesis that warrants further exploration. Others have shown the importance of generating Ag-specific CD4+ T cells to positively influence CD8+ T cell responses directed against \textit{M. tuberculosis} (59). In our study, long-lived vaccine responses in wild-type C57BL/6 mice occurred with two different vaccine strategies, one that included predominantly Ag-specific CD4+ T cell responses (ID93/GLA-SE), and the other that induced both Ag-specific CD4+ and CD8+ T cell responses (ID93/GLA-SE prime, followed by an Ad5/ID93 boost). Adenoviral delivery of ID93 was therefore successful only when given as a boost to the ID93/GLA-SE subunit vaccine. Although we saw long-lived protection with the heterologous prime/boost approach, this did not offer better protection than our current TB vaccine.
ID93/GLA-SE. This suggests that the additional viral-vector vaccine approach, designed to elicit CD8+ T cell responses, is not a suitable replacement for our subunit approach. It is unclear why the Ad5/ID93 vaccine did not work when given as a prime. We are currently pursuing many different reasons for the failure of the Ad5-ID93 prime approach. One such possibility is that the lowered frequency of ID93-specific CD8+ T cells may not have effectively recognized *M. tuberculosis*-infected cells in the lung. Another potential factor for the failed responses in Ad5-ID93–primed mice may have been due to vector immunity, in which immune responses may have been directed to the vaccine after the boost. Importantly, both of the successful vaccine strategies elicited significant numbers of IFN-γ–secreting CD4+ T cells 6 mo following immunization within the spleen after immunization. Increased frequencies of ID93-specific IFN-γ– and TNF-expressing CD4+ T cells were also observed within the lungs after *M. tuberculosis* infection in the mice given either ID93/GLA-SE or ID93/GLA-SE prime/Ad5-ID93 boost, which most likely contributed to the protection observed. Even though we show that lack of Ag-specific CD8+ T cells in MHC class I–deficient mice did not adversely affect any of the ID93 immunization strategies (including the subunit prime/adenoviral boost approach) when tested in short-term vaccine efficacy studies, we do not know whether this would be the case for long-term vaccine efficacy, and so this remains to be tested. The data presented in this study show that, whereas the Ad5-ID93 vaccine, which induced predominantly CD8+ T cell responses, was sufficient to elicit short-lived protection against *M. tuberculosis*, as measured by the ability to reduce the bacterial load in the lungs of *M. tuberculosis*-infected mice, this approach was not sufficient for long-lived vaccine efficacy. This goes against the current dogma, in which CD8+ T cells, suggesting that the generation of a robust Th1 CD4+ T cell response may be required for the durability of each of these vaccine strategies and for induction of protective immunity against TB. These types of approaches will most likely need to be tested in continuing long-lasting vaccine responses that prevent the continuing spread of TB.

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Disclosures

The authors have no financial conflicts of interest.

References


