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Memory CD8 T cell responses exceeding a large but definable threshold provide long-term immunity to malaria

Nathan W. Schmidt
University of Iowa

Rebecca L. Podyminogin
University of Iowa

Noah S. Butler
University of Iowa

Vladimir P. Bladovinic
University of Iowa

Brad J. Tucker
Iowa State University

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Abstract

Infection of mice with sporozoites of *Plasmodium berghei* or *Plasmodium yoelii* has been used extensively to evaluate liver-stage protection by candidate preerythrocytic malaria vaccines. Unfortunately, repeated success of such vaccines in mice has not translated readily to effective malaria vaccines in humans. Thus, mice may be used better as models to dissect basic parameters required for immunity to *Plasmodium*-infection than as preclinical vaccine models. In turn, this basic information may aid in the rational design of malaria vaccines. Here, we describe a model of circumsporozoite-specific memory CD8 T cell generation that protects mice against multiple *P. berghei* sporozoite challenges for at least 19 months. Using this model we defined a threshold frequency of memory CD8 T cells in the blood that predicts long-term sterilizing immunity against liver-stage infection. Importantly, the number of *Plasmodium*-specific memory CD8 T cells required for immunity greatly exceeds the number required for resistance to other pathogens. In addition, this model allowed us to identify readily individual immunized mice that exceed or fall below the protective threshold before infection, information that should greatly facilitate studies to dissect basic mechanisms of protective CD8 T cell memory against liver-stage *Plasmodium* infection. Furthermore, the extremely large threshold in memory CD8 T cell frequencies required for long-term protection in mice may have important implications for development of effective malaria vaccines.

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Comments

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Authors

Nathan W. Schmidt, Rebecca L. Podyminogin, Noah S. Butler, Vladimir P. Bladovinic, Brad J. Tucker, Peter Lauer, Arturo Reyes-Sandoval, Claire L. Hutchings, Anne C. Moore, Sarah C. Gilbert, Adrian V. Hill, Lyric Bartholomay, and John T. Harty

Memory CD8 T cell responses exceeding a large but definable threshold provide long-term immunity to malaria

Nathan W. Schmidt*, Rebecca L. Podyminogin*, Noah S. Butler*, Vladimir P. Badovinac*, Brad J. Tucker†, Keith S. Bahjat^{‡§}, Peter Lauer[‡], Arturo Reyes-Sandoval[¶], Claire L. Hutchings[¶], Anne C. Moore[¶], Sarah C. Gilbert[¶], Adrian V. Hill[¶], Lyric C. Bartholomay[†], and John T. Harty*[¶]

*Department of Microbiology and [¶]Interdisciplinary Graduate Program in Immunology, University of Iowa, Iowa City, IA 52242; [†]Department of Entomology, Iowa State University, Ames, IA 50011; [‡]ANZA Therapeutics, Inc., Concord, CA 94520; and [¶]The Jenner Institute, University of Oxford, Oxford OX3 7DQ, United Kingdom

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Infection of mice with sporozoites of *Plasmodium berghei* or *Plasmodium yoelii* has been used extensively to evaluate liver-stage protection by candidate preerythrocytic malaria vaccines. Unfortunately, repeated success of such vaccines in mice has not translated readily to effective malaria vaccines in humans. Thus, mice may be used better as models to dissect basic parameters required for immunity to *Plasmodium*-infection than as preclinical vaccine models. In turn, this basic information may aid in the rational design of malaria vaccines. Here, we describe a model of circumsporozoite-specific memory CD8 T cell generation that protects mice against multiple *P. berghei* sporozoite challenges for at least 19 months. Using this model we defined a threshold frequency of memory CD8 T cells in the blood that predicts long-term sterilizing immunity against liver-stage infection. Importantly, the number of *Plasmodium*-specific memory CD8 T cells required for immunity greatly exceeds the number required for resistance to other pathogens. In addition, this model allowed us to identify readily individual immunized mice that exceed or fall below the protective threshold before infection, information that should greatly facilitate studies to dissect basic mechanisms of protective CD8 T cell memory against liver-stage *Plasmodium* infection. Furthermore, the extremely large threshold in memory CD8 T cell frequencies required for long-term protection in mice may have important implications for development of effective malaria vaccines.

Infection of humans with *Plasmodium* species, the causative agents of malaria, results in severe morbidity and mortality in the developing world (1), effects that have stimulated intense efforts to develop efficacious vaccines. Protective CD8 T cell immunity against liver-stage *Plasmodium* infection has been demonstrated after vaccination of rodents with irradiated or genetically attenuated parasites and after subunit vaccination against liver-stage antigens (2–12). Immunity in rodents can last for 6–12 months (3, 4, 7, 13), but in several studies also seems to wane with time (7, 14–16). Although irradiated sporozoite vaccines also protect humans (17–19), current subunit vaccinations limit liver-stage infection but rarely prevent blood-stage parasitemia (20). Importantly, it remains unknown whether sterilizing long-term immunity to *Plasmodium* infection can be achieved through subunit vaccines that predominantly evoke memory CD8 T cell responses and, if so, precisely what memory T cell parameters will be required.

A single mosquito bite delivers a few hundred infectious *Plasmodium* sporozoites into dermal tissues (21), a fraction of which traffic to the liver and establish hepatocyte infection leading to release of blood stage parasites 2 days (*P. berghei* infection of mice) (22) or 6–8 days (*P. falciparum* infection of humans) (23) later. As such, infected cells may represent as few as 1 in 10⁹ hepatocytes in humans and 1 in 10⁶ hepatocytes in mice. Thus, both temporal and spatial challenges (analogous to rapidly finding a few needles in a haystack) must be overcome for *Plasmodium*-specific memory CD8 T cells to deal with all infected hepatocytes and prevent the

symptomatic blood stage of infection. The use of mouse models of *Plasmodium* infection to determine how the immune system can be manipulated by immunization to overcome these challenges may have important implications for rational design of malaria vaccines. Filling this knowledge gap will require immunization models to reliably generate memory CD8 T cells that confer long-term immunity, so that the characteristics of these populations leading to protection can be defined. Here, we describe an immunization strategy that generates *P. berghei* circumsporozoite (CS)-specific memory CD8 T cells capable of protecting mice from multiple sporozoite challenges for at least 19 months. Studies with this model revealed that the threshold in memory CD8 T cell numbers required for long-term protection from sporozoite infection reflects a substantial fraction of the CD8 T cell compartment, a finding with potentially important implications for development of effective vaccines to protect against human malaria.

Results

Generation of CS-Specific Memory CD8 T Cells. Protective immunity to infection may be influenced by both the functional attributes and numbers of memory CD8 T cells (24–26). We reasoned that the extremely low frequencies of infected hepatocytes might dictate that a large number of memory CD8 T cells would be required to ensure all infected liver cells are located and dealt with to prevent blood stage infection. To test this hypothesis, we made use of an accelerated “prime-boost” immunization strategy, developed in our laboratory, that rapidly generates large numbers of memory CD8 T cells (27). BALB/c mice initially were immunized with mature dendritic cells (DC) coated with a *P. berghei* epitope (CS_{252–260}, also known as “Pb9,” DC-CS immunization) that is a target of protective CD8 T cells (8). As we reported for other epitopes (27), DC-CS immunization resulted in accelerated acquisition of memory characteristics (CD127^{hi}, KLRG-1^{lo}, IL-2⁺) by the responding CD8 T cells (Fig. 1A), including the ability to respond to booster immunization with recombinant attenuated (*actA*-, *inlB*-deficient) (28) *L.*

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Conflict of interest statement: P.L. is an employee of ANZA Therapeutics, Inc, which owns intellectual property covering the compositions and methods described in this manuscript. In addition, ANZA employees hold stock and/or stock options in the company. The remaining authors disclose no known financial conflicts.

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[§]Present address: Medarex, Inc., Milpitas, CA 95035.

**To whom correspondence should be addressed. E-mail: john-harty@uiowa.edu.

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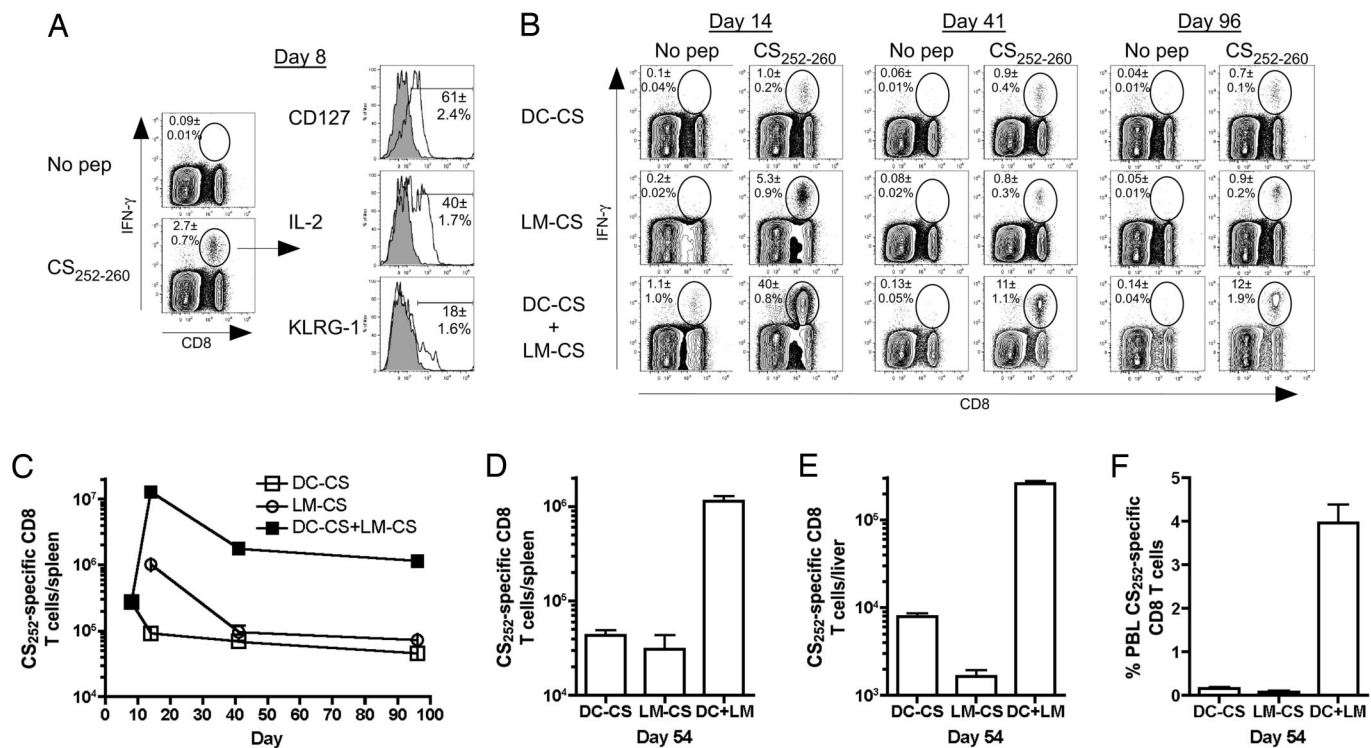


Fig. 1. Generation and maintenance of *P. berghei* CS₂₅₂-specific CD8 T cells. BALB/c mice were primed with 3×10^5 bone marrow-derived dendritic cells coated with CS₂₅₂₋₂₆₀ (DC-CS). Seven days later DC-CS mice were boosted with 2×10^7 LM-CS₂₅₂ (DC-CS + LM-CS) or naive mice were primed with 7×10^6 LM-CS₂₅₂ (LM-CS). (A) Frequency and phenotype of splenic CD8 T cells that are CS₂₅₂ specific as determined by ICS 8 days after DC-CS prime. (B) Frequency of splenic CD8 T cells that are CS₂₅₂ specific on days 14, 41, and 96 as determined by ICS. Profiles from representative mice are shown; numbers represent mean \pm SD; $n = 3$ per group. (C) Total number (mean \pm SD, $n = 3$ per group) of CS₂₅₂-specific CD8 T cells in the spleen at various days after initiation of immunization. Total number (mean \pm SD, $n = 3$ per group) of CS₂₅₂-specific CD8 T cells (D) in the spleen and (E) liver or (F) percent CS₂₅₂-specific CD8 T cells of all PBL 54 days after initiation of immunization for the indicated groups. Data are representative of three experiments.

monocytogenes expressing the CS₂₅₂₋₂₆₀ epitope (here on referred to as “LM-CS₂₅₂”) that is embedded within a secreted ovalbumin fusion protein and does not contain known antibody or CD4 T cell epitopes. This DC-CS + LM-CS immunization generated large frequencies (Fig. 1B) and total numbers (Fig. 1C) of effector and memory CS₂₅₂-specific CD8 T cells that were >10-fold greater than generated by DC-CS or LM-CS₂₅₂ immunization alone. Splenic memory CD8 T cell frequencies and total numbers (Fig. 1B and C) in all groups were maintained stably between day 41 and day 96 and, of critical importance for resistance to liver-stage *Plasmodium* infection, numbers of CS₂₅₂-specific CD8 T cells in the liver and spleen were proportional at day 54 (Fig. 1D and E) and at day 72 (*data not shown*). Additionally, the frequency of CS₂₅₂-specific CD8 T cells of all peripheral blood lymphocytes (PBLs) was proportional to the numbers of antigen-specific cells in the spleen and liver (Fig. 1F). Thus, DC-CS + LM-CS immunization rapidly generated large and stable populations of *P. berghei*-specific memory CD8 T cells in the spleen, PBL, and liver.

It should be noted that this immunization strategy, based on a short peptide epitope prime and epitope-fusion protein boost, does not induce a detectable CD8 negative (i.e., CD4 T cell) IFN- γ response (*data not shown*). Also, antibodies induced by this vaccination would be directed either to the CS₂₅₂-MHC class I complex (after DC-CS₂₅₂ immunization) or to the short CS epitope embedded in the ovalbumin carrier protein (LM-CS₂₅₂ boost). If such antibodies are induced, they are unlikely to react in a meaningful way with the conformationally intact CS protein expressed by *P. berghei* sporozoites. Thus, our immunization strategy permits a focus on the ability of CS₂₅₂-specific CD8 T cells to provide immunity against sporozoite challenge.

DC-CS + LM-CS CD8 T Cells Prevent Blood-Stage Parasitemia. To evaluate individual-to-individual variability and to mimic sampling of humans, frequencies of memory CS₂₅₂-specific CD8 T cells of all PBL were determined at day 98 in individual mice. DC-CS- and LM-CS₂₅₂-immunized mice had <0.2% CS₂₅₂-specific PBL, whereas DC-CS + LM-CS mice exhibited >2% CS₂₅₂-specific PBL (Fig. 2A). This frequency represented a substantial fraction (>21%) of circulating CD8 T cells in the DC-CS + LM-CS mice (*data not shown*). All naive and LM-CS₂₅₂-immune and 11 of 12 DC-CS-immune mice developed blood stage parasitemia after sporozoite challenge (Fig. 2B). In contrast, 10/11 DC-CS + LM-CS mice were protected, with blood-stage parasitemia observed only in the mouse that had the lowest frequency of CS₂₅₂-specific PBL (<0.5%). These data suggest that immunity to liver-stage parasites may depend on the numbers of antigen-specific memory CD8 T cells.

CS-Specific Memory CD8 T Cells Afford Long-Term Sterile Immunity. Although many vaccination strategies are successful in protecting rodents from sporozoite challenge for several months (29), the feasibility of long-term immunity based solely on memory CD8 T cells remains unknown. A representative analysis of DC-CS + LM-CS mice revealed $\approx 10^6$ CS₂₅₂-specific CD8 T cells per spleen on day 209 (Fig. 3A), a number similar to that observed at day 41 (Fig. 1). One hundred percent of additional mice from this group were protected from sporozoite challenge on day 210, indicating that CD8 T cells in DC-CS + LM-CS mice can protect for at least 7 months (Fig. 3B). Immunity in malaria-endemic areas must protect the host from repeated sporozoite exposures. To address this issue and to evaluate further the duration of memory and protection, CS₂₅₂-specific

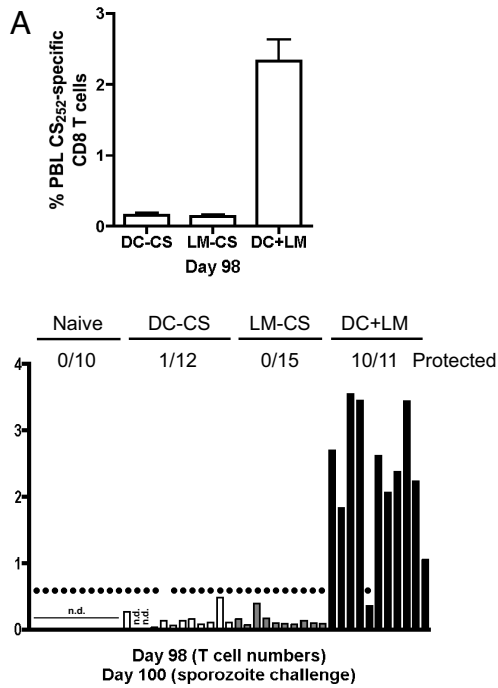


Fig. 2. CS₂₅₂-specific memory CD8 T cells afford protection for >3 months against a *P. berghei* sporozoite challenge. (A) Frequency of CS₂₅₂-specific CD8 T cells in the PBL 98 days after priming. Data (mean \pm SD) are from 10 to 12 mice per group. (B) Percentage total PBL that are CS₂₅₂-specific CD8 T cells as determined by ICS in individual mice from the indicated immunization group before challenge. Filled circles indicate naive or immune mice that developed blood-stage malaria after a challenge with 1000 *P. berghei* sporozoites. Numbers represent protected mice/total challenged for each group. n.d., not determined.

PBL were determined at day 406 in the 5 mice that had resisted challenge at day 210 and in an additional group of unchallenged DC-CS + LM-CS mice (Fig. 3C). Both groups exhibited >2% CS₂₅₂-specific PBL and were protected from sporozoite challenge at day 422 (Fig. 3C). Both groups of mice maintained high levels of CS₂₅₂-specific CD8 T cells (>2% of all PBL on average), and all resisted additional sporozoite challenges at day 455, day 485, and day 565 (19 months after immunization, *data not shown*). Interestingly, we did not observe “boosting” in memory cell frequencies in these groups despite the repeated challenges (*data not shown*). This may result from the very large memory populations already present in the DC-CS + LM-CS immune mice or suggest that the amount of antigen present in the challenges was insufficient to cause noticeable boosting in memory numbers. However, it is possible that the repeated challenge infections induced antibody and CD4 T cell responses that contributed to resistance of multiply challenged mice. These issues are under investigation. Over multiple experiments, 136/141 (>96%) of DC-CS + LM-CS mice were protected from initial sporozoite challenge from day 28 to day 422 after immunization. Thus, CD8 T cell protection can last for >14 months, and immunity is maintained up to 19 months in the face of multiple sporozoite challenges. Importantly, the ability to generate large numbers of CS₂₅₂-specific memory CD8 T cells and sterilizing immunity to sporozoite challenge was not limited to DC-CS + LM-CS immunization but also could be achieved by boosting LM-CS₂₅₂-immune mice at >40 days with a higher dose of LM-CS₂₅₂ (LM-CS + LM-CS data in Fig. 4). These data demonstrate that single-epitope specific-memory CD8 T cells

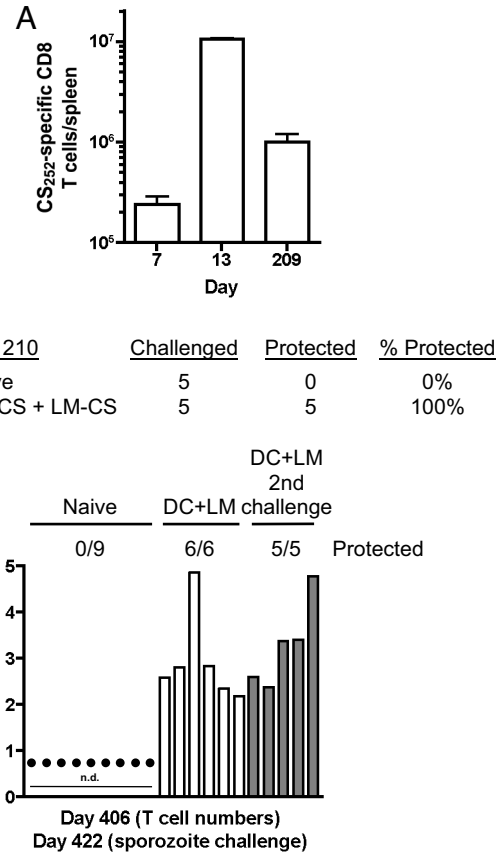


Fig. 3. Long-term protection against multiple *P. berghei* sporozoite challenges. BALB/c mice were primed with 5×10^5 splenic DC (sDC)-CS and boosted with 2×10^7 LM-CS₂₅₂. (A) Total number (mean \pm SD, $n = 3$ mice per day) of CS₂₅₂-specific CD8 T cells in the spleen on various days after the start of immunization. (B) Naive or DC-CS + LM-CS mice were challenged with 1000 *P. berghei* sporozoites on day 210. (C) The percent of total PBL that are CS₂₅₂-specific CD8 T cells at day 406 after immunization was determined by ICS from individual unchallenged or previously challenged DC-CS + LM-CS immunized mice. Naive and immune mice were challenged with 1000 *P. berghei* sporozoites at day 422. Filled circles indicate mice that developed blood-stage malaria. Numbers represent protected mice per total challenged for each group. n.d., not determined.

can provide long-term sterilizing immunity against *Plasmodium* sporozoite challenge.

Defining the Threshold Frequency of Memory CD8 T Cells Required for Sterilizing Immunity. The reliable long-term protection afforded by DC-CS + LM-CS immunization suggests that this model may be well suited to dissect the basic parameters of CD8 T cell immunity to liver-stage *Plasmodium* infection. Initially, we sought to determine whether a threshold frequency of protective memory CD8 T cells could be defined with this immunization model. BALB/c mice were primed with DC-CS and then boosted with a range of LM-CS₂₅₂ (from 2×10^4 – 2×10^7) to stimulate different magnitudes of CD8 T cell memory. Because DC-CS, LM-CS₂₅₂, and DC-CS + LM-CS immunization stimulated memory CD8 T cells that exhibited some differences in phenotype (for example, CD27 and CD62L expression and IL-2 production) [supporting information (SI) Fig. S1], we investigated whether boosting the mice with different doses of LM-CS₂₅₂ altered the phenotype of the CS₂₅₂-specific CD8 T cells. Importantly, the surface expression of certain memory markers (CD27, CD62L, and CD127) was similar in all groups, as was the

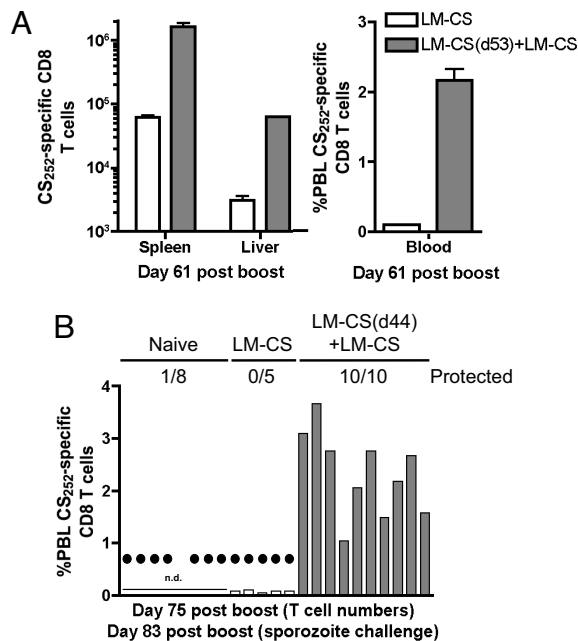


Fig. 4. LM-CS₂₅₂-primed and LM-CS₂₅₂-boosted BALB/c mice are protected against a *P. berghei* sporozoite challenge. (A) In an initial experiment to evaluate conventional prime-boost responses, BALB/c mice were primed with 7×10^6 LM-CS₂₅₂ and boosted with 2×10^7 LM-CS₂₅₂ 53 days later (LM-CS(d53)+LM-CS). On the day of the LM-CS boost, naive BALB/c mice were primed with 7×10^6 LM-CS₂₅₂ (LM-CS). (A) Total number (mean \pm SD, $n = 3$ per group) of CS₂₅₂-specific CD8 T cells in the spleen and liver and percentage of PBL at day 61 after boost or first immunization was determined by ICS. (B) In a second experiment BALB/c mice were primed with 7×10^6 LM-CS₂₅₂ and boosted with 2×10^7 LM-CS₂₅₂ 44 days later (LM-CS(d44)+LM-CS). On the day of the LM-CS₂₅₂ boost, naive BALB/c mice were primed with 7×10^6 LM-CS₂₅₂ (LM-CS). Percentage of total PBL that were CS₂₅₂-specific CD8 T cells at day 75 after the last immunization was determined by ICS in individual mice. Filled circles indicate naive or immune mice that developed blood-stage malaria after a challenge with 800 *P. berghei* sporozoites on day 83 after boost. Numbers represent protected mice per total challenged for each group. n.d., not determined

fraction of CS₂₅₂-specific memory cells that could produce IL-2 after *in vitro* stimulation (Fig. 5A and Fig. S2). Thus, differences in the resistance of individual immunized mice probably would be based on the number of memory CD8 T cells. The average frequency of memory CD8 T cells in the PBL of each group increased with increasing doses of LM-CS₂₅₂ boosting, as did the frequency of protected mice in each group (Fig. 5B). Because there was individual-to-individual variation within each group, and the phenotypes of the memory CD8 T cells were similar, we evaluated all immunized mice based on the frequency of CS₂₅₂-specific CD8 T cells and protection. Strikingly, 20 of 22 DC-CS + LM-CS mice that had $\geq 1\%$ CS₂₅₂-specific PBL were protected from sporozoite challenge at day 98 after immunization, whereas only 1 of 16 similarly immunized mice with $<1\%$ CS₂₅₂-specific PBL were protected (Fig. 5B). When we include all DC-CS + LM-CS mice in which memory CD8 T cells have been evaluated in the blood at day 98 or later, our data demonstrate a 97% chance of protection from sporozoite challenge in mice containing $\geq 1\%$ CS₂₅₂-specific PBL and a 6% chance of protection in mice with $<1\%$ CS₂₅₂-specific PBL (Fig. 5C). Thus, long-term sterilizing immunity to *P. berghei* infection in this model requires maintenance of CS₂₅₂-specific memory CD8 T cells that exceed a large ($\geq 1\%$) but definable frequency of PBL (Fig. 5C).

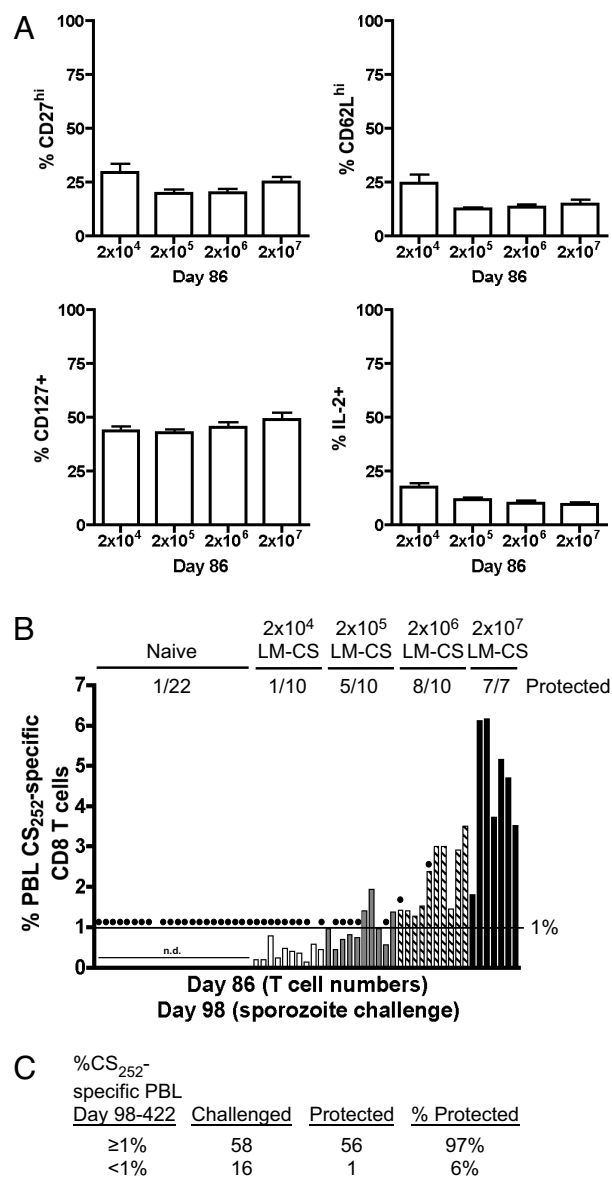


Fig. 5. Numerical requirements for sterile immunity mediated by CS₂₅₂-specific CD8 T cells. BALB/c mice were primed with 2.5×10^5 splenic DC-CS and boosted with titrating doses of LM-CS₂₅₂ (2×10^4 , 2×10^5 , 2×10^6 , or 2×10^7). (A) Phenotype of PBL CS₂₅₂-specific CD8 T cells as determined by ICS at day 98. Data (mean \pm SD) are from 10 mice per group except for 2×10^7 , in which $n = 7$. (B) Before sporozoite challenge the percentage of total PBL CS₂₅₂-specific CD8 T cells was determined in individual mice by ICS. Naive and immune mice were challenged with 1000 *P. berghei* sporozoites. Filled circles indicate mice that developed blood-stage malaria. n.d. = not determined. (C) Cumulative results from DC-CS + LM-CS immunized mice in which the frequency of PBL CS₂₅₂-specific CD8 T cells was determined before challenge with sporozoites.

Immunity to *P. berghei* Requires More CD8 T Cells than Other Pathogens. Although it is clear that the magnitude of CD8 T cell memory can influence resistance to infection (25, 26), there are few data comparing the actual numbers of antigen-specific T cells required for protection against diverse pathogens. To address this issue, we determined that adoptive transfer of 10,000 memory CD8 T cells reduced infection by the liver pathogen *Listeria monocytogenes* by ≈ 100 -fold (Fig. S3). Similarly, adoptive transfer of $\approx 85,000$ memory CD8 T cells dramatically decreased virus titers after lymphocytic choriomeningitis virus

infection (30). Finally, the presence of $\approx 50,000$ memory CD8 T cells in the spleen converted a lethal *L. monocytogenes* infection into a sublethal infection that was cleared from all mice (26). This last situation is analogous to the biological “bar” that must be overcome for CD8 T cell protection against *Plasmodium* infection, in which elimination of all infected hepatocytes is required for survival of the mouse. Thus, the 1% of CS₂₅₂-specific PBL threshold (equivalent to $>10^6$ in spleen and $>2 \times 10^5$ in liver) required for long-term sterilizing immunity to liver-stage *Plasmodium* infection is 100-1000-fold higher than the numbers of memory CD8 T cells required for meaningful immunity against a bacterial or viral pathogen.

Discussion

In this study, we developed a model of epitope-specific immunization to generate large memory CD8 T cell responses capable of protecting mice from sporozoite challenges. Although several studies have shown that protection from challenge at short intervals after boosting correlates with large CD8 T cell responses (6, 8, 9, 31, 32), our results extend the field in at least 3 ways. First, we demonstrate that memory CD8 T cells specific for *Plasmodium* liver-stage antigens are capable of providing long-term sterilizing immunity, approaching the entire lifespan of the laboratory mouse. Protection lasting >6 months has been described only for immunization with irradiated or genetically attenuated sporozoite immunizations, suggesting that long-term immunity after subunit vaccination may not be possible. Our results clearly argue against this notion. Second, our results also reveal that a large but definable threshold of memory CD8 T cells is required for protection against sporozoite challenge. Importantly, this threshold greatly exceeds the number of memory CD8 T cells required for protection against specific bacterial and viral pathogens. These results suggest that the biology of the pathogen will affect the number of memory CD8 T cells required for resistance to infection. In the case of *Plasmodium* infection, the low frequency of infected hepatocytes in combination with the requirement of preventing even 1 infected cell from releasing blood-stage parasites provides a challenge to the immune system that requires commitment of a substantial fraction of the CD8 T cell repertoire to achieve sterilizing immunity. Third, these data describe a novel model system that should facilitate studies to address how CD8 T cells provide immunity against liver-stage *Plasmodium* infection.

Our results were generated with an epitope-specific immunization protocol in inbred mice, and this scenario is unlikely to have immediate relevance as a vaccine strategy in humans. Although the mouse in general and our approach specifically may have limitations as a preclinical model, the results still may have relevance for understanding why subunit vaccines that evoke sterilizing immunity against human malaria have been difficult to obtain. For example, accumulating data from human clinical trials show that current prime-boost immunizations generate *Plasmodium*-specific T cell responses in the range of 0.1% of PBL at the peak after boosting and $<0.01\%$ at memory stages (20, 33–36). These frequencies are 10-fold and 100-fold lower than required to protect mice from *Plasmodium* infection and consist mainly of CD4 T cells, which may explain why these vaccines delay the onset but rarely prevent blood-stage parasitemia (20, 36). Clearly, delayed onset of blood-stage parasitemia indicates partial protection by these vaccines, and such partial protection could have real benefits in malaria-endemic areas. However, results from our model suggest that additional or stronger booster immunizations may be required to generate memory CD8 T cell frequencies that exceed the threshold for optimal resistance to *Plasmodium* infection in humans. Furthermore, it remains to be determined whether immunization against multiple liver-stage antigens will decrease the large frequency of

CS-specific memory CD8 T cells required for sterilizing immunity. The model system we describe here is ideally suited to address this question.

Alternatively, vaccination of humans to achieve the large frequencies of memory CD8 T cells that are required for sterilizing immunity to *Plasmodium* infection in mice may not be feasible. In this regard, CD8 T cells are not the only effectors of immunity to *Plasmodium* infection, and efforts are underway to develop vaccines that also engage *Plasmodium*-specific CD4 T cells and antibodies and that are capable of targeting multiple stages of the parasite infection (23). Importantly, the relationships between these various arms of the immune response resulting in the most effective resistance to *Plasmodium* infection are unknown. The model system described here is well suited for determining these relationships, because it permits quantitative assessment of whether and how *Plasmodium*-specific antibodies and CD4 T cells decrease the threshold frequencies of CS-specific CD8 T cells required for protective immunity.

In addition, the precise mechanisms and pathways required for CD8 T cell immunity to liver-stage *Plasmodium* infection remain to be defined. The DC-CS + LM-CS immunization approach used here provides an informative and reliable model in which immune and susceptible mice can be identified before infection. The ability to differentiate prospectively between resistant and susceptible subjects provides a level of resolution that is particularly important for liver-stage studies because the host must be killed for tissue sampling before the outcome of challenge is known. This feature of the model will facilitate studies to address in detail the molecular and cellular features of long-term CD8 T cell protection against liver-stage *Plasmodium* infection. In turn, this basic information should be useful in devising the most efficacious malaria vaccines.

Methods

Mice and Immunizations. BALB/c mice were housed at the University of Iowa and Iowa State University animal care units. Mice were primed with DC (2.5×10^5 – 5×10^5) coated with CS_{252–260} or with LM-CS₂₅₂ (7×10^6) through i.v. injections. DC-primed mice were boosted 7 days later with 2×10^7 LM-CS₂₅₂ or with titrating doses of LM-CS₂₅₂ (2×10^4 , 2×10^5 , 2×10^6 , or 2×10^7). (Detailed methods are available in [SI Text](#).)

Quantification of Antigen-Specific T Cells. The total number of spleen CS₂₅₂-specific CD8 T cells was determined by ICS for IFN- γ after 5 h of incubation in brefeldin A in the presence or absence of CS_{252–260}. Total liver CS₂₅₂-specific CD8 T cells and the percent of PBL that were CS₂₅₂-specific were determined by ICS for IFN- γ after 5 h of incubation in brefeldin A in the presence or absence of CS_{252–260}-coated P815 cells.

Mosquito Infections. *Anopheles stephensi* (Liston) strain STE2 (MR4–128, MR4, ATCC) were reared in controlled environments ($27^\circ\text{C} \pm 1^\circ\text{C}$ and $80\% \pm 5\%$ relative humidity) and a 16:8-hour photoperiod. Mosquitoes were fed on anesthetized mice ≈ 3 days after subpassage or when parasitemia reached 5–20%. To confirm infection before sporozoite collection, oocyst prevalence and intensity were monitored 7–14 days after exposure.

Sporozoite Challenge. *P. berghei* (ANKA strain clone 234) sporozoites were isolated from the salivary glands of infected *A. stephensi*. Naïve and immunized mice were challenged with 1000 sporozoites i.v. unless otherwise noted.

Identification of Protected Mice. Thin blood smears were performed 7 to 12 days after sporozoite challenge. Parasitized red blood cells were identified by Giemsa stain. Protected mice were defined as those not having blood-stage parasites.

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Supporting Information

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SI Text

Mice. BALB/c mice for DC immunizations were obtained from the National Cancer Institute and housed at the University of Iowa. All experiments were approved by the University of Iowa Institutional Animal Care and Use Committee. BALB/c mice for mosquito infections were obtained from Harlan Sprague Dawley and maintained in a laboratory animal suite at Iowa State University. All mice were treated and handled in accordance with guidelines established by the Institutional Animal Care and Use Committee at Iowa State University.

Dendritic Cells. Mice were primed with between 2.5×10^5 and 5×10^5 BMDC or splenic DC (sDC) coated with CS₂₅₂₋₂₆₀. Priming of mice with peptide-coated bone marrow dendritic cells (BMDC) followed by early boosting with *Listeria monocytogenes* has been described previously (1). Briefly, bone marrow cells were depleted of CD8+, CD4+, and B220+ cells by antibody-mediated complement lysis. Bone marrow cells were cultured in recombinant GM-CSF (1000 U/ml) and recombinant IL-4 (27 U/ml) for 6 days with the addition of LPS (100 ng/ml) for the last 14–18 h as a maturation stimulus. BMDC were pulsed with 2 μ M CS₂₅₂₋₂₆₀, and epitope-coated BMDC were isolated using anti-CD11c microbeads (Miltyni Biotec) resuspended in saline and injected i.v.

sDC were isolated after i.p. injection of BALB/c mice with 5×10^6 B16 cells expressing Flt3L (provided by M. Prlic and M. Bevan, University of Washington). Two weeks later, mice were injected with 2 μ g LPS i.v. to mature the DC. Spleens were harvested 16 h later and were digested with DNase and collagenase for 20 min at 37°C/7% CO₂ with shaking (120 RPM). Spleen pieces were forced through a nylon cell strainer (70 μ m) to generate a single-cell suspension, RBC were lysed, and splenocytes were resuspended in 2 parts supplemented RPMI-1640 to 1 part B16-Flt3L-conditioned media + recombinant GM-CSF (1000 units/ml) + 2 μ M CS₂₅₂₋₂₆₀ and incubated 2 h at 37°C/7% CO₂ with shaking (100 RPM). Spleen cells were washed, and CD11c+ cells were isolated using anti-CD11c microbeads (Miltyni Biotec). sDC were resuspended in saline and injected i.v. BMDC and sDC were analyzed by cell-surface staining for CD11c (> 85%) before injection. CD11c+ cells also were analyzed for expression of CD86 (> 85%) and MHC II (> 90%).

Bacteria. *Listeria monocytogenes* expressing *P. berghei* CS₂₅₂₋₂₆₀ (LM-CS) was generated by ANZA Therapeutics. The LM-CS strain is an attenuated strain because of the in-frame deletion of both the *actA* and *inlB* genes (2). The CS₂₅₂₋₂₆₀ epitope is flanked by 3 native amino acids on either side and is secreted as a fusion peptide (2). Frozen aliquots of LM-CS were diluted in tryptic soy broth containing 50 μ g/ml streptomycin (TSB-strep) and grown to an OD₆₀₀ of ≈ 0.1 , which equates to $\sim 10^8$ LM/ml. LM-CS cells were diluted in saline so that the target dose would be delivered in 0.2 ml. Mice were primed and boosted through the tail vein with 7×10^6 LM-CS or with 2×10^7 LM-CS. In some cases mice were boosted with titrating doses of LM-CS (2×10^4 , 2×10^5 , 2×10^6 , or 2×10^7). The number of injected bacteria was verified by plating diluted aliquots onto tryptic soy agar containing 50 μ g/ml streptomycin (TSA-Strep).

Quantification of Antigen-Specific T Cells. Single-cell suspensions from spleens were treated with Tris-ammonium chloride to lyse RBC and were washed with supplemented RPMI-1640 before stimulation. Livers were perfused with 10 ml cold HBSS through

the hepatic portal vein. After removal of the gall bladder, the liver was excised and was forced through a wire mesh to make a single-cell suspension. Cells were filtered through a 70- μ m filter and were rinsed with HBSS. Liver cells were spun at 400 g for 5 min at 4°C. Cells were resuspended in 15 ml of 35% Percoll/HBSS at room temperature and were spun at 500 g with no brakes for 10 min at room temperature. Pelleted cells were treated with Tris-ammonium chloride to lyse RBC, were washed with HBSS, and were centrifuged at 400 g for 5 min at 4°C. PBL were obtained by treating blood with Tris-ammonium chloride to lyse RBC followed by 2 washes.

Total spleen CS₂₅₂-specific CD8 T cells were determined by ICS for IFN- γ after 5 h of incubation in brefeldin A (Biolegend) in the presence or absence of 200 nM CS₂₅₂₋₂₆₀ as previously described (1). Total liver CS₂₅₂-specific CD8 T cells and the percent of PBL that were CS₂₅₂-specific CD8 T cells were determined by ICS for IFN- γ after 5 h of incubation in brefeldin A in the presence or absence of CS₂₅₂₋₂₆₀-coated P815 cells.

Antibodies. The following antibodies from Biolegend were used: IgG2A-PE (RTK2758), CD127-PE (SB/199), and IL-2-PE (JES6-5H4). The following antibodies from eBioscience were used: CD8-FITC (53-6.7), CD27-PE (LG.7F9), KLRG1-APC (2F1), and Golden Syrian Hamster IgG-APC. The following antibodies from BD PharMingen were used: IFN- γ -APC and CD62L-PE (MEL-14).

Passage of Blood-Stage *P. berghei* Through Mice. Modified *P. berghei* challenge protocols were followed (3, 4). Briefly, mice were infected with a *P. berghei* (ANKA strain clone 234) cryopreserved stock stabilize via i.p. injection. To visualize *P. berghei* infected erythrocytes, thin blood smears were prepared using the Hema 3 stain set (Fisher Diagnostics). Mice were anesthetized with a ketamine/xylazine mix at 80:8 mg/kg for blood collection and mosquito feeding. Parasitemic blood was collected via cardiac puncture into a heparinized needle and syringe, and 0.1 ml was subpassaged immediately to a new mouse. Mosquitoes were fed on anesthetized mice ~ 3 days after subpassage or when parasitemia reached 5% to 20%.

Mosquitoes. *Anopheles stephensi* (Liston) strain STE2 (MR4-128, MR4, ATCC) were reared in controlled conditions (27°C \pm 1°C and 80% \pm 5% relative humidity) with a 16:8-hour photoperiod. Adult mosquitoes were housed in 0.5-L paper cartons and provided 10% sucrose (wt/vol) ad libitum. Sucrose was replaced with a water-soaked cotton ball 24 h before mosquito feeding. After exposure, engorged females were transferred immediately to holding cages and maintained at 20°C \pm 1°C and 80% \pm 5% relative humidity with a 16:8-hour photoperiod. To confirm infection before sporozoite collection, oocyst prevalence and intensity were monitored 7–14 days after exposure. *A. stephensi* midguts were dissected and stained using 0.5% aqueous Eosin Y (JT Baker) then viewed with bright field at 100 \times magnification.

Sporozoite Challenge. Salivary glands from *P. berghei*-infected *A. stephensi* were dissected using a stereomicroscope. Salivary glands were disrupted using a 0.1-ml dounce (Fisher Scientific) to release sporozoites. Sporozoites were quantified and injected i.v. into mice.

Identification of Infected and Protected Mice. Thin blood smears were performed 7 and 12 days after sporozoite challenge. Parasitized RBC were identified by Giemsa stain. Protected mice were

defined by the absence of blood-stage parasites and by the failure to succumb to infection.

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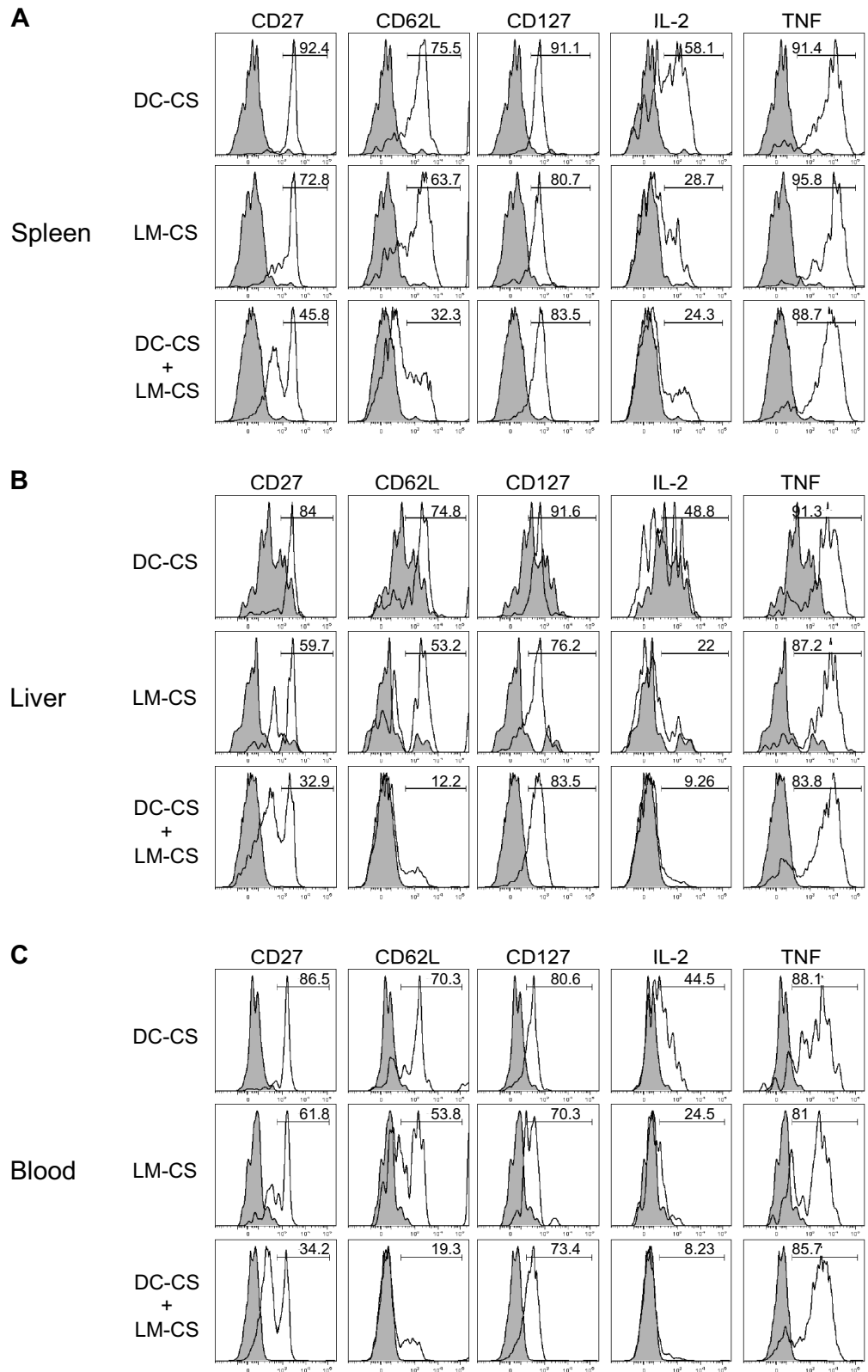


Fig. S1. Phenotype of memory CS252-specific CD8 T cells. BALB/c mice were primed with 5×10^5 DC coated with CS252-260 (DC-CS) or with 7×10^6 LM-CS₂₅₂. Seven days later DC-CS mice were boosted with 2.8×10^7 LM-CS₂₅₂ (DC-CS+LM-CS). Phenotype of (A) spleen, (B) liver, and (C) blood CD8 T cells that are CS₂₅₂ specific on day 61 as determined by ICS. One of 3 representative histograms is shown. Data are representative of 2 experiments.

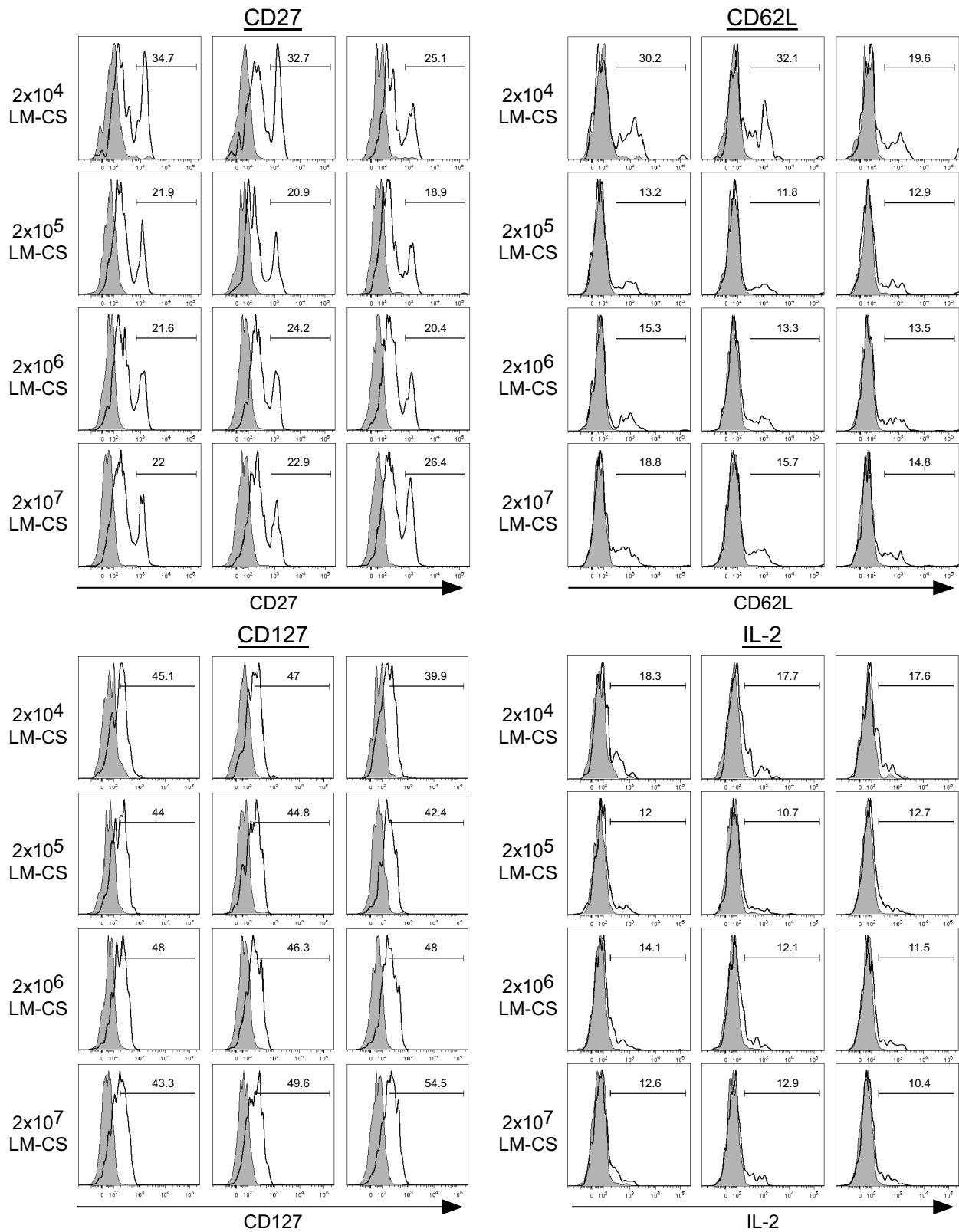


Fig. S2. Similar phenotype of CS₂₅₂-specific CD8 T cells in mice given increasing doses of LM-CS₂₅₂ boost. Mice were primed with 2.5×10^5 DC-CS and boosted with increasing doses of LM-CS₂₅₂. Peripheral blood CS₂₅₂-specific CD8 T cells were identified by ICS and analyzed for the expression of CD27, CD62L, and CD127 and for the production of IL-2 on day 86. Shaded histograms are the isotype control, and open histograms are the indicated marker. Three representative examples from each group (2×10^4 , 2×10^5 , and 2×10^6 , $n = 10$) and (2×10^7 , $n = 7$) are shown.

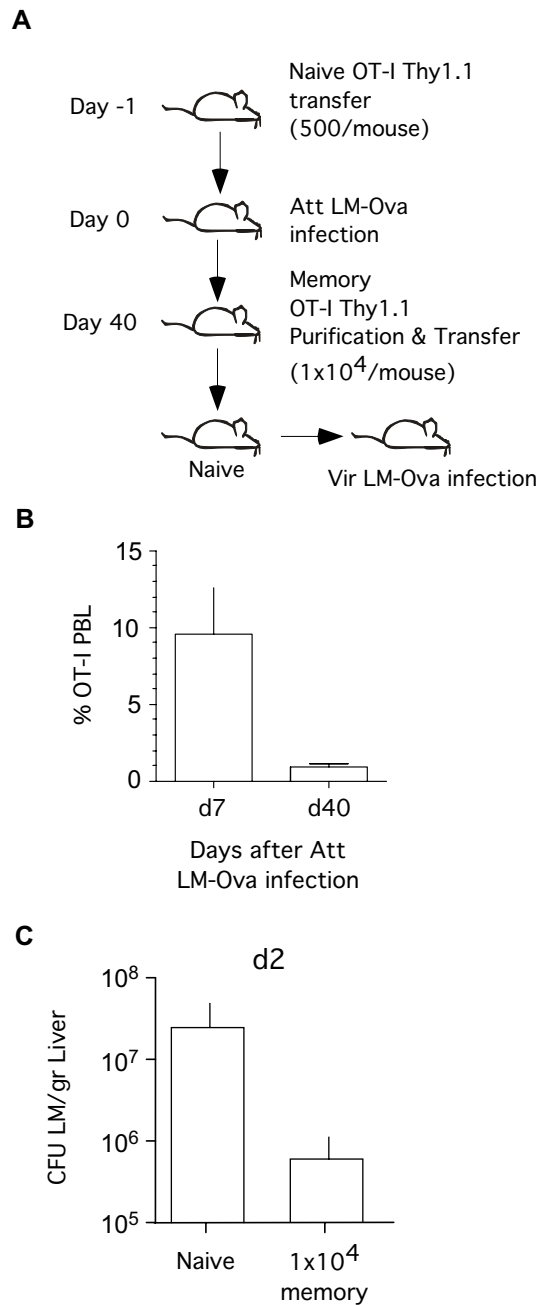


Fig. S3. Anti-listerial immunity provided by low number of memory CD8 T cells. (A) Experimental design. Purified naive OT-I Thy1.1 CD8 T cells (500/mouse) were transferred into naive B6 Thy1.2 mice, and 1 day later mice were immunized with Att LM-Ova (5×10^6 cfu/mouse). At day 40 after immunization, OT-I were purified from the spleens of immune mice by positive selection (Thy1.1) and were transferred (1×10^4 /mouse) into naive B6 recipients 1 day before high-dose virulent LM-Ova infection (1×10^6 cfu/mouse). The group of naive mice (naive) that did not receive memory OT-I cells served as controls. (B) Frequency of OT-I CD8 T cells in the blood at the indicated days after primary LM infection. (C) On day 2 after high-dose virulent LM-Ova infection, bacterial numbers were determined in the liver. Data are presented as mean + SD of 3 mice per group. One of 2 similar experiments is shown.