Peripheral tolerance to developmentally regulated antigens is necessary to maintain tissue homeostasis. We have devised an inducible and reversible system that allows interrogation of T-cell tolerance induction in endogenous naïve and memory CD8 T cells. Our data show that peripheral CD8 T-cell tolerance can be preserved through two distinct mechanisms, antigen addiction leading to anergy for naïve T cells and ignorance for memory T cells. Induction of antigen in dendritic cells resulted in substantial expansion and maintenance of endogenous antigen-specific CD8 T cells. The self-reactive cells initially exhibited effector activity but eventually became unresponsive. Upon antigen removal, the antigen-specific population waned, resulting in development of a self-specific memory subset that recalled to subsequent challenge. In striking contrast to naïve CD8 T cells, preexisting antigen-specific memory CD8 T cells failed to expand after antigen induction and essentially ignored the antigen despite widespread expression by dendritic cells. The inclusion of inflammatory signals partially overcame memory CD8 T-cell ignorance of self-antigen. Thus, peripheral CD8 T-cell tolerance for naïve CD8 T cells depended on the continuous presence of antigen, whereas memory CD8 T cells were prohibited from autoreactivity in the absence of inflammation.

Immune tolerance is mediated by multiple mechanisms. Central tolerance that results in deletion of high-avidity autoreactive T-cell repertoire is observed in the thymus during T-cell development (1, 2). The deletion process is rendered more robust by the action of the Aire system, which promotes expression of nonthymic, tissue-specific proteins in thymic medullary epithelial cells (3). However, this process is not infallible and self-reactive clones escape to the periphery where other control mechanisms come into play. Peripheral tolerance can be mediated through regulatory T cells (Treg) (4), deletion (5), or the induction of an unresponsive state known as anergy (5, 6). Aire also operates in the periphery but to what extent it contributes to each of these tolerance mechanisms is not yet known (7, 8). In addition, T cells specific for self-antigens that are developmentally regulated and whose expression is not controlled by Aire may also be present in the periphery (1). Many studies using a variety of systems have focused on the induction of tolerance of adoptively transferred naïve mononuclear CD4 and CD8 T cells. Few reports have analyzed tolerance induction of endogenous T cells, and fewer still have analyzed the potential for the development of tolerance in endogenous memory T cells (9, 10). Memory T cells may be more relevant to the development of some autoimmune diseases because preexisting cross-reactive memory cells may react with tissue-specific antigens through molecular mimicry (11, 12). However, little is known regarding the mechanisms by which memory T cells may be tolerized. For example, after the transfer of memory CD8 T cells to antigen-bearing hosts, the mice become unresponsive, but whether this unresponsiveness is due to anergy or deletion could not be determined (9), whereas injection of soluble antigen deletes endogenous memory cells (13).

Transgenic systems in which model antigens are expressed under systemic (14, 15) or tissue-specific promoters (16, 17) have been used to study T-cell tolerance. Transgenic mice have also been developed whereby antigen is expressed exclusively by dendritic cells (DCs) (18) that, in some cases, can be temporally controlled (19). These models rely heavily on the analysis of adoptively transferred naïve or memory monocolonal TCR transgenic T cells because the endogenous antigen-specific T-cell repertoire is dramatically altered through deletion via central tolerance. In a more elegant system, administration of tamoxifen results in antigen expression in DCs, but this expression is irreversible (10). Expression of antigen in resting DCs using this model results in tolerance induction without apparent expansion of antigen-specific CD8 T cells. Again, whether anergy or deletion of the endogenous CD8 T cells is the mechanism of tolerance is not known. Even in a case where antigen induction is reversible, adoptive transfer of TCR transgenic T cells was used, likely due to leaky expression of the transgene, perhaps through the action of Aire (20). We now report an inducible and reversible system in which endogenous CD8 T cells are ignorant of transgenic antigen. The system allowed us to observe endogenous CD8 T cells responding to self-antigen and, importantly, allowed the generation of endogenous memory CD8 T cells before the induction of autoantigen. The results reveal surprising characteristics of the endogenous naïve and memory CD8 T-cell responses to developmentally regulated antigen.
expression. Double transgenic mice expressing only CD11c-rtTA and tetO-SED (CS) were “leaky” as indicated by loss of CFSE by a subset of OT-I cells 6 days after transfer (Fig. 1A, Left) and by the absence of an antigen-specific response after infection (26). OT-I cells transferred into mice with all three transgenes (CST) did not proliferate except upon administration of doxycycline (Fig. 1A), where they expanded >250 fold. To generate a large number of experimental animals, we produced chimeras (BMC) by injecting CST bone marrow into lethally irradiated wild-type hosts. These experimental animals, we produced chimeras (BMC) by injecting CST bone marrow into lethally irradiated wild-type hosts. These chimeras also allowed us to study the effects of peripheral tolerance in the absence of potential effects from Aire (8, 27), because antigen expression would be restricted to hematopoietic cells. The OT-I response in CST BMC mice mimicked the response seen in intact CST mice, and the amount of OT-I proliferation directly correlated to the percent of chimerism (Fig. 1A, Right). To determine whether endogenous CD8 T cells were ignorant of the transgenic antigen in the absence of doxycycline, CST BMC mice were infected with recombinant vesicular stomatitis virus containing the SED construct (VSV-SED). Similar OVA\textsubscript{257-264} K\textsuperscript{b}-specific CD8 T-cell responses were generated in CST BMC and wild-type C57BL/6 mice (Fig. 1B). We also examined expression of CD11a (increased upon activation), CD127 (IL-7R, down-regulated by activation), and KLRG1 (induced by inflammation and a marker for senescent CD8 T cells), and their expression levels were also similar between WT and CST chimeras. In WT mouse or CST chimeras, control responses to the VSV nucleoprotein (N) were similar, as was the induction of granzyme B. In addition, the OVA-specific CD8 T cells exhibited similar avidities for OVA\textsubscript{257-264} K\textsuperscript{b} by using a tetramer decay assay. Thus, OVA-specific CD8 T cells were ignorant of the transgene-encoded antigen in the absence of doxycycline.

**Endogenous Naïve CD8 T Cells Undergo Robust Expansion but Not Deletion to Induced Antigen.** We used tetramer enrichment techniques (28, 29) to follow the endogenous antigen-specific T-cell response upon antigen induction. Antigen induction in CST BMC mice resulted in a gradual but robust expansion of endogenous SIINFEKL–specific CD8 T cells whose numbers peaked at ∼day 10 and were maintained in the presence of doxycycline (Fig. 2A). By day 3 after doxycycline administration, a small population of activated CD4\textsuperscript{high} antigen-specific CD8 T cells was detected in the lymphoid tissues, whereas some naïve phenotype cells remained (Fig. 2B). By days 5 and 7, substantial expansion occurred and nearly all of the responding cells expressed an activated phenotype (Fig. 2B). Interestingly, during this time, most cells retained high levels of CD127 (IL-7R), which is generally down-regulated upon CD8 T-cell activation (30) and did not up-regulate KLRG1, whose induction is linked to terminal differentiation (31, 32).

By day 10, tetramer\textsuperscript{+} cells had greatly expanded and were directly detectable in the blood or tissues without using enrichment (Fig. 3A and B). The ratio of chimerism (CST:WT) also correlated with the amount of expansion (Fig. S2). Only by day
day 35 after induction, little cytokine production (IFNγ, IL-2, TNF) was evident from peptide-stimulated cells (Fig. S3A). Thus, antigen induction on resting DCs resulted in robust CD8 T-cell expansion and acquisition of effector function. Nevertheless, the eventual outcome of continuous antigen encounter was the development of anergy and maintenance of cell numbers.

**Maintenance of Self-Specific CD8 T Cells Requires Antigen.** We next tested whether the long-lived self-specific CD8 T cells were proliferating in response to antigen. To this end, CST BMC were administered doxycycline for 45 d with BrdU given during the last week and then splenic tetramer⁺ cells were analyzed. BrdU was incorporated by ~30–40% of the antigen-specific CD8 T cells (Fig. 4A). Nearly all naive OT-I cells transferred to the same mice incorporated BrdU (Fig. 4A). Thus, the maintenance of cell numbers appeared to be due to attrition along with continued proliferation.

We also queried whether antigen was required for the maintenance of the responding CD8 T cells. Mice were doxycycline-treated for 10 d followed by doxycycline removal for 30 d. At 5 d after doxycycline withdrawal, the frequency of OVA-specific cells in the blood increased ~twofold (Fig. 4B), which may be due to release of T cells from the lymphoid tissues as a result of disruption of T-cell–DC interactions. From this timepoint on, the frequency of OVA-specific CD8 T cells slowly waned and the cells regained CD127 expression but rapidly lost GrzB expression with gradual loss of PD-1 expression (Fig. 4B–E). By 33 d after antigen removal, 50–60% of the tetramer⁺ cells were memory phenotype (CD127⁺KLRG1⁻) with a smaller population (~30%) lacking both CD127 and KLRG1 (Fig. 4C). Tetramer enrichment at 35 d after doxycycline cessation revealed that ~1,000 memory phenotype T cells remained in the sampled secondary lymphoid organs (Fig. 4F). These cells were CD127⁺ KLRG1⁻ and heterogeneous for CD62L expression (Fig. 4E), suggesting that both central and effector memory cells had been produced. We therefore tested whether such memory cells could respond to VSV-SED infection. In mice previously doxycycline treated, the OVA-specific response peaked earlier, was of a higher magnitude, and generated more secondary memory cells than the response in naïve mice (Fig. 4G). Interestingly, OVA-specific self-antigen–induced memory cells displayed a higher avidity for H-2K0/OVA₂₃₇ compared with uninduced mice (T½ = 18 min compared with 7 min) (Fig. S4), similar to memory cells responding to infection (26, 33). Thus, even in response to self-antigen, “avidity maturation” (26) occurred. These results indicated that antigen addiction maintained anergy, whereas removal of antigen resulted in development of memory cells.

**Preexisting Antigen-Specific Memory CD8 T Cells Respond Poorly to Self-Antigen.** The ability to generate normal pathogen-specific responses before antigen induction in our system afforded us the ability to examine memory T-cell responses to self-antigen. CST BMC mice were infected with VSV-SED, and memory CD8 T cells were allowed to develop. Induction of antigen in naïve mice resulted in expansion of antigen-specific cells and incorporation of BrdU by most cells (Fig. 5A). In the case of memory cells, in the absence of doxycycline, ~10% of the memory CD8 T cells incorporated BrdU over 7 d, indicative of normal homeostatic proliferation (Fig. 5B). Surprisingly, when antigen was induced, antigen-specific memory CD8 T cells did not increase in number (Fig. S5) and only ~30% of the cells incorporated BrdU (Fig. 5B). No phenotypic changes indicative of antigen recognition (CD69 or PD-1 up-regulation or TCR down-regulation) were detected. Even when doxycycline was administered for >30 d, no further increase in memory cell proliferation was noted. The memory cells readily reactivated in response to OVA-expressing vaccinia virus infection, which induced robust BrdU incorporation (Fig. 5C) and an increase in cell numbers (Fig. S5). We then tested whether the addition of inflammatory signals

**Fig. 3.** Analysis of self-specific CD8 T cells in lymphoid and nonlymphoid tissues. (A) Lymphocytes from secondary lymphoid organs were stained as in Fig. 2A, but without magnetic sorting. (B) Lymphocytes from CST BMC mice were isolated from indicated organs after 35 d of doxycycline treatment, stained as indicated, and analyzed by flow cytometry. These experiments were performed at least two times with a minimum of three mice per group.
could overcome the relative ignorance of memory CD8 T cells for self-antigen. When doxycycline was administered along with infection by vaccinia virus lacking OVA, BrdU incorporation increased ~twofold (from ~30–60%) compared with control mice without doxycycline treatment (Fig. 5D). This increase in proliferation did not, however, result in an increase in cell numbers (Fig. S5). In addition, in the absence of doxycycline, infection with vaccinia virus without OVA resulted in an increase in memory CD8 T-cell proliferation from ~10% to ~30% (compare Fig. 5B–E), likely due to bystander proliferation (34). Thus, inflammation promoted antigen recognition by memory cells to a limited extent, but far from the level to which naïve CD8 T cells responded to self-antigen.

Discussion

One advantage of the inducible antigen model described here is the ability to add or subtract antigen at will. Although we and others have described systems where self-antigen is constitutively expressed or can be irreversibly induced, in most cases, they suffer from leaky promoter-mediated antigen expression or Aire-mediated expression resulting in central tolerance. The inclusion of the transcriptional silencer element in our system blocked aberrant antigen expression, thereby allowing de novo antigen induction and withdrawal of antigen. Thus, this system allowed examination of the endogenous naïve and memory CD8 T-cell response to temporally regulated self-antigen, without the need for adoptive transfer of TCR transgenic T cells.

Our findings identified two distinct mechanisms for endogenous naïve and memory CD8 T cells to maintain self-tolerance. Naïve CD8 T cells responded robustly to self-antigen via direct presentation by DCs, resulting in transient effector activity and the generation of memory T cells by self antigen. (A) OT-I cells were transferred to CST BMC mice that had been treated with doxycycline for 45 d. The mice were given BrdU for the next week, and BrdU incorporation was determined in both endogenous and donor OT-I populations. These experiments were performed at least two times with a minimum of three mice per group. (B–E) Antigen was induced for 10 d in CST BMC mice and then doxycycline was withdrawn, and the response was monitored in the blood at the indicated times for the indicated parameters. SLEC, CD127−KLRG1+ short-lived effector cells; EEC, KLRG−CD127− early effector cells; MPEC, CD127+KLRG1− memory precursor effector cell; DPEC, KLRG1+CD127+ double positive effector cells. (F) Cells from secondary lymphoid organs were enriched for tetramer positive cells and were analyzed by flow cytometry 35 d after doxycycline withdrawal. (G) Naïve CST BMC mice or mice treated with doxycycline for 10 d followed by 35 d without doxycycline were infected with VSV-SED. Graph represents the percent of tetramer + CD8+ T cells in blood. These experiments were performed three times with a minimum of three mice per group.

Fig. 4. Maintenance of self-specific CD8 T cells and the generation of memory T cells by self antigen. (A) OT-I cells were transferred to CST BMC mice that had been treated with doxycycline for 45 d. The mice were given BrdU for the next week, and BrdU incorporation was determined in both endogenous and donor OT-I populations. These experiments were performed at least two times with a minimum of three mice per group. (B–E) Antigen was induced for 10 d in CST BMC mice and then doxycycline was withdrawn, and the response was monitored in the blood at the indicated times for the indicated parameters. SLEC, CD127−KLRG1+ short-lived effector cells; EEC, KLRG−CD127− early effector cells; MPEC, CD127+KLRG1− memory precursor effector cell; DPEC, KLRG1+CD127+ double positive effector cells. (F) Cells from secondary lymphoid organs were enriched for tetramer positive cells and were analyzed by flow cytometry 35 d after doxycycline withdrawal. (G) Naïve CST BMC mice or mice treated with doxycycline for 10 d followed by 35 d without doxycycline were infected with VSV-SED. Graph represents the percent of tetramer + CD8+ T cells in blood. These experiments were performed three times with a minimum of three mice per group.

Fig. 5. Pathogen-specific memory cells ignore self-antigen. (A) Cells from secondary lymphoid organs of CST BMC mice treated with doxycycline and BrdU for 7 d were stained and enriched for tetramer binding cells. (B–E), Tetramer + cells specific for either OVA or VSV nucleoprotein (N) were analyzed from CST BMC mice infected with 1 × 10^5 pfu VSV-SED. Sixty days after infection, mice were given BrdU and additionally treated as indicated with nothing or with doxycycline (B), or infected i.p. with 1 × 10^6 pfu recombinant vaccinia virus expressing either OVA (C) or VSV N (D). Seven days later, tetramer + cells in the spleen were quantitated and analyzed for BrdU incorporation. Values represent the means derived from at least three mice ± SEM. This experiment was performed three times with a minimum of three mice per group.
followed by anergy induction in the apparent absence of deletion. The expansion observed for naïve cells within 10 d after antigen induction was likely primarily due to the recruitment of mature naïve CD8 T cells into the response. Nevertheless, over the course of self-antigen induction, some newly minted T cells from the thymus may also have been recruited into the response, which could explain the increased numbers of antigen-specific CD8 T cells observed after 35 d of antigen induction. This scenario would presumably represent the normal course of events for tolerance induction to developmentally regulated and/or tissue-specific antigens in an intact host. However, it is possible that at later times after antigen induction, deletion was occurring simultaneously with new input from recent thymic emigrants. It might also be expected that deletion of antigen-specific cells in the thymus would occur in response to DC-expressed antigen, but further studies will be needed to dissect this issue. Interestingly, the responding T cells were initially induced to become functionally active, as evidenced by their ability to mediate antigen-specific cytolyis (Fig. S3B). However, DC numbers remained stable in antigen-induced mice and, indeed, antigen continued to be presented because transferred OT-I cells were able to respond in the context of an ongoing endogenous response (Fig. 2C). The eventual induction of anergy also correlated with the sustained expression of PD-1 (Fig. 3A), an inhibitory receptor associated with T-cell exhaustion and chronic viral infection (35), but other exhaustion markers were not induced. Thus, signaling via PD-1 may directly inhibit the effector function of the induced T cells.

Of particular interest was the finding that the immune response to short-term self-antigen exposure resulted in the generation of memory CD8 T cells. In fact, self-antigen encounter selected high-avidity memory cells that were able to mount a secondary response to subsequent challenge. These data potentially hold implications for the induction of autoimmunity because a second exposure to antigen in the face of an inflammatory event could result in tissue damage. This finding also contrasts with our previous observations involving central tolerance, where high-avidity CD8 T-cell clones undergo deletion (26). Similar to virus-induced memory, the self-antigen–induced memory cells up-regulated IL-7R and lost PD-1 expression, but unlike a pathogen-induced CD8 T-cell clones undergo deletion (26). Similar to virus-induced previous observations involving central tolerance, where high-avidity result in tissue damage. This implications for the induction of autoimmunity because a second more readily triggered compared with naïve T cells. Recent results memory CD8 T cells largely ignored the antigen, although in- expansion in response to self-antigen, preexisting endogenous have observed in an adoptive transfer system (38).

Flow Cytometric Analysis. Staining was performed by resuspending cells at 10^5 to 10^6 cells per mL in PBS containing 0.2% BSA and 0.01% NaN_3. OVA and N-specific T cells were identified by staining with APC-labeled H-2K^b tetra- mers containing the SIINFEKL epitope (OVA-tetramer) or VSV-nucleoprotein peptide (N-tetramer) for 1 h at room temperature in the presence of anti- CD8 (clone 53.6.7), followed by staining with antibodies specific for the in- dicated molecules at 4 °C for an additional 30 min (all antibodies were purchased from Biolegend or eBioscience). Cells were washed and fixed with 3% paraformaldehyde/PBS, fluorescence intensities were measured with a LSR II (BD Biosciences), and data were analyzed by using FlowJo software (Tree Star). Avidity of T-cell populations was evaluated by decay of tetramer staining was performed by resuspending cells at 10^5 to 10^6 cells per mL in PBS containing 0.2% BSA and 0.01% NaN_3. OVA and N-specific T cells were identified by staining with APC-labeled H-2K^b tetra- mers containing the SIINFEKL epitope (OVA-tetramer) or VSV-nucleoprotein peptide (N-tetramer) for 1 h at room temperature in the presence of anti- CD8 (clone 53.6.7), followed by staining with antibodies specific for the in- dicated molecules at 4 °C for an additional 30 min (all antibodies were purchased from Biolegend or eBioscience). Cells were washed and fixed with 3% paraformaldehyde/PBS, fluorescence intensities were measured with a LSR II (BD Biosciences), and data were analyzed by using FlowJo software (Tree Star). Avidity of T-cell populations was evaluated by decay of tetramer binding, as described (26).

Flow Cytometric Analysis. Staining was performed by resuspending cells at 10^5 to 10^6 cells per mL in PBS containing 0.2% BSA and 0.01% NaN_3. OVA and N-specific T cells were identified by staining with APC-labeled H-2K^b tetramer- mers containing the SIINFEKL epitope (OVA-tetramer) or VSV-nucleoprotein peptide (N-tetramer) for 1 h at room temperature in the presence of anti- CD8 (clone 53.6.7), followed by staining with antibodies specific for the in- dicated molecules at 4 °C for an additional 30 min (all antibodies were purchased from Biolegend or eBioscience). Cells were washed and fixed with 3% paraformaldehyde/PBS, fluorescence intensities were measured with a LSR II (BD Biosciences), and data were analyzed by using FlowJo software (Tree Star). Avidity of T-cell populations was evaluated by decay of tetramer binding, as described (26).

Analysis of Memory CD8 T Cells. To generate memory cells, CST BMC mice were infected i.v. with 1 x 10^6 pfu VSV-SED (41). Sixty days later, the mice were given doxycycline and subsequently analyzed as detailed in the text.

ACKNOWLEDGMENTS. We thank Dr. Moises Mallo for supplying the tts mice, Dr. Thomas Broker for the CD11c promoter construct, Dr. Wolfgang Hillen for the rTTA construct, and Dr. Jon Yewdell for supplying vaccinia expressing ovalbumin or vesicular stomatitis virus nucleoprotein, and Quynh-Mai Pham and Kristina Williams for expert technical assistance. This work was supported by National Institutes of Health Grant AI76457 and AI41576 (to L.L.), F32-AI84328 (to E.R.J.), and T32 AI07080 (to D.A.B.).


