Autoimmune Intervention by CD154 Blockade Prevents T Cell Retention and Effector Function in the Target Organ

Laurence M. Howard and Stephen D. Miller

*J Immunol* 2001; 166:1547-1553; 
doi: 10.4049/jimmunol.166.3.1547
http://www.jimmunol.org/content/166/3/1547

References

This article cites 32 articles, 17 of which you can access for free at: http://www.jimmunol.org/content/166/3/1547.full#ref-list-1

Why *The JI*? Submit online.

- **Rapid Reviews! 30 days** from submission to initial decision
- **No Triage!** Every submission reviewed by practicing scientists
- **Fast Publication!** 4 weeks from acceptance to publication

*average

Subscription

Information about subscribing to *The Journal of Immunology* is online at: http://jimmunol.org/subscription

Permissions

Submit copyright permission requests at: http://www.aai.org/About/Publications/JI/copyright.html

Email Alerts

Receive free email-alerts when new articles cite this article. Sign up at: http://jimmunol.org/alerts
Autoimmune Intervention by CD154 Blockade Prevents T Cell Retention and Effector Function in the Target Organ

Laurence M. Howard and Stephen D. Miller

The CD40-CD154 interaction is an attractive target for therapeutic intervention in many autoimmune disorders, including multiple sclerosis. Previously, we showed that CD154 blockade both inhibited the onset of experimental autoimmune encephalomyelitis and blocked clinical disease progression (relapses) in mice with established disease. The mechanism of this protection is poorly understood. Because CD154 plays a role in Th1 development, its blockade has been thought to promote anti-inflammatory Th2 responses. However, these conclusions have primarily been based on extrapolated data from in vitro experiments, which may not accurately reflect the more complex events occurring in vivo. In this paper we determine how the immune response develops under the influence of therapeutic CD154 blockade in vivo. We demonstrate that anti-CD154 treatment does not alter the early expansion of Ag-specific T cells in secondary lymphoid organs or result in deviation to a Th2-dominant response. Interestingly, the late expansion and retention of Th1 cells in the lymph nodes were markedly reduced following immunization of Ab-treated mice, and this coincided with a recompartmentalization of these cells to the spleen. Most importantly, anti-CD154 treatment eliminated the retention/expansion of encephalitogenic Th1 cells, but not their entry into the CNS. These data indicate that a major mechanism by which CD154 blockade protects against autoimmune disease is by controlling the amplitude of acute phase Th1 responses in the draining lymph nodes and by preventing the sustained expansion of effector cells within the target organ. *The Journal of Immunology*, 2001, 166: 1547–1553.

R elapsing experimental autoimmune encephalomyelitis (R-EAE) is a CD4 Th1-mediated demyelinating disease model for the human disease multiple sclerosis (1). Histopathologically, the CNS white matter demyelinating lesions in EAE and multiple sclerosis are strikingly similar (2) and are characterized by infiltration of T cells and macrophages (2). In the SJL mouse, immunization with myelin proteins or their encephalitogenic peptides in CFA leads to the development of R-EAE, characterized by moderate to severe hind limb paralysis during the acute disease episode, followed by remission and then spontaneous disease relapse (3).

CD40 was originally characterized as a critical molecule for driving B cell survival, activation, expansion, and differentiation (4). CD154 or CD40 ligand is rapidly, but transiently, expressed following T cell activation (5). In recent years, it has become evident that CD40/CD154 interactions also play a central role in many other immune cell functions, including Th cell differentiation (4) and dendritic cell maturation (6). CD40 ligation increases the expression of MHC class II and costimulatory molecule CD80/CD86 on dendritic cells (6) and is also involved in regulating the expression of innate immune cytokines (7, 8). Increased levels of CD80/CD86 on CD40-activated APCs and the ability of these Ags to induce T cell expression of CD154 have led to the suggestion that CD40/CD154 and CD28/CD80/CD86 interactions form a circuit between APCs and T cells that is important for naive T cell activation (9).

CD40 ligation on dendritic cells and other APCs has been shown to induce high levels of IL-12 secretion (7, 8), which skews T cell differentiation toward Th1 responses (4, 10). However, whether CD40 engagement is the primary factor in the induction of the long term secretion of IL-12 and subsequent Th1 skewing in vivo is still unclear (11). IL-12 may be induced through CD40-dependent or independent mechanisms, depending upon the type and route of infection. Thus, Ag-dependent induction of IL-12 secretion may be induced by coactivators of dendritic cells, such as LPS, in a CD40-independent manner (12). Recently, it has been shown that oral tolerization to peptide fails in the CD40 knockout mouse, resulting in strong Th1 differentiation, as determined by delayed-type hypersensitivity recall responses (13).

CD154 blockade has been shown to prevent the induction and progression of R-EAE (14–16). It is also effective in the treatment of a myriad of other autoimmune disease models, such as oophoritis (17), experimental autoimmune thyroiditis (18), lupus nephritis (19), collagen-induced arthritis (20), spontaneous autoimmune diabetes (21), and atherogenesis in hyperlipidemic mice (22). Based largely on in vitro experiments, it is thought that blockade of CD40 ligation prevents Th1 skewing (23, 24). In reality, the in vivo situation is far more complex, with many innate and adaptive cells influencing the developing immune response and controlling disease induction and progression (25). How the T cell response actually develops under the influence of CD154 therapeutic blockade in vivo is still unclear. We thus investigated the developing immune response to an encephalitogenic T cell Ag in vivo to determine whether immune modulation from Th1 to Th2 or other factors are important for disease prevention.

Our findings demonstrate that CD154 treatment in vivo only delays Th1 differentiation rather than overtly promoting Th2 differentiation. Retention of Th1 cells in the lymph nodes was markedly reduced following immunization of Ab-treated mice, and this...
coincided with a recompartmentalization of these cells to the spleen. In addition, a major mechanism by which CD154 blockade protects against autoimmune disease is by controlling the recruitment and/or expansion of effector cells within the CNS target organ.

Materials and Methods

Mice

Five- to 6-wk-old female SJL mice were obtained from Harlan Sprague-Dawley (Indianapolis, IN). Mice were housed under barrier conditions at the National Institutes of Health-approved Northwestern University Medical School animal facilities. All protocols were approved by the Northwestern University animal care and use committee. Paralyzed mice were afforded easier access to food and water. DO11.10 and SJL CD90.1 congenic mice were bred within the facility, and BALB/cAnNCr mice obtained from National Cancer Institute laboratories (Frederick, MD).

Peptides

Proteolipid protein (PLP)139–151 (HSLGKWLGHPDK) and OVA323–339 (ISQAVHAAHAEINEAGR) were synthesized by the peptide facility at University of North Carolina (Chapel Hill, NC). The amino acid compositions of these peptides were verified by mass spectrometry, and purity (>97%) was confirmed by mass spectroscopy at Michigan State University Biotechnology Center (Ann Arbor, MI).

In vivo Ab treatment

Anti-CD154 (MR-1) was produced in ascites and purified by HPLC over a DEAE column. Normal hamster serum was purchased from Harlan Laboratories (Indianapolis, IN) or Caltag (San Francisco, CA) Total cell numbers recovered were determined by use of a hemocytometer. After nonspecifically blocking the plates with 5% BSA in PBS, incubating for 5 min after each addition. Three days after transfer, the mice were primed with OVA223–239/CFA as described above. Draining lymph nodes (axillary and inguinal) and spleen cells from the primed mice were removed on day 3 after priming. For intracytoplasmic cytokine detection, cells were cultured in a 96-well microtiter plate (Nunc, Copenhagen, Denmark) at 5 × 10^6 cells/ml and stimulated for 4 h with PMA (50 ng/ml; Sigma) and ionomycin (500 ng/ml; Sigma). Two hours before harvest, brefeldin A (Sigma) was added to a final concentration of 1 μg/ml to prevent cytokine secretion. Cells were transferred in 96-well plates in 100 μl of culture medium (Amer sham) and 1% FCS). Cells were stained for cytokines by incubation for 3 h with each of the following Abs or Abs to IL-2, IL-4, IL-5, IL-10, IFN-γ, or TNP-α (BD-PharMingen). The cells were washed twice, resuspended in PBS, and analyzed on a FACScan Calibur cell analyzer (BD-PharMingen).

Identification of CNS-infiltrating T cells

Mice were anesthetized at various times after disease transfer. Mice were perfused with 60 ml of PBS, and then the spinal cords were isolated by intrathecal hydrostatic pressure. The cords were mashed on a 100-mesh screen and resuspended in 30% Percoll and 10% FCS. Cells were then spun for 15 min at 400 × g, and cells at the 30:70% interface were collected. CD4^+ T cells were then examined by flow cytometry for expression of CD90.1 (donor) and CD90.2 (host).

Results

Early in vivo Ag-specific T cell expansion is unaffected by CD154 blockade

We have previously shown that total cell recovery and in vitro Ag-specific T cell proliferation are reduced in the lymph nodes of anti-CD154-treated animals 10 days following immunization (16). One explanation for this reduction is that CD154 blockade inhibits T cell expansion within the lymph nodes. To directly determine the ability of anti-CD154 to block the proliferation of naive T cells in vivo, we examined the proliferation of CD4^+ DO11.10 transgenic T cells in an adoptive transfer system (26). Naive BALB/c recipients of CFSE-labeled transgenic cells were immunized with OVA223–239/CFA, and 3 days later the lymph node and splenic cells were harvested. Ag-specific T cell expansion was evaluated by the reduction in CFSE fluorescence with each division of the transgenic T cells. Immunization with PBS/CFA did not stimulate proliferation; thus, the transgenic cells retained a high level of CFSE fluorescence (Fig. 1A). Immunization with OVA223–239/CFA in the presence of control Ig (Fig. 1B) or anti-CD154 (Fig. 1D) resulted in rapid proliferation of up to seven cell divisions by 72 h. In contrast, as a positive control, treatment with CTLA-4 Ig (an antagonist of B7-CD28/CTLA-4 costimulation) at the time of immunization severely inhibited proliferation of the transgenic T cells. Therefore, blocking the CD154-CD40 interaction in vivo does not affect early T cell expansion in the lymph node similar to the recent observations by Howland et al. (24). Consistent with these data, we found that comparable total cell numbers were recovered from the lymph nodes and spleens of the control Ig and
anti-CD154-treated mice 3 days after immunization (data not shown). Minimal T cell expansion/proliferation was observed in the spleen at this time point regardless of treatment (data not shown).

Anti-CD154 treatment leads to recompartmentalization of the Ag-specific T cell immune response

Because we did not observe a difference in either early T cell expansion or total cell recovery in the BALB/cAnNCr mouse 3 days after immunization, we readdressed this question in relation to the effects of anti-CD154 treatment on a prolonged immune response in both SJL and BALB/cAnNCr mice. SJL mice were immunized on day 0 with the encephalitogenic PLP139–151 peptide in CFA and the absolute numbers of Ag-specific Th0 (IL-2 secretors), Th1 (IFN-γ secretors), and Th2 (IL-5 secretors) cells in the lymph node and spleen determined by ELISPOT every other day for 14 days postimmunization (Fig. 2). Mice were treated with either control Ab or anti-CD154 blocking Ab every other day from days 0–6. As previously observed in the DO11.10 transfer system (Fig. 1), within the first 4 days there was little or no difference in the total numbers of PLP139–151-specific T cells recovered from the lymph nodes or spleens of anti-CD154-treated mice as compared with controls. In contrast, as the immune response progressed, the total numbers of both IL-2- and IFN-γ-secreting cells were significantly decreased in the lymph nodes of anti-CD154-treated mice (Fig. 2, D and E). We observed a similar reduction of Ag-specific lymph node T cells in the BALB/c-DO11.10 transfer system beyond 4 days postimmunization (data not shown), as shown recently by Howland et al. (24). The numbers of peptide-specific, IL-5-secreting Th2 cells in both spleen (Fig. 2C) and lymph node (Fig. 2F) of control mice were low, but were also reduced in the lymph nodes of anti-CD154-treated mice.

Interestingly, the absolute numbers of peptide-specific Th0 and Th1 cells in the spleen showed a pattern different from that seen in the draining lymph nodes. The total numbers of PLP139–151-specific IL-2-producing cells were comparable between anti-CD154-treated and control mice throughout the 14-day time course (Fig. 2A). However, the numbers of peptide-specific Th1 cells in the spleens of anti-CD154-treated mice, although somewhat lower than control levels on days 6 and 8 postpriming, rebounded to

FIGURE 1. Early in vivo Ag-specific T cell expansion is unaffected by CD154-CD40 blockade. CFSE-labeled DO11.10 transgenic OVA23–339-specific T cells (5 × 10⁶) were transferred to groups of naive recipient BALB/cAnNCr mice. The mice were primed with either CFA alone (A) or OVA23–339/CFA (B–D). Peptide-primed mice were treated daily starting 1 day before priming with hamster control Ig (B), CTLA-4 Ig (C), or anti-CD154 (D). Three days after priming, draining lymph nodes were pooled from three mice per group, and CD4⁺, KJ1–26⁺ cells were analyzed for CFSE levels. The data shown are representative of three similar experiments.

FIGURE 2. Anti-CD154 treatment leads to recompartmentalization of the Ag-specific T cell immune response. Splenic and draining lymph node cells obtained from PLP139–151-prime SJL mice treated every other day from the time of priming until day 6 with either control Ig or anti-CD154 were taken at the indicated times postimmunization. Cells pooled from three mice per group were cultured for 24 h with PLP139–151, and an ELISPOT assay was used to determine the total number of Ag-specific T cells in the different groups. IL-2 was used to identify undifferentiated Th0 cells (A and D), IFN-γ was used to identify Th1 cells (B and E), and IL-5 was used to identify Th2 cells (C and F). Data are presented as the absolute number of each Ag-specific Th cell subset per lymphoid organ and are representative of three separate experiments for IL-2 and IFN-γ and two separate experiments for IL-5.
levels approximately twice that of controls on days 10 and 12 postimmunization (Fig. 2B). The increase in the numbers of splenic PLP_{139–151} -specific Th1 cells temporally correlated with the reduction in Th1 T cell numbers observed in the lymph nodes of anti-CD154-treated animals. This suggests that anti-CD154 treatment, instead of absolutely inhibiting long term differentiation Th1 cells, may reduce the retention of Th1 cells in the lymph nodes and/or transiently enhance their retention in the spleen.

Interestingly, if the numbers of IL-2- and IFN-γ-producing T cells are expressed as a frequency of total CD4^+ T cells over the 14-day period following immunization, a somewhat different pattern is evident (Fig. 3). The percentage of IL-2-producing cells from the spleen (Fig. 3A) and lymph nodes (Fig. 3C) of anti-CD154-treated mice did not differ significantly from that seen in controls. In contrast, there was a delay (ranging between 2 and 4 days), but not a reduction in the frequency of peptide-specific IFN-γ-producing Th1 cells in the lymph nodes of anti-CD154-treated mice (Fig. 3D). However, as seen with the absolute numbers of peptide-specific T cells (Fig. 2B), there was a transient increase in the percentage of IFN-γ-producing T cells in the spleens of anti-CD154-treated mice (Fig. 3B).

**Anti-CD154 treatment does not lead to a Th2 skewed response**

Because SJL mice are poor Th2 responders, we readdressed the possibility that anti-CD154 treatment may preferentially lead to a Th2 response using the BALB/c DO11.10 transfer system. Recipients of DO11.10 T cells were immunized with OVA_{323–337}/CFA, and frequencies of peptide-specific Th0 (IL-2), Th1 (IFN-γ and TNF-α), and Th2 (IL-4, IL-5, and IL-10) cells were determined by intracytoplasmic staining for the individual cytokines 3 days postpriming. The frequency of IL-2-secreting cells was significantly reduced in the lymph node, but was comparable in the spleens of anti-CD154-treated vs control Ig-treated animals. As observed previously in SJL mice (Fig. 3), the frequency of OVA_{323–339} -specific Th1 cells was reduced in the lymph nodes (Fig. 4A), but was enhanced in the spleens (Fig. 4B) of anti-CD154-treated BALB/c recipients. As seen previously in the PLP_{139–151} system (Fig. 2), very few Th2 (IL-4- or IL-5-producing) cells were detectable regardless of previous Ab treatment.

**FIGURE 3.** Anti-CD154 treatment delays the differentiation, but not the frequency, of Th1 cells in the draining lymph nodes. Frequencies of Th0 (IL-2) and Th1 (IFN-γ) cells were determined by ELISPOT assay as described in Materials and Methods. Th0 frequencies were largely unchanged in draining lymph node and splenic compartments in both control Ig- and anti-CD154-treated animals (A and C). Th1 differentiation was delayed in the draining lymph nodes of anti-CD154-treated animals, while the peak frequency was comparable to that in controls (D). In contrast, Th1 cells in the spleen were delayed, but appeared transiently in higher frequencies (B). The data shown are representative of three separate experiments.

**FIGURE 4.** Anti-CD154 treatment does not lead to a Th2 skewed response. DO11.10 transgenic OVA_{323–339} -specific T cells (5 × 10^6) were transferred to groups of naive recipient BALB/cAnNCr mice. The mice were primed with OVA_{323–339}/CFA. Peptide-primed mice were treated daily starting 1 day before priming with either hamster control Ig or anti-CD154. Three days after priming, draining lymph nodes (A) and spleens (B) were pooled from three mice per group. Cells were stimulated with PMA and ionomycin for 6 h and with Brefeldin A for the last 4 h as described in Materials and Methods. CD4^+, KJ1-26^+ cells were then analyzed for intracytoplasmic cytokine production by flow cytometry. The data shown are representative of three separate experiments.
indicating that immune deviation is not responsible for anti-
CD154-induced protection from clinical autoimmune disease.

Ab to CD154 inhibits T cell retention/expansion in the CNS

EAE is a complex, multistep immunopathologic process that re-
quires activation and differentiation of encephalitogenic Th1 cells,
migration of the T cells to the CNS, and local production of proin-
flammatory cytokines and chemokines that mediate the inflam-
matory demyelination. The data to this point indicate that although
anti-CD154 treatment has a profound effect on inhibiting induction
and progression of EAE (16), it does not significantly affect very
early T cell expansion and only marginally delays Th1 differenti-
ation without significantly skewing the response to a Th2 pattern.
Phenotypic analysis of DO11.10 T cells 3 days after OVA323–339/CFA
immunization showed that anti-CD154 treatment did not sig-
ificantly affect the expression of homing receptors (e.g., VLA-4,
CD44, and ICAM-1) demonstrated to be involved in trafficking of
T cells to the CNS (data not shown). Based on these findings and
our previous observation that anti-CD154 treatment impaired the
expression of clinical disease in adoptive recipients of encephali-
togenic T cells (16), we asked whether anti-CD154 therapy af-
fected CNS T cell recruitment and/or retention. SJL CD90.1 con-
genic mice were immunized with PLP139 –151/CFA. Ten days
following immunization, lymph node cells were harvested and cul-
tured with peptide for 4 days before transfer. SJL (CD90.2) recipi-
ent mice received four treatments with 200 µg of control Ig or
anti-CD154 beginning immediately after cell transfer. At varying
times post-transfer, spinal cords were harvested, and infiltrating
cells were isolated, stained for CD4 and CD90.1, and analyzed by
flow cytometry. Due to the transfer of only a limited number
(1.75 × 10⁶) of T cell blasts, detection of significant numbers of
donor CD90.1 T cells (0.6%) was first demonstrable in the spinal
cord on day 16 posttransfer (Fig. 5B). The numbers of both donor
(CD90.1⁺) and recipient (CD90.1⁻) T cells increased dramatically
by day 18 (Fig. 5C), which corresponded to the day of disease
onset in the control Ig-treated mice (data not shown). A relatively
comparable number of donor CD90.1⁺ T cells was found in the
CNS of anti-CD154-treated mice on day 16 (Fig. 5E), suggesting
that the Ab treatment did not prevent early T cell entry. However,
unlike the control mice, the percentages of donor and recipient T
cells decreased in the CNS of anti-CD154-treated mice on day 18
(Fig. 5F), indicating that anti-CD154 inhibited the retention/exp-
ansion of these cells in the target organ. Coincident with the
absence of persistent numbers of donor T cells in the CNS of
anti-CD154-treated mice, these animals did not develop clinical
EAE (data not shown).

Discussion

The CD154-CD40 interaction is critical for the induction and pro-
gression of EAE (14–16) and many other autoimmune diseases.
Because of the role of the CD154-CD40 interaction in regulating
IL-12 production, it has been proposed that the protection from
autoimmunity is due to a deviation of T cell response from a proin-
mflammatory Th1 response to an anti-inflammatory Th2 response
(23, 24). However, CD40-CD154 interactions are critical in regu-
lating many other immune cell functions (4). Here we address the
specific mechanism(s) by which clinical autoimmune disease may
be prevented by CD40 ligand blockade. The actual mechanism
appears to have little or nothing to do with Th1 to Th2 cell devi-
ation, but instead is associated with significantly reduced Ag-spe-
cific T cell responses in the lymph nodes and the prevention of
CD4 T cell effector expansion/function within the autoimmune tar-
get organ.

Unlike therapies that target the B7-CD28/CD152 costimulatory
pathways, interference with the CD40-CD154 interaction did not
inhibit the early activation and proliferation of naïve T cells in vivo
(Fig. 1). Although early T cell expansion within the lymph node is
not affected by CD154 blockade, the later progression of the im-
mune response is affected. Up to 4 days postimmunization
the expansion of Ag-specific T cells appeared normal (Figs. 2 and 3).
However, after that time there was a dramatic reduction, but not
ablative, in the continued development of the primary immune
response in the draining lymph nodes of anti-CD154-treated mice.

Engagement of CD40 is known to be a critical survival signal
for B cells (4). In the absence of CD40 ligation, B cells activated
via their B cell receptor undergo apoptosis (4). Similarly, CD40
ligation is also a survival signal for Ag-presenting dendritic cells
(6). In the absence of this event, dendritic cells also undergo ap-
optosis (6). Thus, it is likely that after 4 days of the immune re-
sponse in vivo, dendritic cell death could explain this sudden re-
duction in the normal progression of the T cell immune response.
However, it is notable that this reduction in the T cell response is
not complete and that some continued increase in the development
of the T cell response is observed in anti-CD154-treated mice. This
may be due to the fact that the Ab doses employed to treat clinical
disease do not completely prevent CD40-CD154 interactions and
that some dendritic cells survive. However, as discussed below,
long term expression of clinical disease is dramatically inhibited

FIGURE 5. Ab to CD154 inhibits T cell retention/expansion in the CNS. Disease transfers were conducted as described in Materials and Methods. Spinal cords were
harvested on the days shown, and infiltrating cells were
identified by CD4 Ab. The donor encephalitogenic T
cells were identified on the vertical axis by CD90.1 ex-
pression, which differentiates them from the host CD90.2
T cells. A minimum of four spinal cords were pooled for
each plot. The data shown are representative of four sim-
ilar experiments.
by a brief treatment with anti-CD154 (16), implying that CD154 blockade may act at multiple levels.

We also investigated whether anti-CD154 treatment led to immune deviation, resulting in skewing of the response from Th0 to Th2 instead of Th1 cells. We observed reduced overall numbers of Th1 cells in the lymph nodes employing two different systems, PLP<sub>139-151</sub> immunization of SJL mice and OVA<sub>223-339</sub> immunization using the DO11.10 TCR transgenic adoptive transfer system (Figs. 2–4). However, in neither case did we observe any significant deviation toward Th2-type cells in either the lymph node or the spleen. In fact, in both systems even fewer Th2 cells were observed in the draining lymph nodes of anti-CD154 compared with control Ig-treated mice. This suggests that the mechanism of action of CD154 blockade in preventing the induction/progression of EAE is not due to Th1 to Th2 deviation. This is supported by observations in the CD40 knockout mouse, in which both Th1- and Th2-type responses are significantly diminished or absent (4). Previous studies supporting a role for immune deviation in anti-CD154-treated or CD40 knockout mice (23, 24) showed only moderate short term increases in IL-4 secretion, as measured by ELISA in vitro. This is not supported by the current observation that fewer Th2 cells are found in Ab-treated mice. Those previous observations may be due to reduced IFN-γ secretion, resulting in less functional inhibition of IL-4 secretion by a small number of Th2 cells in the in vitro culture systems employed. Because there are very few Ag-specific Th2 cells in anti-CD154-treated mice, and Th2 cells demonstrate a reduced ability to migrate to target tissues and organs, it is unlikely that immune deviation is a major mechanism in anti-CD154 therapy of autoimmune disease.

We found that Th1 differentiation was only delayed, reaching its peak 2–4 days after that of control treated animals. This indicated that even in the presence of CD154 blockade that effectively prevented EAE, Th1 differentiation was not ablated as dramatically as previously thought (16, 23, 24). At the same time, higher absolute numbers and frequencies of peptide-specific Th1 cells were observed in the spleens of Ab-treated mice compared with controls, while Th0 cell numbers appeared equivalent. This suggests that those cells that had differentiated within the lymph node reprogrammed to the spleen.

We previously showed that anti-CD154 treatment of only recipient mice in a disease transfer model could effectively inhibit the effector phase of EAE (16). One possible explanation for this was that T cells may not gain access to the CNS in the absence of CD40 ligation. However, because murine cerebrovascular endothelial cells that line the blood-brain barrier do not express CD40, and T cells from anti-CD154-treated mice express control levels of homing molecules involved in CNS trafficking (our unpublished observations), it was puzzling how this could occur. Here we show that the initial entry of activated encephalitogenic T cells is not inhibited, but their continued retention/expansion within the CNS is blocked. Prevention of T cell recruitment of other immune effector cells to that target organ via CD40/CD154 regulation of chemokine gradients and/or the expansion of the effector T cells within the target organ appears to be a major mechanism by which CD154 blockade prevents the induction/expression of EAE.

Once disease-initiating encephalitogenic T cells get into the CNS, they may require CD154 expression to up-regulate MHC class II on the resident CNS microglial APCs or infiltrating macrophages, which have been shown to play an effector role in EAE (27). CD40 ligation has been shown to up-regulate class II as well as costimulatory molecule CD80/CD86 expression by macrophages (6), and we speculate that without CD40 ligation within the target organ, Ag-specific T cell expansion cannot occur, as we failed to observe the large increase in T cell numbers observed in control mice (Fig. 5). Furthermore, astrocytes, microglia, and CNS-infiltrating macrophages have been implicated in the secrerion of chemokines necessary for T cell recruitment to the CNS (28). Because CD40 ligation has been shown to induce chemokine secretion (29, 30), it is possible that this is another factor in disease prevention. Finally, proinflammatory cytokines, reactive oxygen species, NO, as well as some matrix metalloproteinases are induced by CD40 engagement on macrophages (31, 32). Thus, these effector molecules may also be inhibited by CD154 blockade. We are currently investigating how these events are affected by CD154 blockade within the CNS during ongoing EAE.

For the first time, we quantitate how the overall T cell immune response develops in varying lymphoid compartments during Ab blockade of the CD154-CD40 ligand pair interaction, which is an effective treatment in many autoimmune disease models. Therapeutic intervention apparently has little to do with early Th1 to Th2 deviation or overall long term reduction in Th1 responses, although the amplitude of the Th1 response leading up to the acute phase of disease is diminished. Whether Th modulation is associated with long term prevention of disease by CD154 blockade is currently under investigation. Rather, CD40/CD154 interactions appear to be critical for recruitment to and/or expansion of Ag-specific T cells within the target organ. Thus, although activated encephalitogenic T cells can apparently initially access the CNS, their retention/expansion and their ability to recruit additional inflammatory cells are blocked.

Acknowledgments
We thank Dr. Randolph J. Noelle for generously supplying MR1 anti-CD154 mAb and for his critical review of this paper.

References


