Kit (W-sh) Mice Develop Earlier and More Severe Experimental Autoimmune Encephalomyelitis Due to Absence of Immune Suppression

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*J Immunol* published online 6 June 2011

http://www.jimmunol.org/content/early/2011/06/06/jimmunol.1003603
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Mast cells (MCs) have been thought to play a pathogenic role in the development of autoimmune diseases, including experimental autoimmune encephalomyelitis (EAE), an animal model of multiple sclerosis. However, an immunoregulatory function of these cells has recently been suggested. We investigated the role of MCs in EAE using the W-sh mouse strain, which is MC deficient. W-sh mice developed earlier and more severe clinical and pathological disease with extensive demyelination and inflammation in the CNS. The inflammatory cells were mainly composed of CD4+ T cells, monocyte/macrophages, neutrophils, and dendritic cells. Compared with wild-type mice, MC-deficient mice exhibited an increased level of MCP-1/CCR2 and CD44 expression on CD4+ T cells in addition to decreased production of regulatory T cells, IL-4, IL-5, IL-27, and IL-10. We also found that levels of IL-17, IFN-γ, and GM-CSF were significantly increased in peripheral lymphocytes from immunized W-sh mice compared with those in peripheral lymphocytes from wild-type mice. Reconstitution of W-sh mice downregulated susceptibility to EAE, which correlated with MC recruitment and regulatory T cell activation in the CNS. These findings indicate that responsiveness is not required in the pathogenesis of immunoregulatory demyelination in the CNS, and that, in the absence of MCs, increased MCP-1, CCR2, IL-17, IFN-γ, CD44, and other inflammatory molecules may be responsible for increased severity of EAE.

Received for publication November 1, 2010. Accepted for publication May 3, 2011.

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Abbreviations used in this article: DC, dendritic cell; EAE, experimental autoimmune encephalomyelitis; MC, mast cell; MNC, mononuclear cell; MOG135–151, peptide 135–151 of myelin oligodendrocyte glycoprotein; MS, multiple sclerosis; p.i., postimmunization; Treg, regulatory T cell.

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www.jimmunol.org/cgi/doi/10.4049/jimmunol.1003603
Materials and Methods

Mice and EAE induction

Eight- to ten-week-old female C57BL/6, Kit$^{W^sh}$/Kit$^{W^sh}$ (W-sh) mice and their wild-type controls were purchased from The Jackson Laboratory (Bar Harbor, ME). To induce EAE, mice were injected s.c. with/without 200 $\mu$g of peptide 35–55 of myelin oligodendrocyte glycoprotein (MOG35–55) in CFA containing 4 mg/ml Mycobacterium tuberculosis H37Ra (Difco, Detroit, MI) at two sites on the back. Two hundred nanograms of pertussis toxin was given i.v. on days 0 and 2 postimmunization (p.i.). EAE was scored according to a 0–5 scale as follows (24): 1, limp tail or waddling gait with tail tonicity; 2, waddling gait with limp tail (ataxia); 2.5, ataxia with partial limb paralysis; 3, full paralysis of one limb; 3.5, full paralysis of one limb with partial paralysis of second limb; 4, full paralysis of two limbs; 4.5, moribund; and 5, death. All work was performed in accordance with the guidelines for animal use and care at Thomas Jefferson University.

Histopathology

On day 18 p.i., mice were extensively perfused, and spinal cords were harvested. Five-micrometer sections were stained with H&E or Luxol fast blue (myelin stain). Slides were assessed in a blinded fashion for inflammation and demyelination (25). For inflammation, the following scale was used: 0, none; 1, a few inflammatory cells; 2, organization of perivascular infiltrates; and 3, increasing severity of perivascular cuffing with extension into the adjacent tissue. For demyelination, the following scale was used: 0, none; 1, rare foci; 2, a few areas of demyelination; and 3, large (confluent) areas of demyelination.

Intracellular cytokine staining and FACS analysis

Mononuclear cells (MNCs) from the spinal cords and brain were isolated as previously described (25). Pooled cells were washed in FACS buffer. After blocking with CD16/CD32 mAb, cells were incubated with Abs to murine CD3, CD4, CD8, CD11b, CD11c, CD45, CD44, Gr-1, and CD11a (all from BD Pharmingen, San Jose, CA). To determine T cell phenotype (Th1, Th2, Th17, and Treg), CD4$^+$ T cells that produced IFN-$\gamma$, IL-4, and IL-17 and expressed Foxp3 were analyzed by flow cytometry. MNCs were stimulated with 15 $\mu$g/ml MOG35–55 peptide for 72 h and restimulated with 50 ng/ml PMA and 750 ng/ml ionomycin for the last 4 h in the presence of 10 $\mu$g/ml brefeldin A. Intracellular cytokine staining (26) and Foxp3 staining were performed as described (25, 27). Cells were analyzed by FACSia flow cytometer (Becton Dickinson), and data obtained were analyzed by FlowJo software (Tree Star).

Cytokine production and proliferation assay

Suspensions of MNCs from the spleen were prepared on day 10 p.i. Cells were cultured at a density of 2.5 $\times$ 10$^6$/ml in medium containing MOG35–55 at final concentrations of 10 $\mu$g/ml, Con A at 5 $\mu$g/ml, or without Ag/mitogen. Supernatants were collected after 48 h. Quantitative ELISA for IFN-$\gamma$, GM-CSF, IL-4, IL-5, IL-10, IL-17, and MCP-1 was performed using paired mAbs according to the manufacturer’s recommendation (BD Biotech).
Pharmingen). To analyze MCP-1 production, spinal cord and supernatants of homogenized spinal cords were prepared as described (28) and MCP-1 levels were quantified using ELISA. To determine IL-17A, IL-27p28, and CCR2 mRNA expression, freshly isolated splenocytes were assayed using real-time PCR, with β-actin expression serving as control. Relative expression was calculated following the previously described protocol (25).

For proliferation, cells were cultured in triplicate with MOG35–55 (25 μg/ml), Con A (5 μg/ml), or without Ag/mitogen. After 60 h of incubation, cells were pulsed for 12 h with 1 μCi [3H]thymidine, were harvested, and [3H]thymidine incorporation (cpm) was read using a β counter. The results were expressed as stimulation index, which was calculated by dividing the cpm from culture in the presence of Ag or mitogen by the cpm from culture without Ag/mitogen.

Transfer of bone marrow-derived MCs in W-sh mice

To prepare bone marrow-derived MCs, bone marrow cells from wild-type mice were differentiated for 5 wk in the presence of mouse IL-3 and stem cell factor (both from PeproTech, Rocky Hill, NJ) as previously described (29). The purity of MCs was 98.7% as determined by CD117+Flt3R-1α expression using flow cytometry. To observe the effect on EAE of transferring MCs in MC-deficient mice, MCs (5 × 10^6 per mouse) were injected by tail vein injection into W-sh mice before onset of EAE. Clinical signs were scored according to a 0–5 scale as described (24).

Statistics

Clinical scores were analyzed using the Mann–Whitney U test, and all other experiments were tested for statistical differences using unpaired, two-tailed, Student t tests. Differences were considered significant if p < 0.05.

Results

Increased susceptibility to EAE in MC-deficient W-sh mice

To investigate the role of MCs in the pathogenesis of EAE, we immunized W-sh mice and their wild-type controls with MOG35–55 peptide in CFA. Chronic progressive EAE was observed in

![FIGURE 2. Pattern of cellular infiltrates in spinal cords of wild-type and W-sh mice. A, Flow cytometric analysis.](http://www.jimmunol.org/)

<table>
<thead>
<tr>
<th>Cell number (×10^4) per spinal cord</th>
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<td>CD8</td>
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<td>W-sh</td>
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<tr>
<td>CD4</td>
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<td>W-sh</td>
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A. Flow cytometric analysis. On day 18 p.i., mice were extensively perfused, and spinal cords were harvested and pooled for each mouse group (n = 4 in wild-type mice and n = 5 in W-sh mice). Total numbers of CD4+ and CD8+ T cells were calculated by multiplying the percentage of total cell numbers in spinal cord. B and C. For infiltrating macrophages (CD11b+CD45high) and neutrophils (Gr-1+ CD45high), CD45high cells were gated, and their expression of CD11b (B) and Gr-1 (C) were determined. D. Percentages of CD11b+CD11c+ and CD8α+CD11c+ DC subsets in spinal cord of wild-type and W-sh mice. One representative experiment of two is shown. *p < 0.05, **p < 0.01.
immunized wild-type mice. No mice from this group \( (n = 15) \) died or were moribund during the time of observation. In contrast, \( \text{W-sh} \) mice developed earlier and more severe EAE (Fig. 1A). Two of 13 mice in the \( \text{W-sh} \) group were moribund at day 17 p.i. The difference in both time of EAE onset and clinical scores between the two groups was significant (both \( p < 0.01 \)). However, \( \text{W-sh} \) mice injected with the mixture CFA, pertussis toxin, \( M. \) \text{tuberculosis} H37Ra, but omitting MOG35–55, did not develop EAE (data not shown).

\textbf{Severe inflammatory demyelination characterizes EAE in \( \text{W-sh} \) mice}

Consistent with clinical signs, typical MNC infiltration and demyelination foci were observed in the white matter of the spinal cord of both wild-type (Fig. 1B, 1C) and \( \text{W-sh} \) (Fig. 1D, 1E) mice. Inflammation scores were 1.8 ± 0.3 in wild-type mice versus 2.7 ± 0.1 in \( \text{W-sh} \) mice \((p < 0.05)\), and demyelination scores were 1.6 ± 0.1 versus 2.6 ± 0.2 \((p < 0.05)\); Fig. 1F). More severe inflammatory infiltration in \( \text{W-sh} \) mice was further demonstrated by the significantly increased total number of CNS-derived MNCs \((2.8 \times 10^7/\text{spinal cord} \text{ versus } 1.1 \times 10^7 \text{ in wild-type mice})\). These MNCs included increased CD4+ and CD8+ T cells (Fig. 2A), macrophages (CD11b+CD45hi, 22.4% in \( \text{W-sh} \) versus 7.9% in wild-type mice; Fig. 2B), and neutrophils (Gr-1+CD45hi; Fig. 2C). The numbers of CNS dendritic cells (DCs), which included both CD8α+CD11c+ and CD11b+CD11c+ cells, were increased in \( \text{W-sh} \) mice compared with those in wild-type mice (Fig. 2D). Thus, a clear correlation was found between clinical and pathological features of EAE in wild-type and \( \text{W-sh} \) mice.

\textbf{Increased proliferative responses to autoantigen and production of proinflammatory cytokines in \( \text{W-sh} \) mice}

At day 10 p.i., a MOG35–55-specific proinflammatory response was observed in spleen-derived lymphocytes from wild-type mice. This response was characterized by vigorous MOG-induced proliferation and production of inflammatory cytokines. In \( \text{W-sh} \) mice, which developed more severe EAE, a significantly higher proinflammatory response was observed compared with that in wild-type mice, including increased proliferation of specific T cells to MOG \((p < 0.05; \text{Fig. 3A})\), high levels of proinflammatory cytokines IFN-γ, GM-CSF, and IL-17 (Fig. 3B), and increased IL-17 mRNA expression \((6\text{-fold higher in } \text{W-sh} \text{ mice than that in wild-type mice}; \text{Fig. 3C})\). In contrast, \( \text{W-sh} \) mice exhibited significantly decreased production of Th2 cytokines IL-4 and IL-5 \((p < 0.05)\) and IL-10 \((p < 0.001)\) (Fig. 3B). Expression of the p28 subunit of IL-27 was also significantly lower in \( \text{W-sh} \) mice than in wild-type mice \((p < 0.05; \text{Fig. 3C})\). Thus, \( \text{W-sh} \) mice exhibited a bias toward proinflammatory response to autoantigen.

\textbf{Th17 versus Treg responses in \( \text{W-sh} \) mice}

By intracellular staining, we found that the percentage of Th17 cells \((\text{CD4}^+\text{IL-17}^+)\) in the CNS was significantly increased in \( \text{W-sh} \) mice compared with that in wild-type mice \((12.4 \pm 2.2 \text{ versus } 5.9 \pm 0.5; p < 0.05)\) (Fig. 4A). In contrast, the CD4+Foxp3+ population in the CNS was decreased from 6.4% in wild-type mice to 3.1% in \( \text{W-sh} \) mice (Fig. 4B). The percentage of Foxp3+ cells in gated CD4+ T cells was analyzed at different time points of EAE (Fig. 4C). We concluded that enhanced severity of EAE in \( \text{W-sh} \)
mice is associated with increased responses of self-reactive T cells and lower proportions of Tregs.

W<sup>sh</sup> cells express higher MCP-1/CCR2 and adhesion molecules

To define the mechanism underlying enhanced CNS infiltration in W<sup>sh</sup> mice, we determined the production of MCP-1 and the expression of its receptor CCR2, a chemokine/receptor system that is involved in cell infiltration into the CNS (30, 31). CD44 and CD11a are adhesion molecules required for the entry of encephalitogenic T cells into the CNS (32). Although both molecules are expressed at low levels in naive T cells, activated T cells express demonstrably higher levels. Consistent with the increased severity of clinical EAE, we found significantly increased MCP-1 production and CCR2 expression (Fig. 5A) at day 10 p.i., the peak of peripheral T cell responses in wild-type mice. A significantly higher proportion of CD44<sup>hi</sup>CD4<sup>+</sup> T cells was also observed in W<sup>sh</sup> mice compared with that in wild-type controls, and there was no significant difference in CD44<sup>hi</sup>CD8<sup>+</sup> T cells (data not shown). There was no difference in CD11a expression between the two mouse strains (data not shown).

Transfer of bone marrow-derived MCs suppresses clinical EAE in MC-deficient mice

To confirm the in vivo regulatory function of MCs, we generated MCs from bone marrow (Fig. 6A) and transferred them into naive W<sup>sh</sup> mice before onset of EAE (Fig. 6B). Clinical EAE was suppressed in these reconstituted mice. Proliferative capacity of CD4<sup>+</sup> T cells was downregulated in reconstituted W<sup>sh</sup> mice (Fig. 6C). Consistent with the clinical scores, splenocytes of MC-transferred mice produced significantly lower levels of MOG<sub>35–55</sub>-induced IL-17 and IFN-γ but higher IL-10 (Fig. 6D) and MC (c-Kit<sup>+</sup>CD45<sup>hi</sup>) accumulation in the spinal cord (Fig. 6E), accompanied by increased repopulation of Tregs in the CNS (Fig. 6F). These data provide direct evidence that MCs possess immunoregulatory properties.

Discussion

In this study, we report that MC-deficient W<sup>sh</sup> mice develop more severe MOG<sub>35–55</sub>-induced EAE, which is characterized by earlier onset, more severe paralysis, and more extensive demyelination and inflammatory infiltration than were observed in MC-sufficient mice. W<sup>sh</sup> mice exhibited elevated proliferative responses to auto-antigen, increased production of proinflammatory cytokines/chemokines GM-CSF, IFN-γ, IL-17, and MCP-1, increased expression of CD44<sup>hi</sup>CD4<sup>+</sup> T cells and CCR2 on MNCs, and decreased levels of anti-inflammatory cytokines IL-4, IL-5, and IL-10. These observations suggest an immunoregulatory role for MCs in the pathogenesis of CNS inflammatory demyelination.

MCs are classically known for their role in Th2-type immune responses including allergic inflammation, asthma, and anaphylaxis. Heterogeneous MCs can produce an array of both pro- and anti-inflammatory mediators (33), which are known to polarize T cell differentiation to Th1 (IFN-γ, IL-12), Th2 (IL-4, IL-13), Th17 (IL-6, TGF-β), and Tregs (IL-10, IL-2, TGF-β) (3, 14). Moreover, MCs are required for limiting leukocyte infiltration that associated with skin pathology (34). MCs can mediate the development of T cell tolerance through the release of soluble mediators (34–36). These reports implicate MCs in an ever-
The observation of a greater number of infiltrating cells in the CNS of W-sh mice raises the possibility that MCs may negatively regulate chemokine/chemokine receptor expression. To study this possibility, we determined the expression of MCP-1 in spleen and the CNS and its receptor CCR2, both of which are upregulated in EAE and MS lesions (55). Although it has been reported that MCP-1 might have an immunoregulatory property (56), the observation that mice lacking MCP-1 exhibited decreased severity of EAE directly supports an immunoregulatory role of this molecule in EAE (57). MCP-1 present in brain endothelial cells contributes to increased brain endothelial permeability (58). Consistent with the increased severity of clinical EAE, we found significantly increased MCP-1 production and CCR2 expression (Fig. 5) in W-sh mice. Our results are in agreement with the observation that CCR2−/− mice did not develop clinical EAE or CNS histopathology and showed a significant reduction in T cells and CNS-infiltrating monocyte subpopulations (30, 31). As CCR2 is an important determinant of DC migration and localization (59, 60), increased CCR2 would result in more profound DC infiltration in the CNS. Together, these data suggest that upregulation of CCR2 and MCP-1 in W-sh mice may promote upregulation of DC infiltration in the CNS, thus enhancing autoimmune inflammatory infiltration.

MCs are present in small numbers within secondary lymphoid organs, and their number increases in lymph nodes in response to immune challenge (4, 13). It has been recently observed that the number of MCs increases in bone marrow biopsy specimens in parallel with the increase of Tregs (61). An increased MC population in Treg-rich lymphoid infiltrates suggests that Tregs recruit and activate MCs in situ (15, 61). It has been shown that transfer of Tregs enhanced survival, resulting in a marked increase in the number of MCs in the peritoneal cavity (62). Fujita et al. (63) demonstrated that IFN-α treatment of FcεRI-activated human MCs caused a shift from TNF to an enhanced production of IL-10 and TGF-β by T cells, with a concomitant decrease in OX40L expression. IL-10 and TGF-β affected Treg differentiation and effector function (64) and induced alloreactive CD4+CD25+ T cells to acquire regulatory cell function (65). At the same time, the decrease in OX40L expression may stabilize Treg lineage commitment and their suppressive activity (11). Also, another study has reported that MC deficiency can directly downregulate expansion of Tregs (10). In this study, we verified that the T cell compartment of naive W-sh mice was intact and that there were no intrinsic differences in T cell development in the thymus or in peripheral T cell populations compared with their wild-type counterparts (data not shown). It was only after MOG35–55 immunization that the enhancement in T cell responses and decreased Foxp3 expression in infiltrating CD4+ T cells in W-sh mice were evident. These data confirm a role for MCs in the generation of Ag-specific T cell responses in vivo and are consistent with the report that MCs play a regulatory role in inflammation and autoimmune diseases (15–17). Further, we found that the proportion of CD44hi cells was significantly higher on CD4+ T cells in splenocytes of W-sh mice at early time points p.i. Thus, the characterization of peripheral immune-cell cytokine response to MOG35–55 demonstrated that W-sh mice generate enhanced effector T cell responses, with simultaneous reduction in antagonizing anti-inflammatory responses. These results, together with observations from others (15, 37), suggest that MCs play an important role in regulating T cell functions.

IL-4, IL-13, IL-5, and IL-6 have been localized to MCs at both the protein and mRNA levels. MCs have been named as the source of the large majority of these cytokines (66–68). It has been reported that heterogeneity in MCs is based on cytokine...
MCs release Th2 cytokines independent of T cell help (70). However, although T cells are known to be an important source of cytokines, they require activation and, in the case of Th2 cells, priming with IL-4 before they can release them (71, 72). Moreover, Anderson et al. (73) showed that MCs can skew the development of a Th2-like immune response before Ag-mediated activation. Thus, the early onset and severe disease in W-sh mice may explain, at least in part, the decreased Th2 immune response in these mice.

The difference between our results and those of Secor et al. (19) may be due to differences in the MC-deficient mouse strains used. In addition to MC deficiency, the reduced c-Kit function in W/Wv mice results in many other phenotypic abnormalities. These include macrocytic anemia, impaired melanogenesis, a virtual lack of interstitial cells of Cajal, and a decline in the number of intestinal TCRγδ intraepithelial lymphocytes with age. W/Wv mice also develop a high incidence of spontaneous inflammation, such as dermatitis (74). These abnormalities may result in unexpected immune deficits and skew conclusions, including these in EAE. Recently, W-sh mice have been used as a model for studies of MC function in vivo (75). Phenotypic characterization of W-sh mice indicates that they have more circulating neutrophils and an enlarged spleen (76, 77). In the spleen, W-sh animals have abundant neutrophils, more F4/80+ cells (macrophages) and megakaryocytes, while showing a normal number of DCs (76). In the bone marrow cell population, W-sh animals also show more of both CD45+ and F4/80+ cells. Therefore, the data presented by Secor et al. (19) and those of the current study cannot be directly compared because they relate to the role played by MC. Indeed, it has been recently found that W/Wv mice are resistant to anti-collagen/LPS-induced arthritis, whereas W-sh mice are susceptible, suggesting that other host differences determine the extent of MC involvement (37).

Given that both neutrophils and macrophages play a key role in the pathogenesis of EAE (78), hematopoietic changes between MC-deficient strains could make a difference. Depletion of MC in WBB6 could not influence neutrophil or monocyte recruitment, whereas in W-sh, MCs could allow for a stronger reaction of effector T cells, which may be phagocyte mediated. The absence of MCs in W-sh animals may, for example, allow a more active neutrophilic (or macrophagic) reaction.
In summary, we found that MCs have a suppressive role in EAE. Mechanisms underlying more severe CNS inflammation include increased generation of Th17 cells and production of pro-inflammatory cytokines, elevated MCP-1/CCR2 expression, decreased production of anti-inflammatory cytokines IL-4, IL-5, IL-10, and IL-27, and decreased numbers of CD4+Foxp3+ Tregs. The demonstration that the absence of MCs can enhance the severity of EAE should encourage further study of these cells in experimental and human autoimmunity.

Acknowledgments
We thank Katherine Regan for editorial assistance.

Disclosures
The authors have no financial conflicts of interest.

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4. Dietsch, G. N., and D. J. Hinrichs. 1989. The role of mast cells in the elicitation of experimental and human autoimmunity. The demonstration that the absence of MCs can enhance the severity of EAE should encourage further study of these cells in experimental and human autoimmunity.

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