Multiple sclerosis (MS) is an inflammatory disease of the CNS that is characterized by BBB dysfunction and has a much higher incidence in females. Compared with other strains of mice, EAE in the SJL mouse strain models multiple features of MS, including an enhanced sensitivity of female mice to disease; however, the molecular mechanisms that underlie the sex- and strain-dependent differences in disease susceptibility have not been described. We identified sphingosine-1-phosphate receptor 2 (S1PR2) as a sex- and strain-specific, disease-modifying molecule that regulates BBB permeability by destabilizing adherens junctions. S1PR2 expression was increased in disease-susceptible regions of the CNS of both female SJL EAE mice and female patients with MS compared with their male counterparts. Pharmacological blockade or lack of S1PR2 signaling decreased EAE disease severity as the result of enhanced endothelial barrier function. Enhanced S1PR2 signaling in an in vitro BBB model altered adherens junction formation via activation of Rho/ROCK, CDC42, and caveolin endocytosis-dependent pathways, resulting in loss of apicobasal polarity and relocation of abluminal CXCL12 to vessel lumina. Furthermore, S1PR2-dependent BBB disruption and CXCL12 relocation were observed in vivo. These results identify a link between S1PR2 signaling and BBB polarity and implicate S1PR2 in sex-specific patterns of disease during CNS autoimmunity.

Introduction

Multiple sclerosis (MS) is an autoimmune, demyelinating disease of the CNS that has a strong sex bias, with the female to male ratio currently ranging from 3:1 to 4:1 (1–3). Relapsing-remitting MS (RRMS), the most common form of the disease in women and men, is a condition in which recurrent relapses of new neurological dysfunction (relapses) are separated by periods of clinical stability. The mechanisms underlying sex differences in MS and whether they predominantly affect immune responses, CNS susceptibility to inflammation, or both are unclear.

EAE in the inbred SJL mouse strain is commonly used to model the sexual dimorphism observed in MS. Female SJL mice exhibit increased sensitivity to EAE and a relapsing-remitting phenotype, while male SJL mice exhibit monophasic disease resembling EAE induced in both sexes of other mouse strains, such as C57BL/6. Gonadal hormones and epigenetic regulation of sex chromosomes are postulated to contribute to sex differences in SJL mice during EAE and other autoimmune disorders (4, 5). Several studies also indicate that the CNS itself may be responsible for the observed sex differences in disease expression, primarily via alterations in endothelial cell–mediated regulation of immune cell entry (6–9).

Studies of endothelium in peripheral organs implicate cadherins and sphingosine-1-phosphate (S1P) signaling in mediating alterations in cadherin-dependent barrier properties between endothelial cells (10). Cadherins are plasma membrane proteins associated with adherens junctions (AJs), whose expression at cell-cell contacts depends on endocytic transport (11–13). Vascular endothelial–cadherin (VE-cadherin) expression is required for CNS endothelial polarity and vascular lumen organization (14), and cytokine-mediated alterations in VE-cadherin expression in CNS endothelium influence leukocyte entry (15, 16). S1P, a bioactive metabolite of sphingolipids, is produced by erythrocytes in the plasma, vascular and lymphatic endothelial cells, and neuronal lineage cells within the CNS (17–19). S1P signals via 5 G protein–coupled receptors (S1PRs) to regulate various physiological responses, including vascular permeability (20–22). Endothelia express different combinations of S1P receptors (S1PRs), which regulate endothelial cell survival, migration, AJ assembly, and barrier integrity (20, 21, 23). S1PRs have received considerable attention in the MS field due to recent success with the broad S1PR inhibitor, fingolimod (FTY720-phosphate), which binds to S1PR subtypes S1PR1, S1PR3, S1PR4, and S1PR5 but not S1PR2 (24), and inhibits vascular endothelial cell growth factor–induced vascular permeability in vivo (22). Several in vivo studies demonstrate roles for S1PR2 in vascular biology, including regulation of portal vein pressure (25), the formation of atherosclerotic plaques (26), inflammation (27), and retinal angiogenesis (28). In vitro studies implicate S1PR2 in the regulation of vascular integrity via phosphorylation of VE-cadherin, preventing its translocation to cell-cell contact sites (29). The expression or function of S1PR2 at endothelial barriers within the CNS or during induction of CNS autoimmunity has not been investigated.

Here, we identify a sexually dimorphic target for the treatment of relapsing-remitting CNS autoimmunity. Microarray analysis of specimens from naive male and female adult SJL mice revealed
a significant increase in the expression of S1PR2 in disease-susceptible CNS regions only in females. Expression and activity of S1PR2 were associated with decreased VE-cadherin at AJs and reversal of endothelial cell polarity, as assessed by movement of S1PR2 to lumenal locations exclusively in white matter compared with naive male SJL mice, S1PR2-deficient mice and their wild-type controls, which are devoid of S1PR2 and do not alter BBB permeability in naive SJL mice. In female mice, fluorescein permeability was significantly increased in the cerebella of naive female SJL mice compared with that in male SJL mice (P < 0.01) (Figure 1D). Similar to wild-type B6 mice, S1PR2-deficient mice and their wild-type controls, which are both on a 129S/B6 background, do not exhibit sexual dimorphism in S1PR2 expression and deficiency of S1PR2 does not alter BBB permeability in naive animals (Supplemental Figure 1B). Immunohistochemical detection of extravasated albumin in CNS white matter of naive SJL mice was also observed in the spinal cord, which is a disease-susceptible CNS region in SJL mice. In addition, alterations in levels of claudin 5, as assessed

**Table 1**

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<th>Gene symbol (sexually dimorphic)</th>
<th>Fold change (female vs. male)</th>
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Summary of sexually dimorphic genes or loci in SJL cerebella (CB) and frontal cortices (CTX) and chromosome locations. Four novel autosomal loci were differentially expressed in the female cerebella (shown in bold).

**Results**

Whole transcriptome analyses of sexually dimorphic gene sets elevated S1PR2 in disease-susceptible CNS regions in naive female SJL mice. The inbred SJL mouse strain has been used as a model of the sexual dimorphism observed in MS, as female SJL mice are more susceptible to EAE than male SJL mice and exhibit a relapsing-remitting disease pattern similar to that observed in patients with MS (33). We hypothesized that sexual dimorphism in this MS model arises from sexually dimorphic and CNS-region specific expression of genes that regulate BBB permeability and leukocyte entry. Thus, we used a whole transcriptome microarray to identify sexually dimorphic RNA transcripts that are differentially expressed in disease-susceptible versus nonsusceptible CNS regions of male and female SJL mice. Profiling total RNA from the cerebella and frontal cortices of naive female SJL mice versus male SJL mice revealed differential expression of 44 and 23 gene transcripts, respectively, with 20 being unique to the cerebellum (Table 1 and Supplemental Table 1; supplemental material available online with this article; doi:10.1172/JCI73408DS1). Sixteen of these transcripts have uncharacterized genetic function and are only identified by their locus link or RIKEN database numbers (Supplemental Table 1). Fifteen of these uncharacterized loci are linked to the Y chromosome, and one is autosomal. The 3 loci that were dimorphic in both cortex and cerebellum are linked to the X or Y chromosomes, including Xist, which regulates X-chromosome inactivation (Table 1). Of the 4 novel autosomal loci that were unique to the cerebellum, 2 were of interest for autoimmune disease: the IL-20 receptor b, a receptor associated with skin autoimmune diseases (34–37), and sphingosine-1-phosphate receptor 2 (S1PR2), which regulates vascular permeability in peripheral organs (refs. 29, 38, 39, and Figure 1A). Because S1PR2 belongs to a family of G protein-coupled receptors expressed by cells of the vascular, immune, and nervous systems and S1PR2 signaling, in particular, disrupts endothelial AJ's, we focused our studies in CNS autoimmunity on this protein (29). Quantitative PCR (QPCR) evaluation of sexually dimorphic expression of S1PR2 in cerebella of SJL mice validated microarray results (P = 0.0255) (Figure 1B). Western blot analysis confirmed microarray and QPCR data, revealing significantly enhanced expression of S1PR2 in the cerebella of naive female SJL mice compared with that in male SJL mice (P < 0.05), while no sexual dimorphism was observed in naive C57BL/6 mice (Figure 1C), and whole brain extracts from S1PR2-deficient mice confirmed antibody specificity (Supplemental Figure 1A). Of interest, Western blot examination of S1PR2 levels within the cerebella of naive SJL-Chr YB10.5 male mice compared with those of SJL male and female mice did not suggest that a Y-chromosome polymorphism (40) is responsible for sexually dimorphic S1PR2 expression in the CNS of SJL mice (Supplemental Figure 2).

Because S1PR2 has known roles in vascular biology, we assessed disruption of the BBB, via administration of sodium fluorescein to naive male and female animals of both B6 and SJL backgrounds. Consistent with increased S1PR2 expression in the cerebella of naive female SJL animals, fluorescein permeability was significantly increased in the cerebella of naive female SJL mice compared with that in male mice (P < 0.01) (Figure 1D). Similar to wild-type B6 mice, S1PR2-deficient mice and their wild-type controls, which are both on a 129S/B6 background, do not exhibit sexual dimorphism in S1PR2 expression and deficiency of S1PR2 does not alter BBB permeability in naive animals (Supplemental Figure 1B). Immunohistochemical detection of extravasated albumen in CNS white matter of naive SJL mice also exhibited sexual dimorphism (Figure 1E). Of note, sexual dimorphism in S1PR2 expression and vascular permeability was not observed in the spinal cord, which is a disease-susceptible CNS region in SJL mice. In addition, alterations in levels of claudin 5, as assessed
by Western blotting, did not exhibit sexual dimorphism in naive B6 or SJL mice (Supplemental Figure 3). Immunohistochemistry (IHC) analysis of cellular sources of S1PR2 in the CNS of naive female and male SJL mice revealed localization mostly along endothelial cells, with some astrocytes and pericytes as additional sources (Figure 2).

Female SJL mice and humans exhibit increased vascular S1PR2 during CNS autoimmunity. To assess sexually dimorphic alterations in BBB permeability during CNS autoimmunity, we administered sodium fluorescein to male and female animals of both B6 and SJL backgrounds after induction of EAE via immunization with appropriate myelin peptides. During the course of EAE, fluorescein permeability increased in all CNS regions in both sexes and strains, with significantly higher permeability in female SJL mice compared with that in male SJL mice at peak of disease and during remission in cortices (peak: \( P < 0.05 \); remission: \( P < 0.05 \)) and cerebella (peak: \( P < 0.05 \); remission: \( P < 0.001 \)) (Figure 3A). Expression of S1PR2 was also sexually dimorphic during EAE, as S1PR2 expression was increased in disease-susceptible regions (cerebella: \( P < 0.05 \); spinal cord: \( P < 0.001 \)) in female SJL mice at peak of EAE, with no detectable differences in cortices (Figure 3B). Again, no such sexual dimorphism was observed in C57BL/6 mice. Although ovariectomy and estrogen exposure affect disease in female SJL mice (33, 41–45), levels of S1PR2 expression in all CNS regions of naive female SJL mice or of female SJL mice immunized with proteolipid protein epitope 139–151 (PLP 139–151) were unaffected by ovariectomy, with or without 17\( \beta \)-estradiol replacement (Supplemental Figure 4). Of note, sham-ovariectomized and ovariectomized mice were evaluated when they attained clinical scores of 2, whereas ovariectomized mice treated with 17\( \beta \)-estradiol did not develop symptomatic EAE. Thus, suppression of clinical symptoms by 17\( \beta \)-estradiol in PLP 139–151–immunized mice did not affect CNS levels of S1PR2 expression. These data are also consistent with studies demonstrating that 17\( \beta \)-estradiol does not affect systemic inflammation in the setting of active immunization (41).
S1PR2 immunoreactivity was localized to endothelium, vessel-associated astrocytes, and occasional pericytes within the CNS of SJL mice with EAE (Figure 3C) and within human post-mortem cerebellar specimens derived from patients with and without MS (Supplemental Table 2 and Figure 4, A and B). Furthermore, quantitative IHC assessment of human specimens showed significantly higher levels of vessel-associated S1PR2 in patients with MS compared with that in patients without MS \((P = 0.01)\) and a trend toward increased S1PR2 expression in female patients with MS compared with that in male patients with MS (Figure 4C). Of interest, the highest levels of S1PR2 expression in female patients with MS were in those with RRMS (2 cases), and the 1 male patient with high levels of S1PR2 had a history of occipital head trauma. These results suggest that S1PR2 may play a role in sexually dimorphic patterns of BBB dysfunction in the setting of CNS autoimmunity.

Clinical disease severity and BBB permeability during EAE are reduced by pharmacologic or genetic inactivation of S1PR2. To investigate whether S1PR2 modulates the pathogenesis of EAE, we evaluated clinical disease scores in the setting of both pharmacologic blockade and genetic deletion of S1PR2. Female SJL mice treated with the specific S1PR2 antagonist JTE-013 \((1.5 \text{ mg/kg})\) (46), beginning when mice reached a clinical score of 2 and continuing for 10 (Figure 5A, top) or 30 (Figure 5A, bottom) days, exhibited less severe daily clinical scores \((P < 0.0001, \text{both lengths of treatment})\), maximum severity scores \((P < 0.0001, \text{both lengths of treatment})\), and mean cumulative scores \((P < 0.01 \text{ for 10 days treatment, } P < 0.001 \text{ for 30 days treatment})\), while male SJL mice did not respond to treatment (Supplemental Figure 5). No changes in body weight were observed after JTE-013 treatment, regardless of treatment duration (Supplemental Figure 6, A–C). Consistent with clinical assessments, H&E staining revealed significantly fewer inflammatory foci within the white matter of both spinal cords \((P < 0.01)\) and cerebella \((P < 0.05)\) of JTE-013 mice compared with that in vehicle-treated female SJL mice at peak of EAE (Figure 5B), and cerebellar lesions were significantly reduced \((P < 0.05)\) during remission. Luxol fast blue (LFB) staining further revealed that JTE-013 treatment reduced demyelination of spinal cords and cerebellar white matter during peak and remission phases of EAE (Figure 5B). Female SJL mice with EAE treated with JTE-013 for 5 days also exhibited significantly reduced fluorescein permeability in both cerebella \((P < 0.001)\) and spinal cords \((P < 0.01)\), compared with
vehicle controls (Figure 5C, top) and a significant reduction in spinal cord permeability after prolonged treatment for 30 days ($P < 0.01$) (Figure 5C, bottom). Similar results were observed via immunohistochemical detection of extravasated albumen within the white matter of diseased mice (Supplemental Figure 7A).

Consistent with results after antagonist treatment, S1PR2-deficient mice immunized with MOG35–55 exhibited significantly decreased severity of EAE compared with that of wild-type controls, indicated by lower daily clinical scores ($P < 0.0001$), maximum severity scores ($P < 0.0001$), and mean cumulative scores.
S1pr2−/− animals also exhibited less demyelination and fewer inflammatory foci during peak of EAE, compared with wild-type mice, in the spinal cords (P = 0.03) but not the cerebella (Figure 6B), in addition to significant reductions in fluorescein permeability in the spinal cords during both acute (P < 0.01) and chronic (P < 0.01) EAE (Figure 6C). There was also less detection of extravasated albumen in the spinal cords of S1pr2−/− mice compared with that in wild-type animals at peak of disease (Supplemental Figure 7B).

**Figure 4**

BBB expression of S1PR2 is increased in MS. (A) Endothelial cell (CD31, green) and (B) astrocyte (GFAP, green) localization of S1PR2 (red) in female and male cerebellar tissue obtained from patients with and without MS. Nuclei are counterstained with ToPro3 (blue). (A) Control stains, in which sections were first blocked with immunogen (1 mg/ml) prior to detection of CD31 (green) and S1PR2 (red), are included. Scale bar: 25 μm. (C) Quantification of amounts of vessel-associated S1PR2 fluorescence in female (red circles) and male (blue circles) samples from patients with and without MS. Levels of S1PR2 fluorescence were determined by examining S1PR2 staining in venule ROIs in 10 images per patient (4–6 patients per group), normalized by area of CD31 staining to control for size and numbers of vessels. Note that the outlier in the male MS group also had a history of occipital head trauma. *P < 0.05. Horizontal bars represent geometric means.

(S1PR2 signaling enhances BBB permeability via caveolin-endocytosis, Rho/ROCK, and CDC42-dependent pathways. To further assess the impact of S1PR2 signaling on BBB function, we used a well-characterized transwell in vitro model of the BBB consisting of human cerebral microvascular endothelial cells (HCMECs) grown on porous filter membranes over primary human astrocytes (47). Barrier integrity was evaluated by electrode recording of transendothelial electrical resistance (TEER). Treatment with exogenous S1P permeabilized in vitro BBBS in a dose-dependent manner over the course of 4 hours, indicated by significant reductions in TEER (P < 0.001, all comparisons) (Figure 7A). This disruption of barrier integrity was S1PR2 dependent, as treatment with an S1PR2 antagonist (Figure 7B), but not an S1PR1 antagonist (Figure 7C), rescued TEER reduction after S1P treatment. Moreover, treatment with an S1PR1-specific agonist led to a small increase in TEER in both vehicle- and S1P-treated cultures (P < 0.05) (Supplemental Figure 8A), in contrast to the TEER decreases produced by S1P via S1PR2. Use of RNA interference to specifically knockdown S1PR1 and S1PR2 similarly demonstrated S1PR2-dependent disruption...
of barrier integrity (Supplemental Figure 9, A and B). Further characterization of the signaling components that contribute to S1PR2 dysregulation of the in vitro BBB revealed that pharmacological blockade of the caveolin-dependent endocytic pathway (Figure 7D) prior to S1P treatment prevented TEER reductions (P < 0.001), while blockade of clathrin-dependent endocytosis (Supplemental Figure 8B) or macropinocytosis (Supplemental Figure 8C) produced either small or no changes in TEER after S1P administration, respectively. TEER reductions after S1P treatment were also prevented by pretreatment with inhibitors of the Rho GTPase effectors Rho/ROCK (P < 0.001) (Figure 7E) and CDC42 (P < 0.001) (Figure 7F) but not Rac (Supplemental Figure 8D).

S1PR2 signaling leads to breakdown of AJs and loss of polarized expression of CXCL12 on basolateral/abluminal surfaces. We next examined whether S1PR2-dependent disruption of BBB function resulted in molecular changes to the structure of the BBB endothelium. Similar to results with TEER recording, S1P treatment resulted in a breakdown of AJs, indicated by loss of intensity and discreteness of VE-cadherin staining at intercellular borders (Figure 7G, left). Diminished AJ integrity was also associated with a loss of polarized protein expression on the apical and basolateral surfaces of endothelial cells, as assessed via z-plane confocal microscopy (imaging on same plan of microscopy z axis) for canonical markers of apical (γ-glutamyltransferase-1 [GGT]) and basolateral (CXCL12) BBB surface markers (Figure 6G, right). Again, loss of AJ integrity and polarized GGT/CXCL12 expression after S1P treatment was specific to S1PR2, as it could be reversed by JTE-013 treatment (Figure 7H) but not by treatment with a specific antagonist (Figure 7I) or agonist of S1PR1 (Supplemental Figure 8E). Knockdown of S1PR2, but not S1PR1, RNA in the context of S1P treatment also led to loss of AJ integrity (Supplemental Figure 9C). Similarly, pretreatment with inhibitors of caveolin-dependent endocytosis (Figure 7J) and Rho/ROCK or CDC42 (Figure 7, K and L) prevented loss of AJs and endothelial polarity, while inhibition of clathrin-dependent endocytosis, macropinocytosis, and Rac (Supplemental Figure 8, F–H) had no effect.

Given the mouse strain- and sex-specific differences in CNS levels of expression of S1PR2, we next analyzed polarized CXCL12 expression at the BBB in naive female and male mice of various strains susceptible to EAE via quantification of fluorescence intensity across vessels using confocal microscopy (32). In the spinal cord white matter, CXCL12 expression was primarily abluminal on the vessels of male SJL mice and in C57BL/6 and B10.PL mice of either sex, whereas vessels in female SJL mice instead exhibited a unique pattern of primarily lumenal CXCL12 expression (Supplemental Figure 10A). Similar analyses of brain vasculature in female and male SJL mice revealed a predominantly lumenal display of CXCL12 in the brainstem and cerebellar white matter tracts in the female mice only, while vessels in all brain regions of male mice and in supratentorial brain regions of female mice exhibited proper abluminal patterns of CXCL12 (refs. 31, 32, and Supplemental Figure 10B). After induction of EAE, inflamed vessels within infratentorial regions of male mice exhibited a shift in CXCL12 expression from abluminal to lumenal locations, while female mice exhibited loss of CXCL12 expression (Supplemental Figure 11), as previously reported (30). To test whether inactivation of S1PR2 altered BBB expression of CXCL12 in vivo, we analyzed the location of CXCL12 at CNS vasculature within the cortices, cerebella, and spinal cords of female SJL mice treated with vehicle or JTE-013 as well as wild-type mice and S1pr2−/− mice at peak of disease. JTE-013–treated
female SJL mice exhibited significantly increased levels of abluminal CXCL12 in infratentorial CNS regions (cerebella: \( P < 0.01 \); spinal cords: \( P < 0.05 \)), with no changes observed in cortical vessels (Figure 8, A and B). Similarly, \( S1pr2^{-/-} \) mice exhibited significantly higher levels of abluminal CXCL12 within spinal cord white matter regions than wild-type controls at peak of EAE (\( P < 0.001 \)) (Figure 8, C and D). These data suggest that \( S1PR2 \) activity dysregulates proper abluminal expression of CXCL12 and that this affects disease course during CNS autoimmunity.

**Discussion**

We have defined a sexually dimorphic role for \( S1PR2 \) in the disruption of polarity at the BBB. Elevated levels of \( S1PR2 \) were detected in EAE-susceptible CNS regions in female SJL mice compared with that in male SJL mice and compared with C57BL/6 mice of both sexes. Consistent with this, antagonism of \( S1PR2 \) ameliorated EAE and alterations in BBB permeability. Wild-type and \( S1pr2^{-/-} \) mice were immunized with MOG and followed for disease progression. (A) Clinical EAE scores ± SEM. The inset shows mean of cumulative score and highest severity score ± SEM for 10 to 15 mice per genotype. (B) H&E-stained (left panels) and LFB-stained (right panels) sections derived from spinal cords and cerebella of WT and \( S1pr2^{-/-} \) mice at peak of EAE. Scale bar: 25 \( \mu \)m. Bar graphs depict mean numbers of white matter lesions within both CNS regions ± SEM for 4 to 6 mice per genotype. (C) Relative BBB permeability of cortex, cerebellum, and spinal cord tissues derived from WT and \( S1pr2^{-/-} \) mice at peak and chronic stages of monophasic EAE. Data are depicted as mean fluorescence intensity, normalized against plasma values for individual mice ± SEM for 4 to 6 mice per genotype, with means normalized against mean values for WT naive controls. *\( P < 0.05 \); **\( P < 0.01 \); ***\( P < 0.001 \).

\( S1PR2 \) deficiency ameliorates EAE and alterations in BBB permeability. Wild-type and \( S1pr2^{-/-} \) mice were immunized with PLP139–151 to induce EAE. \( S1PR2 \) was expressed similarly in male SJL mice and compared with C57BL/6 mice of both sexes. Consistent with this, antagonism of \( S1PR2 \) ameliorated EAE and polarity at the BBB. Elevated levels of \( S1PR2 \) were detected on endothelial cells and vasculature-associated astrocytes within the CNS and was significantly higher in white matter regions of patients with MS compared with controls without MS, with female patients with MS exhibiting higher levels than male patients. In vivo and in vitro studies evaluating the role of \( S1PR2 \) in BBB permeability revealed its critical involvement in loss of apical basal expression of canonical markers of BBB polarity, including higher levels of abluminal CXCL12 and that this affects disease course during CNS autoimmunity.

Recent research has characterized genetic, hormonal, and environmental contributions to sex bias in MS; however, an understanding of sexual dimorphism in CNS autoimmunity has yet to result in novel, successful therapeutics that target these mechanisms (4, 5, 49, 50). This report identifies a potential contributor to MS sex bias and is the first to identify a sexually dimorphic regulator of the BBB. The identification of sexually dimorphic changes in mRNA levels within different CNS regions was not due to direct effects of sex steroids on transcriptional programs. Thus, analysis of \( S1PR2 \) expression in the cerebella of SJL/J-Chr YB10.5 male mice did not link sexually dimorphic effects to the Y chromosome (40), and analysis of \( S1PR2 \) expression in the CNS of naive or skewed, ovariectomized mice, with or without estradiol replacement, also did not reveal acute regulation of \( S1PR2 \) by gonadal hormones. Most current therapies for RRMS are immunomodulators, while others address the consequences of relapses by managing symptoms or improving function (51, 52). However, these drugs often have off-target side effects, because they do not specifically target myelin-reactive leukocytes (53, 54). Targeting \( S1PR2 \) may avoid common off-target effects and maybe more CNS specific than the use of FTY720, which targets several \( S1PRs \) but not \( S1PR2 \) (24). As \( S1PR2 \) also maintains germinal center B cells (55), its blockade is unlikely to lead to the lymphopenia observed with FTY720. FTY720 is also associated with severe adverse events, including fatal herpesvirus infections, hemorrhagic focal encephalitis, and vasospasm of the brachial artery, mostly mediated by \( S1PR3 \) signaling after prolonged use (56–62).

\( S1PR2 \) activity in our study was associated with several critical markers of endothelial barrier dysfunction, including higher transendothelial permeability and loss of apical basal polarity, in vitro and in vivo. Our findings corroborate in vitro prior reports, suggesting counterbalancing roles of \( S1PR1 \) and \( S1PR2 \) in maintaining vascular endothelial integrity via Rho GTPase signaling, with \( S1PR1 \) enhancing barrier function primarily via Rac activation (20, 63, 64) and \( S1PR2 \) disrupting barrier function through cytoskeletal contraction, stress fiber formation, and junction protein disassembly via RhoA/ROCK signaling (29, 65). Our results also implicate potentially complementary roles for RhoA and CDC42, a key regulator of cellular polarity (66), in \( S1PR2 \)-mediated BBB dysregulation, perhaps by convergent downstream effector signaling (67). The caveolin-dependent endocytic pathway, but not the clathrin-dependent endocytic or macropinocytic pathways, also appears to be an important mediator of barrier dysregulation via \( S1PR2 \), likely due to the enrichment of \( S1PRs \) in close proximity with their associated effectors in membrane caveolae (64), though evidence...
S1PR2 signaling dysregulates CNS endothelial barrier structure and function through Rho/ROCK, CDC42, and caveolin endocytosis-dependent pathways. (A–F) Paracellular permeability of in vitro BBB cultures was assessed by electrode recording of TEER, reported in $\Omega$/cm$^2$. (A) TEER after treatment of in vitro BBB cultures with 10, 100, or 1,000 nM exogenous S1P for 4 hours or (B and C) 1,000 nM S1P for 4 hours with or without (B) 1,000 nM JTE-013 at 2 hours or (C) the S1PR1-specific antagonist W146 (1,000 nM) at 2 hours. (D–F) TEER after 1,000 nM S1P treatment of BBB cultures pretreated for 2 hours with (D) the caveolin endocytosis inhibitor MBCD (10 mM), (E) Rho-associated protein kinase (ROCK) inhibitor H1152P (10 nM), or (F) CDC42 inhibitor ML141 (100 nM). TEER values are mean ± SEM of 6 to 9 replicates of 2 to 3 independent experiments. ***$P < 0.001$, repeated-measures 2-way ANOVA. (G–L) Immunocytochemical staining of AJs in HCMEC/D3 cells via labeling of VE-cadherin (red, left and middle panels; scale bar: 30 μm) and confocal z-stack reconstruction of HCMEC/D3 cells (right panels; scale bar: 15 μm), demonstrating polarized expression of canonical apical marker GGT-1 (green) and basolateral CXCL12 (red) after treatment with (G) vehicle or 1,000 nM S1P for 4 hours followed by treatment with (H) JTE, (I) W146, (J) MBCD, (K) H1152P, or (L) ML141 treatment at 2 hours. Inhibitor concentrations in H–L are identical to those in B–F. Immunocytochemical images are representative images of 2 to 3 independent experiments. IC, isotype controls.
research article

A

SC | CB | CTX

Veh

JTE

Intensity

Intensity

CXCL12/CD31/Topro3

B

Ablumenal
Lumenal
Absent

% CXCL12 vessels

Veh | JTE | Veh | JTE | Veh | JTE

SC | CB | CTX

C

WT | KO

Intensity

Intensity

CXCL12/CD31/Topro3

D

Ablumenal
Lumenal
Absent

% CXCL12 vessels

WT | KO | WT | KO | WT | KO

SC | CB | CTX
also suggests that AJs can be disrupted via caveolin-mediated endothyosis of junctional proteins (13, 68, 69). Of interest, interferon-beta, which prevents inflammatory events in RMRs, promotes stability of VE-cadherin (70), suggesting that the specific targeting of this pathway could greatly improve therapy. Finally, as S1PR2 antagonism does not affect receptor expression by endothelial cells (71), targeting the receptor to prevent alterations in BBB permeability should not lead to long-term effects on BBB function.

Association of S1PR2 with endothelial permeability by VE-cadherin-mediated tight junction dysfunction was first reported by Sanchez et al. using an in vitro model of HUVECs genetically modified to express S1PR2 (72). However, the observed amelioration of EAE in S1PR2-deficient mice could be attributed potentially to other immune mechanisms that do not incorporate effects of endothelial barriers. Among the possibilities are the effects of receptor deficiency on astrocytes or pericytes (73–76); the absence of antigen capture, as observed in vitro for Langerhans cells (77) and alveolar macrophages (78); or loss of B cell retention at germinal centers (79, 80), which could alter their ability to function as antigen-presenting cells within the CNS. Last, S1PR2 signaling is required for degranulation and cytokine release by activated mast cells (81, 82), which have been implicated in the neuropathogenesis of MS and EAE (83).

We reported previously that postcapillary venules in the center of MS lesions display the normally abluminal chemokine, CXCL12, aberrantly along luminal surfaces (30–32, 84). In our study, altered patterns of CXCL12 expression at the BBB were found to be associated specifically with MS compared with other neuroinflammatory conditions, including viral encephalitis and CNS lymphoma (31). Redistributed CXCL12 was associated with increased activation of CXCR4 on leukocytes within vessel lumen, suggesting that altered CNS vasculature polarity increases leukocyte capture at endothelial cell surfaces. The finding that humans with susceptibility for MS exhibit high levels or sexually dimorphic expression of S1PR2 suggests that the molecule may underlie susceptibility to CNS autoimmunity and might be a disease-modifying target in MS, similar to that observed in the female SJL mouse. The identification of S1PR2 as a target for BBB stabilization that preserves CXCL12 polarity and therefore immune privilege is an exciting advance toward the development of novel MS therapies that limit CNS inflammation without compromising immune function.
able sutures. Hormonal replacement was initiated 14 days after ovarioectomy by subcutaneous implantation of either 0.25 mg 17β-estradiol or placebo (vehicle) 21-day release pellets (Innovative Research of America). A cohort of these mice was immunized with PLP139-151, together with sham-ovariocto-
mized mice, to induce EAE 7 days after hormone replacement. Immunized
animals were followed for EAE progression by monitoring clinical score and
body weight. Tissues were obtained from sham-ovarioctomized and plaque-
bo-treated mice when they reached a score of 2 at 14 days after immuniza-
tion and from 17β-estradiol-treated mice, which remained free of disease, at 21 days after immunization. Protein lysates were prepared from CNS tis-
ues, while uteri and the upper third of vasa of all mice were drop-fixed in 4% PFA for 48 hours. Following fixation, uterine tissue was trimmed of fat and connective tissue prior to determination of uterine weight.

EAE induction and in vivo treatment with JTE-013. EAE was induced in SJL/J
mice via active immunization with proteolipid protein (PLP139-151) 200 μg (GenScript USA Inc.) emulsified in complete Freund’s adjuvant containing
Mycobacterium tuberculosis (H37Ra; Difco Laboratories). In addition, mice
were inoculated at the time of immunization and 2 days after. Mice were graded for clinical manifestations of EAE by the following criteria: 1, tail weakness; 2, difficulty
at the time of immunization and 2 days after. Mice were graded for clinical
(both from BioTek Instruments Inc.). Tissue values were standardized
was determined via a microplate reader, Synergy H1, and Gen5 software
for 18 hours after death from 5 female and 5 male patients
Table 2). The control group consisted of 8 patients without any clinical his-
tory of neurological disease and 1 patient with a history of CNS lymphoma.

Human subjects. The use of human postmortem biopsies for this study was
approved by the Human Studies Committee of Washington University. Post-
mortem CNS tissue from 2 groups of patients was studied: 11 patients with
clinically defined MS followed in the Washington University Multiple Sclerosis Center and 9 control individuals without histories of MS (Supplemental
with a false discovery rate <0.2 were selected for further characterization.
Two-tailed, Student’s t test was used to determine the statistical signif-
ificant of immunohistochemical, mean maximal disease severity, and
sample yielded 27,333 probes), quantile normalized by CNS region, and
submitted to 2-way ANOVA for sex- and region-specific gene regulation.

Histological and immunohistochemical analyses of murine samples. Murine
CNS tissues underwent histological analyses (H&E; LFB staining) and IHC
detection of CD31, GFAP, PDGF-Rβ, VE-cadherin, and CXCL12, as per-
formed previously (30). Analysis of polarized expression of CXCL12 across
vasculature was performed as previously described (32). IHC detection of
S1PR2 was performed in a fashion similar to that outlined for human CNS
visualizations was done by confocal microscopy, as described above.

Preparation of in vitro human BBB. In vitro human BBB cultures were gen-
erated using HCMEC/D3, an endothelial cell line developed from brain
tissue derived from the temporal lobe of an adult human female with epi-
lepsy (88). HCMEC/D3 cells were cocultured with primary human astrocy-
tes (ScienCell), within a transwell system in which TEER values (Ω/cm²)
were measured via chopstick electrode recording with an EVOM apparatus
(Word Precision Instruments), as previously described (47). Resistance val-
ues are reported as recorded values for each replicate minus the resistance
of cell-free inserts (≈90 Ω) measured alone. Measurements were taken
24 hours after initial seeding of endothelial cells (day 1); subsequent mea-
surements were taken daily for 10 days, at which point cultures were ready
for experimentation. Changes in permeability were evaluated via TEER
measurements after vehicle or S1P (Cayman Chemical Company) was added
top and bottom chambers (10–1,000 nM) and incubated for 2 hours, followed
by addition of vehicle or JTE-013 (10–1,000 nM). Similar experi-
ments were done using the following agents: S1PR1-specific agonist, W146
(1,000 nM), and S1PR1-specific antagonist, SEW2871 (1,000 nM, both
from Cayman Chemical Company), as well as cavelin endocytosis inhibi-
tor, methyl-β-cyclodextrin (MBCD, 10 nM); clathrin endocytosis inhibi-
tor, chlorpromazine (10 μg/ml); or the macropinocytosis/P3K inhibitor,
wortmannin (100 nM, all from Sigma-Aldrich). To determine the effector
molecules involved in S1PR2 signaling, we also pretreated for 2 hours with
the Rac1 inhibitor, Z62954982 (1,000 nM, Cayman Chemical Company),
the Rho/ROCK inhibitor, H-1152P (10 nM, Cayman Chemical Company),
and the CDC42 inhibitor, ML141 (100 nM, Tocris, R&D Systems).

In vitro RNA interference. HCMEC/D3 cells in BBB cultures or grown
on chamber slides were treated with 25 nM siRNA SMARTpools against
S1PR1, S1PR2, or a nontargeting control pool (ON-TARGETplus, Thermo-
Scientific) complexed with a 1:500 dilution of DharmaFect 1 transfection
complex (Thermo Fisher Scientific) before being visualized via confocal microscopy.

Statistics. All microarray statistical analyses for the characterization of
sexually dimorphic gene expression in female cerebella were performed
using Partek Genomics Suite (Partek Incorporated). Data were filtered
for detectable probes (Illumina detection using P < 0.05 in at least one sample yielded 27,333 probes), quantile normalized by CNS region, and
submitted to 2-way ANOVA for sex- and region-specific gene regulation.
Transcripts that demonstrated upregulation or downregulation of >1.3
with a false discovery rate <0.2 were selected for further characterization.
Two-tailed, Student’s t test was used to determine the statistical signif-
icance of immunohistochemical, mean maximal disease severity, and
cumulative clinical score analyses. Statistical significance of qRT-PCR, disease severity curve, fluorescein permeability, and TEER measurements was done by 2-way ANOVA, followed by Bonferroni’s post-hoc test with appropriate correction for repeated measures. Comparison of CXCL12 polarity was done via χ2 test. For all graphs, error bars represent ± 1 SEM. All statistical analysis was performed with GraphPad Prism software, version 5.0. P values of less than 0.05 were considered significant for all comparisons.

**Study approval.** This study was carried out in strict accordance with the requirements pertaining to animal subjects within the Public Health Service Policy and USDA Animal Welfare Regulations. All experiments were performed in compliance with Washington University Institutional Animal Care and Use Committee (Animal Welfare Assurance A3381-01), which approved our animal protocol (20120160, 8/3/12). All efforts were made to minimize the suffering of animals used in this study. Postmortem human tissues banked for research purposes are not exempt from institutional review board approval, and researchers do not have direct access to any identifying information.

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