Roles for lysophospholipid S1P receptors in multiple sclerosis

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Abstract

Sphingosine 1-phosphate (S1P) signaling in the treatment of multiple sclerosis (MS) has been highlighted by the efficacy of FTY720 (fingolimod), which upon phosphorylation can modulate S1P receptor activities. FTY720 has become the first oral treatment for relapsing MS that was approved by the FDA in September 2010. Phosphorylated FTY720 modulates four of the five known S1P receptors (S1P1, S1P3, S1P4, and S1P5) at high affinity. Studies in human MS and its animal model, experimental autoimmune encephalomyelitis (EAE), have revealed that FTY720 exposure alters lymphocyte trafficking via sequestration of auto-aggressive lymphocytes within lymphoid organs, representing the current understanding of its mechanism of action. These effects primarily involve S1P1, which is thought to attenuate inflammatory insults in the central nervous system (CNS). In addition, FTY720’s actions may involve direct effects on S1P receptor-mediated signaling in CNS cells, based upon the known expression of S1P receptors in CNS cell types relevant to MS, access to the CNS through the blood–brain barrier (BBB), and in vitro studies. These data implicate lysophospholipid signaling – via S1P, and perhaps other lysophospholipid receptors – in therapeutic approaches to MS and potentially other diseases with immunological and/or neurological components.

Keywords: sphingosine 1-phosphate; FTY720; fingolimod; GPCR; experimental autoimmune encephalitis

Introduction

Sphingosine 1-phosphate (S1P) is a lysophospholipid, which exerts diverse biological activities under physiological and pathological conditions through cell surface G protein-coupled receptors (GPCRs), named S1P1, S1P2, S1P3, S1P4, and S1P5 (Ishii et al., 2004). S1P is present at submicromolar concentrations in various biological fluids and tissues (Ishii et al., 2004) and is produced intracellularly by a series of enzymatic reactions involving membrane-derived sphingolipids that ultimately provide sphingosine as a substrate for sphingosine kinase type 1 (SphK1) and type 2 (SphK2), to produce S1P, which can then act in both autocrine and paracrine fashions (Alvarez et al., 2007).

This receptor-mediated signaling system, along with its sphingolipid metabolic pathway, is central to the actions of a compound known as FTY720 (fingolimod) that was recently approved by the FDA as a treatment for relapsing multiple sclerosis (MS). FTY720 was initially reported as a myricin derivative identified through studies of fungal metabolites, which possessed immunosuppressive properties by selectively depleting mature T cells in skin allograft models (Adachi et al., 1995). FTY720 is a sphingosine analog that is also phosphorylated in vivo by SphKs, particularly SphK2, to produce FTY720-phosphate (FTY720-P) (Paugh et al., 2003; Billich et al., 2003; Zemann et al., 2006), whereupon it can activate four subtypes of S1P receptors, S1P1/S1P3/S1P4, with single-digit or lower nanomolar affinities (Brinkmann et al., 2002; Mandal et al., 2002). FTY720 was evaluated in humans as an agent to prevent renal transplantation rejection, although these studies were ultimately terminated for lack of efficacy (Budde et al., 2006). However, studies of FTY720 in experimental autoimmune encephalitis (EAE), an animal model of MS, supported therapeutic relevance to this disease (Brinkmann et al., 2002; Fujino et al., 2003; Webb et al., 2004; Kataoka et al., 2005).
Papadopoulos et al., 2010), warranting further clinical evaluation.

MS is a chronic inflammatory demyelinating disease of the central nervous system (CNS) and can be associated with irreversible progression of neurological disability (Frohman et al., 2006). Currently, there is no cure for MS. Until the recent approval of FTY720 as an orally bioavailable treatment for relapsing MS, FDA-approved disease modifying therapies only consisted of injectable, immunosuppressive drugs such as interferons (IFNs) β-1a and -1b, glatiramer acetate and natalizumab (Martin, 2010). FTY720 has been assessed in extensive clinical trials for relapsing-remitting MS (Kappos et al., 2010; Cohen et al., 2010), where it has shown efficacy along with an acceptable safety profile, and has received an approval from FDA in September 2010. The side-effect profile consists of a range of generally rare events (Cohen et al., 2010; Kappos et al., 2010), the most common of which is a transient bradycardia with initial treatment, resolving with continued exposure. Rarer events include nasopharyngitis, slightly reduced pulmonary function, and reversible macular edema (reviewed in Chun and Hartung, 2010). FTY720 recently received approval from the FDA as the first oral treatment for relapsing MS.

The current view on the mechanism of action of FTY720 is that it improves MS signs and symptoms by altering immune responses, particularly through effects on lymphocyte trafficking. In addition, the fact that relevant S1P receptors are expressed within the brain, and that FTY720 can penetrate the blood–brain barrier (BBB), raises the possibility that FTY720 may have direct effects on the CNS cells as well. This review will focus on S1P receptor mechanisms and relevant cell types that could contribute to the efficacy of FTY720 in MS to produce its demonstrated in vivo effects on the immune system, along with possible contributions of direct CNS influences.

S1P signaling and FTY720 efficacy in the immune system

**T cells**

MS is thought to be caused, at least in part, by an autoimmune attack of the CNS by myelin-specific CD4-positive T cells. The pathogenesis of MS is characterized by demyelination associated with infiltration of inflammatory cells and release of various cytokines and chemokines in the CNS (Frohman et al., 2006). In EAE animal models, therapeutic or prophylactic administration of FTY720 reduces the infiltration of lymphocytes into the spinal cord with a rapid reduction in lymphocyte numbers in the peripheral blood produced by sequestration of lymphocytes within primary and secondary lymphoid organs. This is thought to be the central mechanism of action of FTY720 for disease attenuation (Brinkmann et al., 2002; Fujino et al., 2003; Webb et al., 2004; Kataoka et al., 2005; Mehling et al., 2008). In addition, FTY720 reduces levels of proinflammatory products, such as interleukin (IL)-17, IFN-γ, and inducible nitric oxide synthase (iNOS), in the spinal cord of EAE animals, which also may contribute to attenuating the disease state (Fujino et al., 2003; Webb et al., 2004; Kataoka et al., 2005; Papadopoulos et al., 2010).

As just noted, FTY720 reduces lymphocyte numbers in the blood and lymph by sequestering them in the thymus and the secondary lymphoid organs such as lymph nodes and Peyer’s patches (Chiba et al., 1998; Pinschewer et al., 2000; Mandala et al., 2002). Histology has shown that FTY720 treatment induces emptying of lymphoid sinuses, suggesting that lymphocytes cannot access egress structures and cannot egress into lymph (Mandala et al., 2002). The effect is reversible (Pinschewer et al., 2000) and observed in both naïve and activated T cells (Xie et al., 2003). Thus, the mechanism of action of FTY720 in MS is believed to be a blockage of the inflammatory cell infiltration into the lesion site, resulting from sequestration of lymphocytes in the thymus and secondary lymphoid organs and a subsequent depletion of circulating auto-aggressive lymphocytes.

The regulation of lymphocyte egress involves the S1P receptor subtype S1P1, which allows lymphocytes to sense an S1P concentration gradient existing between blood/lymph and lymphoid tissues. This process regulates lymphocyte recirculation from within lymphoid organs back to the blood. Several lines of evidence support this model. In the normal condition, S1P concentrations are high in blood and lymph, and low in lymphoid organs (Schwab and Cyster, 2007). When S1P in lymph is lost by genetic deletion of the S1P producing enzymes SphK1/2 from lymphatic endothelial cells, lymphocytes cannot egress from lymph nodes into lymph circulation (Pappu et al., 2007; Pham et al., 2010). Expression level of S1P, in thymocytes increases during their maturation, and CD4 or CD8 single-positive mature T cells acquire the ability to migrate towards increasing S1P concentrations (Matloubian et al., 2004). S1P deletion from lymphocytes results in an inhibition of lymphocyte egress from the thymus and peripheral lymphoid organs. This has been shown in studies of conditional S1P deficiency from lymphocytes using a Lck promoter-driven Cre or transplantation of S1P-null hematopoietic cells into irradiated wild-type animals (Allende et al., 2004; Matloubian et al., 2004). These studies indicate that lymphocyte egress is dependent on lymphocyte expression of S1P, and requires an S1P concentration gradient. Since FTY720 treatment mimics the effect of S1P deletion from lymphocytes, FTY720, via its active phosphorylated metabolite, may act predominantly as a functional antagonist of
lymphatic S1P under therapeutic conditions despite its agonist properties under acute exposure conditions. In contrast to the dramatic effect on lymphocyte egress, FTY720 does not appear to affect significantly the activation, proliferation, or effector functions of T and B cells (Pinschewer et al., 2000; Brinkmann et al., 2001).

B cells

Although investigations into MS pathophysiology have focused mainly on T cells, growing evidence suggests a contribution of B cells which act as antigen presenting cells to T cells and secrete proinflammatory cytokines, chemokines and autoantibodies targeting structures on the myelin sheath and the axon (McLaughlin and Wucherpfennig, 2008). Rituximab (rituxan), a monoclonal antibody against CD20, has provided direct evidence of B cell involvement in MS pathology. Rituximab inhibits MS-related inflammation by specific depletion of B cells and B cell-producing autoantibodies (Hauser et al., 2008). In addition, several studies have demonstrated that S1P1-mediated signaling regulates trafficking of B cells. Deletion or downregulation of S1P1 in developing bone marrow B cells inhibits the release of newly generated immature B cells from the bone marrow into the blood (Allende et al., 2010). Either FTY720 treatment or S1P1-deletion reduces the number of IgG- and IgA-secreting mature B cells in blood and bone marrow by sequestration in secondary lymphoid organs (Kabashima et al., 2006; Kunisawa et al., 2007). Indeed, B cell numbers in the blood of EAE animals decrease following FTY720 treatment (Kataoka et al., 2005). Thus, it is likely that S1P signaling in B cells, as well as T cells, is altered during FTY720 exposure by regulating the distribution of B cells, and possibly altering the release of cytokines, chemokines and autoantibodies. Other S1P receptor subtypes may be involved in this process based on a report identifying S1P5 as contributing to B cell positioning (Cinamon et al., 2008).

Other immune cells

Natural killer (NK) cells have been shown to play a role in MS, but controversy exists as to whether they are protective or pathogenic (Morandi et al., 2008). S1P5 is highly expressed in NK cells and is required for NK cell egress from bone marrow and lymph nodes (Walzer et al., 2007; Jenne et al., 2009). In addition, S1P1 is expressed in NK cells and may be involved in the regulation of NK cell egress (Jenne et al., 2009). S1P1 deficiency severely blocks NK cell egress, whereas S1P deficiency does not, indicating that NK cell egress is regulated mostly by S1P1. Thus, targeting S1P receptors in NK cells may influence the pathogenesis of MS by altering their tissue distribution, although the outcome could be either protective or pathogenic. Whether FTY720 efficacy involves alterations of NK cells through S1P1 remains unclear.

Antigen presenting cells, such as dendritic cells (DCs), macrophage/microglia, and astrocytes, are also involved in MS pathology (Slavin et al., 2010). FTY720 treatment affects DC features such as migration and cytokine production in vitro, which are essential as antigen presenting cells ( Muller et al., 2005), and modulates DC trafficking in vivo (Czeloth et al., 2005; Lan et al., 2005). It is possible that S1P signaling in DCs may be involved in MS pathogenesis and could therefore be a therapeutic target.

S1P signaling and FTY720 efficacy in the CNS

S1P receptors are expressed in the CNS. FTY720 can penetrate the BBB and enter the CNS where it can be phosphorylated to its bioactive form, FTY720-P (Meno-Tetang et al., 2006; Foster et al., 2007). Brain levels of FTY720 and FTY720-P increase dose-dependently, and over time, exceed levels present in blood by several fold (Meno-Tetang et al., 2006; Foster et al., 2007). In addition, studies have demonstrated effects of FTY720 on CNS cell types as described below, consistent with their expression of S1P receptors. These observations raise the possibility that FTY720 efficacy for MS may involve direct actions on CNS cell types, in addition to effects on the immune system.

Astrocytes

Astrocytes are glial cells involved in the maintenance of the BBB, CNS metabolism, and synaptic functioning, as well as responding to pathological insults in the CNS. Recent evidence suggests a dual role of astrocytes in CNS inflammatory diseases such as MS. Astrocytes not only have the ability to enhance immune responses and inhibit myelin repair by forming a glial scar and preventing migration and maturation of oligodendrocyte progenitor cells, but can also be protective and limit CNS inflammation while supporting oligodendrocyte and axonal regeneration in some experimental systems (Williams et al., 2007; Nair et al., 2008).

There is evidence for the involvement of S1P signaling in astrocytes relevant to the pathogenesis of MS. Activation of S1P signaling induces astrogliosis in vivo, a prominent feature of CNS injury and neurodegenerative diseases, including MS (Sorensen et al., 2003), and promotes proliferation of astrocytes in vitro (Pebay et al., 2001; Sorensen et al., 2003; Yamagata et al., 2003; Bassi et al., 2006). An animal model of Sandhoff disease, another neurodegenerative disease associated with astrogliosis, can be attenuated by genetic deletion of either SphK1 or S1P5 (Wu et al., 2008). S1P is released from astrocytes in an SphK dependent manner and acts
in both autocrine and paracrine manners (Riboni et al., 2000; Anelli et al., 2005). Upon injury, S1P production is locally increased and is associated with reactive astrocytes and microglia, suggesting S1P production from these cell types at the injury site (Kimura et al., 2007).

In cultured astrocytes, FTY720 exposure activates G-protein-mediated signaling cascades, such as decreases in cyclic AMP, inositol phosphate formation and extracellular signal-regulated kinase (ERK) 1/2 phosphorylation, and stimulates migration (Mullershausen et al., 2007; Osinde et al., 2007). Many of these cell culture effects are mimicked by S1P, agonists (S1P, SEW2871 and AUY954) and are attenuated by S1P3 antagonists (VPC23019, W123 and W146) or genetic deletion of S1P3 (Mullershausen et al., 2007; Osinde et al., 2007; Dev et al., 2008), suggesting the involvement of S1P3. Astrocytes in culture preferentially express S1P1 and S1P2 and a low level of S1P5 (Pebay et al., 2001; Rao et al., 2003; Anelli et al., 2005). By comparison, S1P3 expression appears to be below detectable limits under basal conditions, but can be upregulated in culture when cells are exposed to growth factors (Rao et al., 2004). In vivo effects in EAE models as well as direct and indirect actions of signaling on astrocytes remain to be determined.

Oligodendrocytes

Oligodendrocytes are myelin-forming glial cells of the CNS. Loss of CNS myelin and a failure of remyelination by oligodendrocytes are a characteristic of the disease and likely contribute to subsequent irreversible disability in MS (Miller and Mi, 2007). Thus, overcoming remyelination failure could be a therapeutic strategy in MS. Remyelination requires proliferation and migration of oligodendrocyte progenitor cells into demyelinated lesion sites and subsequent differentiation into mature myelin-forming cells (Miller and Mi, 2007).

In vivo, therapeutic administration of FTY720 reduces the area of demyelination in the spinal cord of animals with EAE (Kataoka et al., 2005; Papadopoulos et al., 2010). In organotypic culture where the systemic immune system is absent, FTY720 treatment enhances remyelination following lysolecithin-induced demyelination. This includes an increase in the number of oligodendrocyte progenitor cells, membrane outgrowth and elaboration of processes, as well as increases in microglia number and immunoreactivity for the astrocyte marker glial fibrillary acidic protein (GFAP). Both microglia and astrocytes can create an environment permissive for remyelination. Enhanced remyelination and associated astrogliosis are thought to be mediated through S1P3, whereas microgliosis may occur through S1P5, based upon in vitro experimental studies (Miron et al., 2010). Other in vitro studies have demonstrated direct effects of FTY720 on oligodendrocytes and progenitor cells that include survival, proliferation, migration, and differentiation, all of which are involved in the process of remyelination. In cultured oligodendrocytes and progenitor cells, FTY720 exposure activates ERK1/2 and Akt, which are involved in cell survival signals (Coelho et al., 2007; Jung et al., 2007). Indeed, exposure to FTY720 or FTY720-P protects these cells from apoptosis induced by deprivation of serum/growth factor, as well as apoptosis induced by inflammatory cytokines (e.g. tumor necrosis factor (TNF)-α and IFN-γ) and microglial activation, which have all been implicated in the pathogenesis of MS (Coelho et al., 2007; Jung et al., 2007; Miron et al., 2008). A study using primary cells prepared from S1P1-null animals has shown that S1P1 is required for survival of mature, but not immature, oligodendrocytes (Jaillard et al., 2005).

In addition, FTY720 can synergistically increase platelet-derived growth factor-dependent cell cycle progression of oligodendrocyte progenitor cells (Jung et al., 2007), inhibit migration of oligodendrocyte progenitor cells through S1P5 (Novgorodov et al., 2007), and induce process retraction in oligodendrocytes, although the effect is transient and followed by subsequent re-extension (Jaillard et al., 2005; Miron et al., 2008). FTY720 can either promote or inhibit differentiation of oligodendrocyte progenitor cells into oligodendrocytes depending on its dose (Coelho et al., 2007; Jung et al., 2007). Thus, direct action of FTY720 exposure on oligodendroglial lineage cells can be both beneficial (promotion of survival, proliferation, and differentiation) and detrimental (inhibition of migration and differentiation) for remyelination. However, FTY720 seems to enhance remyelination in conjunction with other CNS cells combined with altering immune system influences.

Gene expression studies have identified S1P receptors, along with other lysophospholipid receptors, on oligodendrocytes and/or their precursor cells (Weiner et al., 1998; McGiffert et al., 2002), and oligodendroglial lineage cells preferentially express S1P3, with lower levels of S1P1, S1P2 and S1P5 (Terai et al., 2003; Yu et al., 2004; Miron et al., 2008). Overall, S1P3 gene expression is prominent in oligodendroglial lineages, but it is still unclear if the FTY720-S1P3 signaling axis is actually involved in remyelination of MS lesions. It is of note that S1P3-deficient mice do not show deficits in myelination (Jaillard et al., 2005).

Microglia

Microglia, brain-resident, non-neural cells, play a role in MS throughout the disease process. They are rapidly activated and recruited to inflammatory sites within the CNS, and function as antigen-presenting cells, initiating and propagating immune responses, phagocytosing damaged tissues and debris, and producing various factors that are both tissue-toxic and protective (Jack et al., 2005).
SIP signaling in microglia may be involved in migration and enhancement of the inflammatory response, but its in vivo role for MS remains unclear. In vitro, SIP treatment increases the expression of proinflammatory cytokines such as TNF-α and IL-1β and nitric oxide in lipopolysaccharide (LPS)-activated microglia (Tham et al., 2003; Nayak et al., 2010). In vivo, FTY720 treatment attenuates the infiltration of reactive macrophages/microglia into lesion sites produced by traumatic brain injury (Zhang et al., 2007). Gene expression levels of SIP receptors in microglia vary depending on their activation state. Microglia in inactive states express SIP₁ and S1P₃, with little SIP₂ and very low SIP₅ (Tham et al., 2003). Upon activation, downregulation of SIP₁ and S1P₃ and upregulation of SIP₁ occur (Tham et al., 2003). SIP may be produced from activated microglia, as described above (Kimura et al., 2007). The effects of in vivo FTY720 exposure on microglial responses, as mediated by identified receptors, remain to be established, particularly with respect to MS therapeutic effects.

**Neurons**

SIP receptors SIP₁₋₃ are expressed in the developing brain (McGiffert et al., 2002), and can influence neurogenesis (Mizugishi et al., 2005). Mice with constitutive deletion of either SphK1/SphK2 or SIP₁ show neurogenic defects (Mizugishi et al., 2005). In primary cultures of neural progenitor cells, SIP treatment induces survival, proliferation, and morphological changes, and enhances nerve growth factor (NGF)-induced neurite extension (Edsall et al., 1997; Harada et al., 2004; Toman et al., 2004). In primary dorsal root ganglion neurons, SIP treatment affects NGF-induced neurite extension and enhances NGF-induced neuronal excitability (Toman et al., 2004; Zhang et al., 2006). In Xenopus, SIP signaling can influence axon guidance (Strochlic et al., 2008). In addition, SIP signaling may promote neuronal repair after injury: neural stem/progenitor cells transplanted into the injured spinal cord migrate toward injured sites in an SIP₁-dependent manner (Kimura et al., 2007).

FTY720 has been reported to have neuroprotective effects. Treatment with FTY720 may reduce sequelae in an ischemic stroke rat model (Hasegawa et al., 2010) and may reduce inflammation and promote functional recovery after spinal cord injury (Lee, KD et al., 2009). However, it is unclear whether these effects involve direct actions on neurons or secondary effects of immunosuppression. Uncertainties inherent to these models, particularly their inability to predict efficacy in humans, support further studies to ascertain both possible neuroprotective functions, as well as direct versus indirect mechanisms.

**Blood-brain barrier (BBB)**

The pathogenesis of MS includes the penetration of inflammatory cells across the BBB into the CNS parenchyma (Correale and Villa, 2007). The penetration occurs through (a) adherence of activated T cells and other lymphocytes to endothelial cells; (b) subsequent degradation of endothelial basement membrane; and (c) migration through the endothelium into the CNS parenchyma (Correale and Villa, 2007). SIP receptors are expressed on the endothelium and could therefore participate in aspects of the BBB since vascular endothelial cells express SIP₁ and S1P₃ (Lee, MJ et al., 1999). SIP₁ expression within endothelial cells is essential for embryonic blood vessel development, which was shown by a study using conditional mutants with specific deletion of SIP₁ from endothelial cells (Allende et al., 2003). Furthermore, SIP enhances physical barrier properties of endothelial cells by inducing adherens junction assembly and tight junction formation (Lee, MJ et al., 1999; Sanchez et al., 2003; Lee, JF et al., 2006). It also attenuates vascular permeability induced by thrombin, vascular endothelial cell growth factor (VEGF) or LPS-mediated acute lung/renal injury (Sanchez et al., 2003; Schaphorst et al., 2003; Peng et al., 2004). Like SIP₁, FTY720 exposure can also induce adherens junction assembly and attenuate vascular leakage induced by VEGF or in LPS-mediated acute lung injury (Sanchez et al., 2003; Peng et al., 2004). In addition, both SIP and FTY720 can activate Gᵢ/Akt/ERK cell survival signals in endothelial cells, and can protect endothelial cells from apoptosis induced by serum deprivation or C₂-ceramide (Lee, MJ et al., 1999; Sanchez et al., 2003). Thus, unlike lymphocyte trafficking in which FTY720 exposure may result in functional antagonistic activities, FTY720’s effects on endothelial cell functions seem to be agonistic. Interestingly, SIP₁-induced barrier enhancement and survival of endothelial cells appear to be mediated through SIP₁ and S1P₃ (Lee, MJ et al., 1999; Schaphorst et al., 2003; Dudek et al., 2007), while FTY720-induced barrier enhancement is likely through non-S1P₁, Gᵢ-coupled receptor(s) (Dudek et al., 2007). Additionally, an integral cellular element of the BBB is the astrocyte through its documented interactions with endothelial cells (Abbott et al., 2006), which may have particular relevance to FTY720’s effects in view of the aforementioned SIP receptor-mediated activities influenced by FTY720 exposure.

In MS patients and EAE animals, lesion sites, cerebrospinal fluid and/or serum exhibit evidence of upregulation for vascular cell adhesion molecules (i.e. ICAM-1, P-selectin, and VCAM-1) and matrix metalloproteinases (i.e. MMP-2, -3, -7, and -9), the former facilitating cell adhesion and the latter, basement membrane degradation (Czunzer and Opdenakker, 1999; Waubant et al., 1999; Foster et al., 2009). FTY720...
treatment could conceivably reduce or reverse the BBB breakdown that occurs in MS/EAE, as evidenced by therapeutic FTY720 treatment on EAE animals that displayed a reduction in immunoglobulin precipitation that reflects BBB damage in the spinal cord (Foster et al., 2009). Moreover, both prophylactic and therapeutic treatment of FTY720 normalized upregulated gene expression of vascular cell adhesion molecules (ICAM-1, P-selectin, and VCAM-1) and MMP-9 in the spinal cord of EAE animals, suggesting at least a partial recovery of the BBB (Foster et al., 2009). A recent study using a BBB model with isolated human brain endothelial cells has suggested the involvement of S1P1 in protection from oxygen/glucose deprivation (Zhu et al., 2010). Additional evidence is needed to establish effects of FTY720 on BBB regulation.

Receptor mechanisms

Several studies have shown that FTY720 can inhibit S1P signaling by inducing prolonged receptor internalization and degradation (Matloubian et al., 2004; Graler and Goetzl, 2004). These effects can be attributed to the irreversible internalization of bound FTY720-P that results in ubiquitination and proteosomal degradation of at least S1P1 (Oo et al., 2007). As a result of this irreversible internalization, S1P1 is unavailable to sense the S1P gradient that is necessary for lymphocytes to egress out of the immune compartment via the efferent lymph (e.g. within lymph nodes) (Schwab and Cyster, 2007). This mechanism, referred to as functional antagonism as noted above, may be more complex based on a report of persistent intracellular signaling from internalized S1P1 by FTY720-P (Mullershausen et al., 2009), although the biological significance of such signaling on lymphocyte trafficking remains to be determined. The endogenous levels of FTY720 within tissues may dictate the actual modulatory effects observed within lymphoid organs (Sensken et al., 2009). These data indicate that the precise definition of whether FTY720-P functions as an agonist or an antagonist in an experimental disease setting may vary depending on experimental conditions. In humans, reductions of peripheral blood lymphocytes, indicative of reduced lymphocyte egress, clearly follow a dose-response (higher FTY720 concentrations are proportional to a reduction in peripheral blood lymphocytes) (Tedesco-Silva et al., 2005), indicating that the dominant effect of FTY720 on lymphocytes is likely to be through functional antagonism of S1P1, and possibly other S1P receptors, at least with respect to lymphocyte trafficking. In contrast, FTY720’s effects on endothelial cells are most consistent with agonism of non-S1P1, \( G_i \)-coupled receptor(s).

Conclusion

The discovery of FTY720 and establishment of its efficacy in humans for the treatment of relapsing-remitting MS have revealed the relevance of receptor-mediated S1P signaling to MS. A majority of in vivo functional studies have demonstrated that FTY720, through identified S1P receptors, affects lymphocyte trafficking, which in turn has been inferred as the major mechanism for ameliorating MS signs and symptoms. In addition, experimental data support the actions of FTY720 exposure on CNS components that could theoretically contribute to efficacy in MS. However, CNS functional in vivo data relevant to MS remain to be established. Further studies will elucidate the mechanism of action of FTY720 in MS, including a more complete view of affected cell types, S1P receptor subtypes, downstream signaling pathways, and interactions between the immune system and the CNS. With the recent FDA approval of FTY720 (fingolimod) as the first orally bioavailable therapy for relapsing MS, a new chapter in the treatment of MS could be opening, based upon S1P lymphospholipid receptor signaling.

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