Review Article

Lysophospholipid receptors in drug discovery

Yasuyuki Kihara\textsuperscript{a}, Hirotaka Mizuno\textsuperscript{a,b}, Jerold Chun\textsuperscript{a,*}

\textsuperscript{a}Department of Molecular and Cellular Neuroscience, Dorris Neuroscience Center, The Scripps Research Institute, DNC-118, 10550 N, Torrey Pines Road, La Jolla, CA 92037, USA
\textsuperscript{b}Exploratory Research Laboratories, Ono Pharmaceutical Co., Ltd., Ibaraki 300-4247, Japan

\textbf{Abstract}

Lysophospholipids (LPs), including lysophosphatidic acid (LPA), sphingosine 1-phosphate (S1P), lysophosphatidylinositol (LPI), and lysophosphatidylserine (LysoPS), are bioactive lipids that transduce signals through their specific cell-surface G protein-coupled receptors, LPA\textsubscript{1–6}, S1P\textsubscript{1–5}, LPI\textsubscript{1}, and LysoPS\textsubscript{1–3}, respectively. These LPs and their receptors have been implicated in both physiological and pathophysiological processes such as autoimmune diseases, neurodegenerative diseases, fibrosis, pain, cancer, inflammation, metabolic syndrome, bone formation, fertility, organismal development, and other effects on most organ systems. Advances in the LP receptor field have enabled the development of novel small molecules targeting LP receptors for several diseases. Most notably, fingolimod (FTY720, Gilenya, Novartis), an S1P receptor modulator, became the first FDA-approved medicine as an orally bioavailable drug for treating relapsing forms of multiple sclerosis. This success is currently being followed by multiple, mechanistically related compounds targeting S1P receptor subtypes, which are in various stages of clinical development. In addition, an LPA\textsubscript{1} antagonist, BMS-986020 (Bristol-Myers Squibb), is in Phase 2 clinical development for treating idiopathic pulmonary fibrosis, as a distinct compound, SAR100842 (Sanofi) for the treatment of systemic sclerosis and related fibrotic diseases. This review summarizes the current state of drug discovery in the LP receptor field.

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Abbreviations: LP, Lysophospholipid; LPA, lysophosphatidic acid; S1P, sphingosine 1-phosphate; LPI, lysophosphatidylinositol; LysoPS, lysophosphatidylserine; LPC, lysophosphatidylcholine; LPE, lysophosphatidylethanolamine; LPG, lysophosphatidylglycerol; ATX, autotaxin; Sphk, sphingosine kinases; GPCR, G protein-coupled receptor; MS, multiple sclerosis; EAE, experimental autoimmune encephalomyelitis; NMO, neuromyelitis optica; IPF, idiopathic pulmonary fibrosis; FDA, Food and Drug Administration; EMA, European Medicines Agency; NLM ID, National Laboratory of Medicine Identifier.

*Corresponding author.
E-mail address: jchun@scripps.edu (J. Chun).

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Introduction

Lysophospholipids (LPS) such as lysophosphatidic acid (LPA) and sphingosine 1-phosphate (S1P) are a class of bioactive lipids [1,2], which have a phosphate head group and a single fatty acyl chain attached to a 3-carbon backbone in their chemical structures. LPS have a fairly long history dating back to the early 20th century, but the field has shown markedly accelerated growth in recent decades (Fig. 1A). LPA and S1P are the best studied LPS and play pivotal roles in physiological events including cell proliferation, survival, motility, cytoskeletal changes, and electrophysiological changes as well as pathophysiological processes that include autoimmune disease, fibrotic disease, cancer, inflammation, bone diseases, pain, metabolic syndrome, infertility, and hair loss. LPA is produced through several enzymatic pathways. Lysophospholipase D (known as autotaxin, ATX) liberates a choline group from lysophosphatidylcholine (LPC), whereas phospholipase A$_1$ and A$_2$ deacylate phosphatidic acid to produce 2-acyl and 1-acyl LPA, respectively [2]. Importantly, LPA is also de novo synthesized from glycerol-3-phosphate by the action of acyltransferases [3]. By comparison, S1P is produced by phosphorylation of sphingosine via the sphingosine kinases, Sphk1/2 [4].

LPS exert their effects by binding to specific G protein-coupled receptors (GPCRs) [5] that are the largest membrane receptor family in the human genome and contain nearly 800 receptors (including olfactory receptors) [6]. There are currently six LPA (LPA1–6) and five S1P receptors (S1P1–5) [2,7,8]. Recently, lysophosphatidylinositol (LPI) and lysophosphatidylserine (LysoPS) have been also shown to activate cognate GPCRs [9]. About 40 receptors within the 350 non-olfactory GPCRs have been identified as lipid GPCRs to date, of which ~40% are LP receptors (Fig. 1B). It is likely that additional receptors for LPLs may...
be identified that interact with not only known receptor ligands but also other LPs such as lysophosphatidylethanolamine (LPE) and lysophosphatidylglycerol (LPG).

GPCRs remain a major target for drug discovery [10–12], and progress in the LP GPCR field has led to drug discovery efforts targeting LP receptors for a wide range of disorders, including the development of an actual medicine: fingolimod (FTY720, Gilenya) that was approved by the FDA for the treatment of multiple sclerosis (MS), and follow-up compounds targeting S1P receptors are being developed. Similarly, LPA signaling pathways are being explored and LPA1 antagonism is currently being evaluated clinically as a novel and effective drug for treating fibrotic disease. Here, we briefly review the LP receptors and recent advances of drug discovery efforts to target LP receptors; recent reviews on additional aspects of LP receptors have been published for LPA receptors [2,7], S1P receptors [4,13], and other LP receptors [9,14].

**Lysophospholipid receptors and signaling**

The International Union of Basic and Clinical Pharmacology (IUPHAR) receptor nomenclature currently lists two LP receptor groups as class A GPCRs that are the LPA receptors (LPA1–4) and the S1P receptors (S1P1–5) [8]. Recent studies identifying other LP receptors for LPI (LPI1) and LysoPS (LysoPS1–3) [8] will add to the LP receptor family (provisional IUPHAR names are noted). Fig. 1C summarizes the G proteins that couple with LP GPCRs.

**LPA receptors (LPA1–4)**

A first LP receptor that recognizes LPA was reported in 1996 and is now called LPA1 [15], and subsequently LPA2 and LPA3 were found by homology as reported in 1998 by Götzl’s group and in 1999 by Aoki’s group, respectively (Fig. 1A) [16,17]. In 2003, Shimizu and co-workers discovered a fourth LPA receptor, LPA4, from an orphan GPCR, GPR23/p2y9, that showed less than 20% amino acid sequence identity with LPA1–3 [18]. In 2006, we and others identified GPR92, which was another orphan GPCR closely related to LPA4, as a fifth LP receptor, LPA5 [19,20]. In 2008, a P2Y family orphan GPCR, p2y5, was deorphanized as the latest LP receptor, LPA6 [21].

LPA1 couples to Gα1/0, Gα11, and Gα12/13, resulting in LPA1-dependent cellular responses such as cytokines release, cell migration, adhesion, and Ca2+ mobilization [2,7,8]. Studies of mice lacking LPA1 showed pathophysiological roles of LPA–LPA1 axis in neural development, bone homeostasis, pain, neurodegeneration, and autoimmune disorders [2,5,7,22,23]. LPA4 antagonists have been developed and are entering Phase 2 clinical trials to treat idiopathic pulmonary fibrosis and fibrotic diseases (discussed below). LPA2 couples to multiple G-proteins including Gαi/0, Gα11, and Gα12/13 and is associated with cell migration and survival, cancer metastasis, neurodevelopment, and immune function [2,7,8]. LPA3 transduces signaling through Gαi/0 and Gα11/13 and prefers 2-acetyl-LPA containing unsaturated fatty acids. LPA3 knockout mice showed a reproductive defect where embryo implantation was abnormal [23]. In addition, LPA3 also regulates chemotaxis of immature dendritic cells and levels of pain [2,7,8]. LPA4 couples to Gαs, Gα11/0, Gα111, and Gα12/13 and is involved in neurite retraction, cell motility, cell aggregation and adhesion, osteoblast differentiation, and blood and lymphatic vessel formation [2,7,8]. A Japanese patent (2012-239450) indicates that LPA4 mediates adipocyte differentiation and its removal improves insulin resistance, based upon LPA4 knockout mice. LPA5 can couple to Gαs11/1 and Gα12/13, and increases cAMP accumulation via a non-αi/o mechanism [20]. LPA3 regulates neuropathic pain [24] and immune function [25,26]. LPA6 utilizes Gα12/13 for transducing signals through the Rho pathway and it has some preference for 2-acetyl-LPA rather than 1-acetyl-LPA [27]. LPA6 was discovered as an autosomal dominant genetic factor from patients with hypothyroidism simplex that is characterized by familial hair loss [21]. Genetics and in vitro studies support the idea that PA-PLA1α was required to activate LPAs by generating 2-acetyl-LPA [28].

**S1P receptors (S1P1–5)**

Hla and Macaig discovered an orphan GPCR, endothelial differentiation gene-1 (Edg-1), by a differential display method in 1990 [29], and Hla and co-workers identified it as a S1P receptor in 1998 based on the sequence homology with LPA1/Edg-2/Vzg-1 [30], which is now designated as S1P1. In 1997, two orphan GPCRs (Edg-5 and Edg-3, now called S1P2 and S1P3, respectively) were deorphanized as S1P receptors by Götzl and co-workers [31]. In 2000, the other two orphan GPCRs (Edg-6 and Edg-8), which show a highly conserved amino acid sequence with S1P1/2/3, were reported as S1P receptors S1P1 and S1P5, respectively [32,33]. S1P1 couples to Gα1/0 and induces intracellular signaling such as inhibition of cyclic AMP accumulation, intracellular Ca2+ increase, MAPK activation, small GTPase Rac activation, and likely other signals. S1P1 knockout mice [34] identified important roles of S1P1 in vascular and cardiac morphogenesis. Studies using genetic and pharmacological approaches have established that S1P1 regulates cell migration and lymphocyte trafficking in both homeostatic and disease settings [35], and is a major target of drug discovery as evidenced by fingolimod, which is discussed below. S1P2 preferably utilizes Gα12/13 for activating Rho signaling, while coupling to multiple G-proteins including Gαi/0 and Gα11/13. S1P2 abrogates motility by inhibiting Rac activity. Indeed, Cyster and co-workers demonstrated that B cells are retained in the germinal centers of lymphoid follicles through the S1P1–S1P2 axis [36]. S1P2 is reported to play important roles in vascular development and remodeling, cardiovascular function, bone maintenance, inner ear function, and metastasis [4,7,8,13]. S1P3 couples to Gαi/0, Gα11, and Gα12/13. No obvious phenotype or developmental defects were observed in S1P3 knockout mice [37]. S1P3 double knockout mice have reduced fertility [38], indicating the existence of redundancy among S1P receptors. S1P1–S1P3 signaling may be relevant to several diseases including breast cancer, sepsis, and liver fibrosis [4,7,8,13]. S1P1 transduces signaling through Gα11 and Gα12/13. This receptor is most prominent in adult hematopoietic tissues and is thought to promote cell migration. Studies in S1P1 knockout mice showed pivotal roles in thrombopoiesis, neutrophil migration, and T/H17 differentiation [4,7,8,13]. S1P3 can couple to Gα11 and Gα12/13 and considering its common roles in inhibition of cell migration and promotion of cell process retraction, it may preferentially couple to Gα12/13. S1P3 plays important roles in lymphocyte trafficking and NK cell differentiation [4,7,8,13]. S1P3 has yet-to-be determined functions in the central nervous system (CNS) in view of its expression in oligodendrocytes [39,40].
Other lysosphospholipid receptors (LPI and LysoPS₁₋₃)

GPR55 was first reported as an LPI receptor in 2007 [41], although it was thought at the time to be a cannabinoid receptor. Other studies support its identity as an LPI receptor [14], leading to its provisional IUPHAR name [8], LPI, couples with G₂₀α₁₃ and transduces signals to the RhoA–ROCK pathway [9,14]. Studies of mice lacking Lpir1 gene identified effects on bone homeostasis, pain, and autoimmune disorders [9,14].

The first LysoPS receptor, GPR34, was reported in 2006 [42] and confirmed by Aoki and co-workers who identified 2-acyl-LysoPS as a preferred ligand over 1-acyl-LysoPS [43]. They developed a novel TGFβ shedding assay that detects GPCR signaling [44]. This assay validated the first LysoPS receptor and identified additional members, leading to the proposed IUPHAR names designed to avoid confusion between the well-known abbreviation LPS for lipopolysaccharides [8]: GPR34 as LysoPS₁, P2Y10 as LysoPS₂, A630033H20 as LysoPS₂₀, and GPR174 as LysoPS₃. Further studies are necessary for understanding the roles of LysoPS₁–LysoPS₃x axis.

Drug discovery targeting S1P receptors

The most important success of drug discovery in the LP receptor field has been fingolimod (also known as FTY720) (Fig. 2A) [45]. In 1995, fingolimod was first synthesized from an immunosuppressive natural product, myriocin (ISP-1), that was isolated from culture broth of Isaria sinclairii [45]. As expected, oral administration of fingolimod prevents rodents from exhibiting symptoms in the allograft model [45]. In addition, fingolimod sequesters circulating lymphocytes, resulting in decreased peripheral blood lymphocyte count and increased numbers of lymphocytes in the secondary lymphoid organs [45]. However, the molecular basis of fingolimod activities was not demonstrated until 2002, when two groups independently proposed that fingolimod interacts with S1P receptors [46,47] through a phosphorylated metabolite of FTY720, FTY720-P, which binds to S1P₁, S1P₂, S1P₄, and S1P₅ as a high affinity agonist. Fingolimod was reported to be phosphorylated in vivo by S1P-generating enzyme, Sphk1 or particularly Sphk2 [48]. Paradoxically, fingolimod activity on lymphocytes involves not agonist but rather functional antagonist activity against S1P₁, revealed by phenocopying S1P₁ loss in lymphocytes [49]. FTY720-P downregulates S1P₁ on the cell surface by sustained internalization and subsequent degradation of the receptor [50,51], explaining reductions of lymphocyte egress from secondary lymphoid organs, thymus, and bone marrow [45]. In 2002, Brinkmann et al. first reported the prophylactic effects of fingolimod on an animal model of MS, experimental autoimmune encephalomyelitis (EAE) [46]. Moreover, Webb et al. demonstrated the therapeutic use of fingolimod on relapsing–remitting EAE in SJL mice [52]. These studies indicated that fingolimod had the potential for treating autoimmune diseases like MS. Fig. 2B illustrates the possible actions of fingolimod in MS.

Because of its hoped-for immunosuppressive effects, fingolimod was first tested in humans as an agent to improve renal transplantation [53]. However, it failed to reach its clinical endpoints even as an adjunctive agent at high dosage combined with cyclosporine for preventing renal allograft rejection in two Phase 3 studies, and was accompanied by adverse events [53], resulting in termination of the renal transplantation program. However, evidence from animal models of MS suggested fingolimod utility in MS, and in 2006, Phase 2 clinical data supported fingolimod use in MS [54]. In 2010, fingolimod (Gilenya, Novartis) received Food and Drug Administration (FDA) approval in the U.S. as a first-line agent for the treatment of relapsing forms of MS, followed by European Medicines Agency (EMA) approval in 2011 [55]. A 2014 Phase 3 extension study (FREEDOMS II) report confirmed the beneficial effects of fingolimod on relapse rates in MS patients and showed a consistent safety profile [56]. Fingolimod was ranked in the top 100 prescribed medicines by U.S. National Sales in the 4th quarter 2013 [57]. On the other side of the coin, fingolimod has potential side effects [58] that will need to be assessed, as well as in other agents targeting S1P receptors.

S1P receptor-targeted drugs, including fingolimod, are in clinical trials for treatment of several diseases including MS (Fig. 2A), ulcerative colitis, dermatomyositis, along with proof-of-concept evaluations in other disorders like amyotrophic lateral sclerosis (ALS) and stroke. Newer compounds are designed to have receptor subtype selectivity, such as S1P₁/S1P₅ specificity (spongimod, ponesimod, and RPC1063) and S1P₁ specificity (KRP-203 and GSK2018682). Considering the success of fingolimod, these next-generation compounds may exhibit improved efficacy and/or fewer side effects for a range of possible therapeutic indications.

Drug discovery targeting LPA receptors

Currently, no drugs targeting LPA receptors have been approved by any regulatory agency, although advances in the LP field support therapeutic relevance for a range of diseases including fibrotic diseases of the skin, lung, kidney, and liver (Fig. 2C). One disease that may benefit from LPA receptor modulation is idiopathic pulmonary fibrosis (IPF) which is characterized by interstitial infiltrates in lung bases, progressive dyspnea, and worsening of pulmonary function [59], and is associated with high mortality rates and thus represents an unmet medical need. In 2008, Tager et al. identified receptor-mediated LPA signaling as an important mechanism in lung fibrosis [60]. In a mouse model of bleomycin-induced lung fibrosis, LPA concentrations in bronchoalveolar lavage rose to 400 nM at 14 days after challenge. LPA₁ knockout mice were significantly protected from bleomycin-induced fibrosis based upon reduced mortality, fibroblast and leukocyte recruitment, and vascular leakage. In 2010, Amira Pharmaceuticals reported that a potent and orally bioavailable LPA₁ antagonist, AM966, was beneficial in treating bleomycin-induced lung fibrosis [61]. In 2011, Bristol-Myers Squibb acquired Amira Pharmaceuticals and had completed Phase 1 clinical trials of an LPA₁ antagonist, BMS-986202 (previously AM152). In 2014, another LPA₁ antagonist, BMS-986020, began Phase 2 clinical trials to test its efficacy on IPF (NLM ID: NCT01766817).

Another fibrotic disease is systemic sclerosis (scleroderma), which is a chronic connective tissue disease characterized by vasculopathy, autoimmunity, and extensive fibrosis [62]. Toku-mura et al. reported elevated levels of 2-arachidonoyl-LPA (as well as S1P) in sera of systemic sclerosis patients [63]. In 2011, Tager and co-workers revealed that LPA₁ knockout mice were protected in a mouse model of scleroderma [64], suggesting that LPA₁ antagonists may be effective for treating systemic sclerosis. Sanofi
has entered Phase 2 clinical trials of an LPA1/3 inhibitor, SAR100842, for systemic sclerosis (NLM ID, NCT01651143) with results suggesting efficacy but that require validation in larger clinical trials [65].

Conclusions

The LP field has advanced with an expanding repertoire of both receptors and ligands. Fingolimod’s entry into the treatment of MS has established lysophospholipid signaling as a clinically validated molecular pathway, raising prospects for novel therapeutics in a number of medically important therapeutic areas. Basic studies on LP receptor signaling mechanisms and their relationship with normal physiological and pathophysiological processes should continue to expand the development of novel therapeutics.

Conflict of interest

Y.K. declares no competing financial interests. H.M. is an employee of Ono Pharmaceuticals.

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