

PTP σ functions as a presynaptic receptor for the glypican-4/LRRTM4 complex and is essential for excitatory synaptic transmission

Ji Seung Ko^{a,1}, Gopal Pramanik^{b,c,1}, Ji Won Um^{a,1}, Ji Seon Shim^d, Dongmin Lee^e, Kee Hun Kim^f, Gug-Young Chung^a, Giuseppe Condomitti^{g,h}, Ho Min Kim^f, Hyun Kim^e, Joris de Wit^{g,h}, Kang-Sik Park^d, Katsuhiko Tabuchi^{b,c,i}, and Jaewon Ko^{a,j,2}

^aDepartment of Biochemistry, College of Life Science and Biotechnology, Yonsei University, Seoul 120-749, Korea; ^bDepartment of Molecular and Cellular Physiology, Shinshu University School of Medicine, Matsumoto 390-8621, Japan; ^cNational Institute for Physiological Sciences, The Graduate University for Advanced Studies, Okazaki 444-8787, Japan; ^dDepartment of Physiology, Kyung Hee University School of Medicine, Seoul 130-701, Korea; ^eDepartment of Anatomy and Division of Brain Korea 21 Biomedical Science, College of Medicine, Korea University, Seoul 136-705, Korea; ^fGraduate School of Medical Science and Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea; ^gVIB Center for the Biology of Disease, 3000 Leuven, Belgium; ^hCenter for Human Genetics, KU Leuven, 3000 Leuven, Belgium; ⁱPrecursory Research for Embryonic Science and Technology, Japan Science and Technology Agency, Kawaguchi 332-0012, Japan; and ^jDepartment of Psychiatry, Yonsei University College of Medicine, Seoul 120-751, Korea

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Leukocyte common antigen-related receptor protein tyrosine phosphatases—comprising LAR, PTP δ , and PTP σ —are synaptic adhesion molecules that organize synapse development. Here, we identify glypican 4 (GPC-4) as a ligand for PTP σ . GPC-4 showed strong (nanomolar) affinity and heparan sulfate (HS)-dependent interaction with the Ig domains of PTP σ . PTP σ bound only to proteolytically cleaved GPC-4 and formed additional complex with leucine-rich repeat transmembrane protein 4 (LRRTM4) in rat brains. Moreover, single knockdown (KD) of PTP σ , but not LAR, in cultured neurons significantly reduced the synaptogenic activity of LRRTM4, a post-synaptic ligand of GPC-4, in heterologous synapse-formation assays. Finally, PTP σ KD dramatically decreased both the frequency and amplitude of excitatory synaptic transmission. This effect was reversed by wild-type PTP σ , but not by a HS-binding-defective PTP σ mutant. Our results collectively suggest that presynaptic PTP σ , together with GPC-4, acts in a HS-dependent manner to maintain excitatory synapse development and function.

PTP σ | glypican | LRRTM4 | synaptic cell adhesion | heparan sulfate

Synaptic adhesion molecules orchestrate every aspect of synapse development, and certain synaptic adhesion proteins, called “synapse organizers,” coordinate the structure and function of mammalian synapses (1, 2). The leukocyte common antigen-related receptor protein tyrosine phosphatases (LAR-RPTPs), which comprise three members in vertebrates (LAR, PTP δ , and PTP σ), have recently emerged as synapse organizers (3). They mediate presynaptic differentiation via various postsynaptic ligands (3). All three members of the LAR-RPTP family bind to netrin-G ligand 3 (4): PTP δ binds to interleukin 1-receptor accessory protein-like 1 (5); PTP σ binds to TrkC (6); and PTP δ and PTP σ , but not LAR, bind to the Slit- and Trk-like proteins (7, 8). However, we do not yet understand the molecular basis for these various binding modes.

The above-mentioned LAR-RPTP ligands exist only in vertebrates, arguing that their synaptic adhesion pathways do not account for all of the evolutionarily conserved synaptic functions of the LAR-RPTPs. Indeed, studies have shown that invertebrate LAR-RPTP orthologs (dLAR in *Drosophila melanogaster* and PTP-3 in *Caenorhabditis elegans*) are crucial for nervous system development and function in such organisms (9). The candidates for the evolutionarily conserved LAR-RPTP ligands include the glypican (GPC) family of heparan sulfate proteoglycans (HSPGs), which are linked to the cell membrane via a glycosylphosphatidylinositol (GPI) anchor (10). The GPCs comprise six members (GPC-1 to -6) in mammals, two [Dally and Dally-like protein (Dlp)] in fruit fly, and one (GPN-1) in worm (11). In fruit

fly, Dlp and another HSPG syndecan (Sdc) function redundantly to regulate midline axon guidance (12), but perform distinct functions in synapse development via binding to dLAR (13, 14). In vertebrates, GPCs are predominantly expressed during nervous system development, where they serve as guidance cues for axonal navigation and neuronal migration. Consistent with the role in axon guidance, GPCs also interact with the axon guidance molecule Slit (15, 16). Moreover, they regulate several signaling pathways, including the Wnt, Hedgehog, fibroblast growth factor, and bone morphogenic protein pathways (17). Furthermore, GPCs are proteolytically cleaved by a furin-like convertase, generating two subunits that are attached by one or more disulfide bonds, although the requirement for this processing for various GPC functions has not been clearly established (18). We do not yet fully understand the mechanisms through which GPCs function at mammalian synapses, but they were recently found to be presynaptic receptors for leucine-rich repeat transmembrane protein 4 [LRRTM4 (refs. 19 and 20; see also ref. 21)]. Given that GPCs

Significance

This paper documents and systematically characterizes the molecular interactions of protein tyrosine phosphatase σ (PTP σ) with glypicans (GPCs). The identified interactions require heparan sulfate (HS), suggesting that GPCs are a major source of HS for PTP σ at excitatory synapses. Strikingly, we found that leucine-rich repeat transmembrane protein 4 (LRRTM4) induces presynaptic differentiation via the PTP σ /GPC interaction, suggesting that PTP σ may function as a coreceptor for GPCs in presynaptic neurons. More importantly, we found that HS-binding ability of PTP σ is critical for excitatory synaptic transmission. These results expand our previous understanding of how synaptic adhesion pathways regulate excitatory synapse development and shed light on GPCs/LRRTM4 *trans*-synaptic signaling. Moreover, to our knowledge, this is the first study to document the physiological significance of HS in the presynaptic function of mammalian neurons.

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¹J.S.K., G.P., and J.W.U. contributed equally to this work.

²To whom correspondence should be addressed. Email: jaewonko@yonsei.ac.kr.

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are GPI-anchored, it seems likely that yet-unidentified presynaptic membrane protein(s) may act as coreceptors for the GPC/LRRTM4 interaction.

Here, we show that GPC-4 binds PTP σ with high affinity in a heparan sulfate (HS)-dependent manner. Intriguingly, PTP σ binds only to cleaved GPC-4, which is highly expressed at an early stage of brain development, and further associates with LRRTM4 in postnatal and adult brains. More importantly, the HS-binding property of PTP σ is functionally critical for the synaptogenic action of LRRTM4 and for excitatory synaptic transmission in cultured neurons. Thus, we herein show, to our knowledge, for the first time that PTP σ is a bona fide presynaptic receptor for the GPC-4/LRRTM4 synaptic adhesion complex.

Results

GPC-4 Is a Potential Ligand for PTP σ . To identify additional ligand(s) for LAR-RPTPs in vivo, we chose to search for ligands of PTP σ because it is the most highly expressed LAR-RPTP in rat brain (22). We generated an expression vector that encoded the PTP σ extracellular domains fused to the Fc domain of human Ig (PTP σ -IgC) and one encoding the human Fc domain alone as a control protein (IgC; Fig. 1A). We immobilized these Ig fusion proteins and performed affinity chromatography using rat brain synaptosomes (Fig. 1B). The proteins from each silver-stained gel slice that showed a distinct band were purified on immobilized PTP σ and subjected to mass spectrometry (MS) (Fig. 1B). Among the identified peptides (Table S1), three were derived from GPC-4 (Fig. 1C and D and Fig. S1A and B). Previously,

GPC-2 was shown to bind to PTP σ to promote outgrowth of dorsal root ganglion neurons (23); however, whether other GPCs also bind PTP σ has not been determined. First, to validate whether GPC-4 directly binds to PTP σ on the cell surface, we performed binding assays between recombinant Ig-fusion proteins of GPC-4 (Ig-GPC-4) and HEK293T cells expressing HA-tagged PTP σ (Fig. 1E). EGFP-fused LRRTM4 (Fig. 1E; ref. 19) and mVenus-fused LRRTM2 were expressed in HEK293T cells as positive and negative controls, respectively (Fig. 1E). We found that PTP σ and LRRTM4 avidly bound to GPC-4, whereas LRRTM2 did not (Fig. 1E). No interaction was observed between LRRTM4 and neurexin-1 β recombinant proteins (Fig. S1C), which is consistent with our previous observation that excess soluble neurexin-1 β recombinant proteins do not inhibit the synaptogenic activity of LRRTM4 (19). We did, however, observe an interaction between neurexin-1 β and LRRTM4 recombinant proteins (Fig. S1D), suggesting that these proteins interact with each other under certain conditions (19). In addition, GPC-4 failed to show binding to any other cell-surface protein examined, indicating that it forms a specific interaction with PTP σ (Fig. S2). To estimate the binding affinity between GPC-4 and PTP σ , we incubated HA-PTP σ -expressing and control HEK293T cells with increasing amounts of Ig-GPC-4 and measured the cell-surface-bound proteins with an HRP-tagged secondary antibody. After we subtracted the nonspecific binding, we performed Scatchard analysis, assuming a single independent binding site for GPC-4 in each PTP σ molecule, and obtained a K_d of 41.3 ± 3.6 nM (Fig. 1F). Although this finding should be interpreted with some caution because the used dimeric GPC-4 ligands can produce an increased interaction affinity, our results indicate that GPC-4 binds to PTP σ with high affinity.

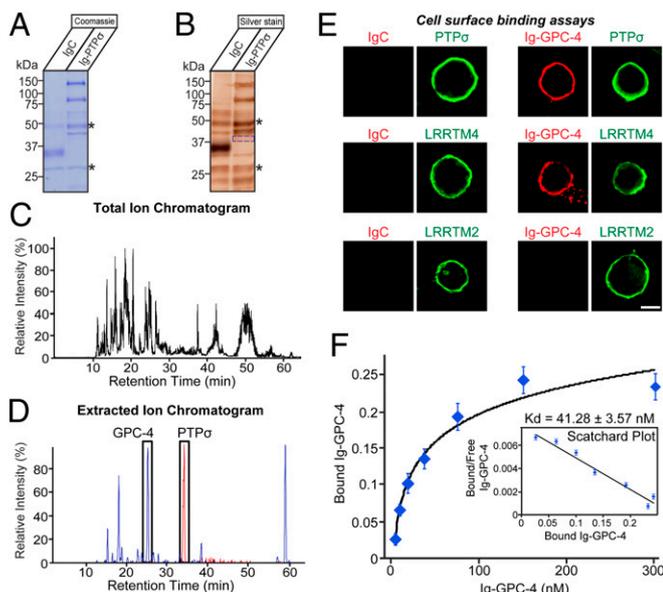


Fig. 1. Affinity purification of GPC-4 as a PTP σ -ligand in rat brain. (A) Coomassie blue-stained gel of recombinant Ig-control and Ig-PTP σ fusion proteins used for affinity chromatography. (B) Solubilized rat synaptosomes were subjected to pull-down assays with IgC or Ig-PTP σ . A blue box indicates a specific band unique to the Ig-PTP σ -bound fraction. Asterisks indicate the cleaved Ig-PTP σ proteins or IgC heavy chain. (C and D) Total ion chromatogram of a liquid chromatography (LC) separation of Ig-PTP σ -bound eluates (C). (D) Extracted ion chromatograms of ion m/z 972.03 and 517.28 from PTP σ (34.05 min) and GPC-4 (24.88 min). (E) Cell-surface binding assays. HEK293T cells expressing HA-PTP σ , LRRTM4-EGFP, or LRRTM2-mVenus were incubated with control IgC or Ig-GPC-4 and analyzed by immunofluorescence imaging for Ig-fusion proteins (red) and HA/mVenus (green). [Scale bar: 15 μ m (applies to all images).] (F) Saturation binding of Ig-GPC-4 to PTP σ expressed in HEK293T cells. Inset shows a Scatchard plot generated by linear regression of the data, with the K_d calculated from three independent experiments. Data are presented as means \pm SEM.

PTP σ Ig Domains Are Required for the Interaction with GPC-4.

To determine which PTP σ domains interact with GPC-4, we performed cell-surface binding assays using constructs expressing full-length PTP σ (PTP σ -full), its Ig domains alone (PTP σ -Ig), or an Ig-domain-deleted protein (PTP σ - Δ Ig) (Fig. 2A). IgC-GPC-4 bound to HEK293T cells expressing PTP σ -full and -Ig, but not those expressing PTP σ - Δ Ig (Fig. 2B). Recent studies have established that alternative splicing events at the Ig domains of LAR-RPTPs determine their binding affinity toward postsynaptic ligands (3, 5, 6). Thus, we examined whether the GPC-4/PTP σ interaction is regulated by similar alternative splicing inserts (Fig. 2C). GPC-4 strongly bound to all four splice variants of PTP σ and three splice variants of LAR (Fig. 2C and D), but showed weaker binding to all four splice variants of PTP δ (Fig. 2E). To assess the affinities of these GPC-4 interactions with PTP σ variants, we expressed PTP σ variants on the surfaces of HEK293T cells and estimated the binding affinity of different PTP σ isoforms (Fig. 2F and Fig. S3A). All PTP σ variants displayed nanomolar affinities comparable to that of the PTP σ -full (Fig. 2F and Fig. S3A). Moreover, all LAR and PTP δ variants bound to GPC-4 recombinant proteins with similar nanomolar affinities (Fig. S3B and C). These data suggest that alternative splicing of the LAR-RPTPs does not regulate their binding affinity for GPC-4 per se.

The GPC-4/PTP σ Interaction Occurs in the Same Cell Membrane.

Our observation of a GPC-4/PTP σ interaction in cell-surface binding assays (Figs. 1 and 2) raised the possibility that such binding could mediate *trans*-cellular adhesion, as observed in synapses. Therefore, we performed cell-adhesion assays (Fig. 3A and B). We prepared L cells (red fluorescent cells) expressing DsRed alone (control) or coexpressing DsRed with PTP σ , and L cells (green fluorescent cells) expressing EGFP alone (control) or coexpressing EGFP with GPC-4 or TrkC. These cells were mixed and incubated for up to 60 min, and cell aggregation was measured (Fig. 3B). Quantification revealed that GPC-4-expressing cells did not form any aggregated clumps with PTP σ -expressing cells (Fig. 3A and B). In contrast, TrkC-expressing cells formed

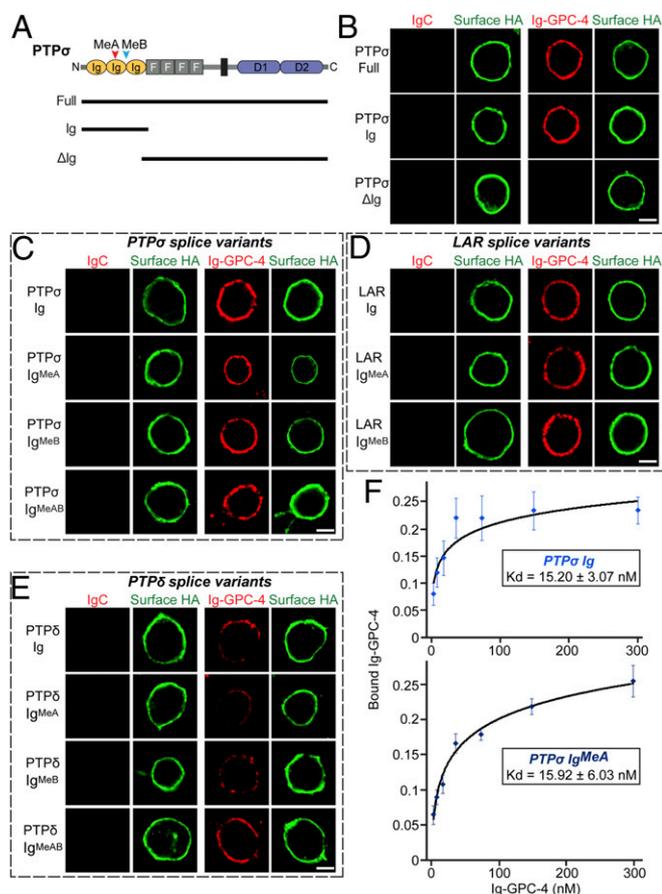


Fig. 2. Analysis of the GPC-4-binding domain of LAR-RPTPs. (A) Diagrams of the PTP σ vectors used in the cell-surface binding assays. F, fibronectin type III (FNIII) domains; D1, phosphatase domain 1 (catalytically active); D2, phosphatase domain 2 (catalytically inactive). (B) HEK293T cells expressing HA-tagged PTP σ -full (a splice variant of PTP σ that lacks an insert in splice sites MeA and MeB), PTP σ -Ig, or PTP σ - Δ Ig were incubated with IgC or Ig-GPC-4 and analyzed by immunofluorescence imaging for the Ig-fusion proteins (red) and surface-exposed HA-PTP σ proteins (green). (C–E) HEK293T cells expressing the indicated splice variants of LAR-RPTPs Ig1–3 were incubated with IgC or Ig-GPC-4 and analyzed by immunofluorescence for the Ig-fusion proteins (red) and surface-exposed HA-tagged LAR-RPTPs (green). [Scale bars, B–E: 10 μ m (applies to all images).] (F) Saturation binding of Ig-GPC-4 to a subset of PTP σ splice variants (PTP σ Ig and PTP σ Ig^{MeA}) expressed in HEK293T cells. See also Fig. S3 for the other splice variants of PTP σ . Data are presented as means \pm SEM.

strong aggregations with PTP σ -expressing cells, which is consistent with their reported *trans*-interaction (ref. 6; Fig. 3A and B). These data suggest that the GPC-4/PTP σ interaction mainly occurs in the *cis*-configuration.

PTP σ Requires HS to Interact with GPC-4. PTP σ was previously shown to bind the HS chains of HSPGs, such as agrin and collagen XVIII, and to colocalize with HSPGs on sensory neurons (23, 24). Therefore, we next examined whether the HS chains of GPC-4 mediate their binding to PTP σ . We first generated a PTP σ construct (PTP σ -AAAA) in which four lysines of the first Ig domain (K68, K69, K71, and K72) were all replaced with alanines to abrogate HS binding (Fig. 3C and ref. 23). We then expressed either PTP σ wild-type (WT) or PTP σ -AAAA in HEK293T cells, treated the cells with heparinase III (hep III; 1 U/mL) for 2 h to remove the HS chains from PTP σ , and stained the cells with a monoclonal 3G10 antibody that reacts only with hep III-treated HS chains (25). We found that cells

expressing PTP σ WT, but not PTP σ -AAAA, reacted to the 3G10 antibody (Fig. 3D). To further examine whether the HS chains attached to PTP σ are required for the interaction with GPC-4, we treated PTP σ WT-expressing HEK293T cells with hep III and then used hep III-treated Ig-GPC-4 in cell-surface binding assays (Fig. 3E). Hep III treatment drastically reduced the binding of hep III-treated Ig-GPC-4 to PTP σ (Fig. 3E), suggesting the HS chains of PTP σ are required for this interaction. Consistently, PTP σ -AAAA failed to bind to GPC-4 (Fig. 3E). Whether the Ig1 domain of PTP σ was necessary and sufficient for GPC-4 binding could not be demonstrated because of poor surface transport of the PTP σ Ig1 construct (Fig. S4A and B). Together, these data unequivocally demonstrate that the HS-binding ability of PTP σ is required for its interaction with GPC-4 (Fig. 3E). Lastly, because many cell-adhesion interactions, including those mediated by neuroligins/neurexins or neuroligins/LRRTM2, require extracellular Ca²⁺ ions (26, 27), we tested whether the GPC-4/PTP σ interaction requires Ca²⁺. However, we found that the Ca²⁺ chelator EGTA did not influence their binding (Fig. 3F). This finding suggests that the interaction of PTP σ with GPC-4 is Ca²⁺-independent, analogous to the interactions of PTP σ with other ligands (4, 6).

PTP σ Interacts with Cleaved GPCs. To further corroborate the GPC-4/PTP σ interaction (Figs. 1–3), we performed pull-down assays using Ig-GPC-4 or IgC (negative control) against lysates from HEK293T cells expressing HA-PTP σ , HA-PTP σ AAAA, HA-LAR, HA-PTP δ , or NL1-mVenus. Ig-GPC-4 captured all three LAR-RTP isoforms, but not PTP σ -AAAA or NL1 (Fig. 3G). We also used Ig-PTP σ or IgC to conduct pull-down assays with HEK293T cells expressing HA-tagged GPCs. The GPC-1 and -5 vectors were not efficiently processed in the HEK293T cells, because no bands were observed around \sim 37 kDa in HA-GPC-1- or HA-GPC-5-transfected cell lysates; in contrast, the other GPCs showed both \sim 65-kDa bands representing uncleaved species and \sim 37-kDa bands representing cleaved species (Fig. 3H). Our pull-down assays showed that the immobilized Ig-PTP σ effectively bound to cleaved GPCs, but not uncleaved GPCs (Fig. 3H). We also confirmed this finding using Ig-GPC-4 351-AISA (in which the furin-like convertase cleavage consensus R³⁵¹ISR³⁵⁴ of GPC-4 was changed to A³⁵¹ISA³⁵⁴), showing that the uncleaved recombinant GPC-4 proteins do not interact with PTP σ (Fig. S4C; see also Fig. S5). This binding property differs from that of the GPC-4/LRRTM4 interaction, where both uncleaved and cleaved GPCs bind to LRRTM4 (Fig. S4D) (19). Surprisingly, SDC-2 and -3, members of another HSPG family, failed to interact with PTP σ (Fig. S5A), suggesting that LAR-RPTPs use an evolutionarily distinct strategy for mediating synaptic adhesion; whereas dLAR binds both GPCs and SDCs, mammalian LAR-RPTPs prefer GPCs (28). Consistent with our above-described results (Fig. 3E), a GPC-4 mutant [GPC-4 AAA, in which the HS-attachment sites of GPC-4 (S494/S495/S500) were all mutated; ref. 19] showed no interaction with PTP σ in pull-down assays (Fig. 3H). We also observed a significant degree of enrichment of GPC-4, LRRTM4, and TrkC—but not NL1 or GluA1 (additional negative controls)—in the PTP σ -bound fraction of detergent-solubilized postnatal day 7 (P7) and P42 rat brain membrane fractions in pull-down assays using Ig-PTP σ fusion proteins (Fig. S5B). In addition, LRRTM4 antibodies coprecipitated with GPC-4 and PTP σ in coimmunoprecipitation assays performed on P7 rat brain membrane fractions (Fig. S5C). Notably, proteolytic cleavage of GPC-4 was developmentally regulated, exhibiting decreased cleavage during postnatal development (Fig. S5D), and only cleaved GPC-4 formed complexes and cofractionated with PTP σ in rat brains (Fig. S5B and E), in accordance with the results from pull-down assays in HEK293T cells (see also Fig. 3H). Moreover, we showed that Ig-PTP σ bound to LRRTM4 expressed in HEK293T cells in the presence of GPC-4 WT, but not in the presence of GPC-4 AAA

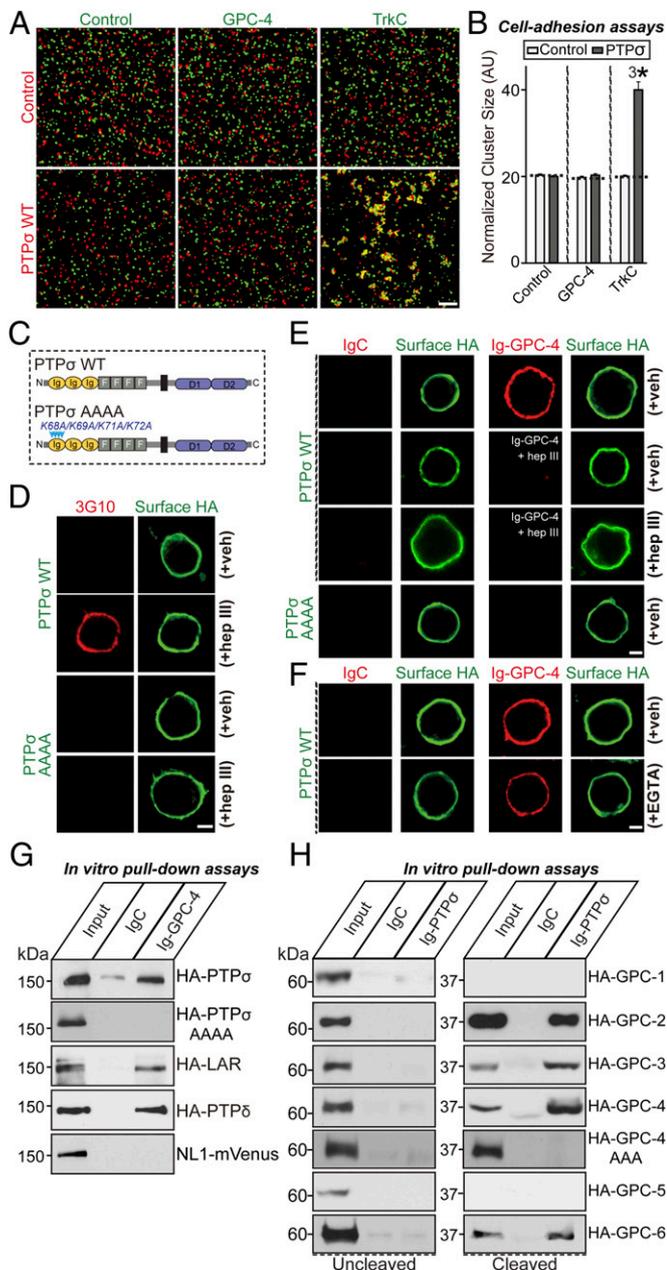


Fig. 3. PTP σ interacts with GPC-4 in a HS-dependent manner. (A and B) Representative images (A) and quantification of data (B) from cell-adhesion assays. HEK293T cells expressing EGFP alone (control) or coexpressing PTP σ with EGFP were mixed with HEK293T cells expressing DsRed alone (control) or coexpressing GPC-4 or TrkC with DsRed. The cells were imaged, and aggregations were quantified. [Scale bar: 100 μ m (applies to all images).] $^{3*}P < 0.001$. (C) Schematic diagrams of PTP σ constructs used in D and E. (D) HEK293T cells were transfected with the indicated PTP σ vectors and treated with vehicle (+veh) or 1 U/mL heparinase III (+hep III). The cells were then stained with HA antibody (green) to detect surface-exposed PTP σ (red) under nonpermeabilized conditions. They were then permeabilized and stained with the 3G10 antibody. (E) Transfected HEK293T cells were treated with vehicle or hep III, incubated with IgG or IgG-GPC-4, and then analyzed by double-immunofluorescence microscopy for Ig-fusion proteins (red) and surface-exposed HA-PTP σ (green). (F) As in E, except that cells were also incubated with 10 mM EGTA (+EGTA). [Scale bars, D–F: 10 μ m (applies to all images).] (G and H) Pull-down assays were performed with IgG and Ig-GPC-4 (G) or Ig-PTP σ (H) by using HEK293T cells expressing the indicated vectors (input: 1% of total). The numbers on the left indicate molecular mass markers (kDa). Immunoblot analyses showed that GPCs are expressed in two positions: a ~65-kDa band representing the full-length HA-GPCs (uncleaved) and a ~37-kDa band representing the N-terminal proteolytic fragment (cleaved).

(Fig. S5F). These results suggest that PTP σ specifically forms complexes containing GPCs and LRRTM4 (inferred through GPCs) in vivo.

PTP σ Is Required for LRRTM4-Mediated Presynaptic Differentiation in Cultured Neurons. Based on the direct interaction of GPCs with LAR-RPTPs (this work), the direct interaction of GPCs with LRRTM4 (19, 20) and the biochemical nature of GPCs as GPI-anchored proteins, we hypothesized that LAR-RPTPs might be functional presynaptic receptors for LRRTM4. To directly address this hypothesis, we used previously characterized lentiviral short-hairpin interference RNAs (shRNAs) against PTP σ (sh-PTP σ) or LAR (sh-LAR) [ref. 8; see also Fig. S5G for validation of PTP σ knockdown (KD) at the protein level]. Cultured hippocampal neurons were infected with control lentivirus (control) or lentiviruses expressing sh-LAR or sh-PTP σ , or coinfecting with lentiviruses expressing LAR-KD and PTP σ -KD (sh-LAR/sh-PTP σ), and various heterologous synapse-formation assays were performed with infected neurons and HEK293T cells expressing LRRTM2, LRRTM4, or EGFP alone (control) (Fig. 4). PTP σ -KD alone, but not LAR-KD alone, significantly reduced the synaptogenic activity of LRRTM4, but not that of LRRTM2 (Fig. 4). These data are consistent with a previous report that LRRTM2 requires neu-rexins for its synaptogenic activity (29). Reexpression of PTP σ WT (+PTP σ WT) completely reversed the deficit in the synapse-formation activity of LRRTM4 observed in LAR/PTP σ -deficient neurons (Fig. 4), whereas reexpression of PTP σ -AAAA (+PTP σ -AAAA) did not. The data suggest that the HS-dependent interactions of PTP σ with GPCs are essential for inducing the pre-synaptic differentiation elicited by LRRTM4 (Figs. 3E and 4). We confirmed our previous observation that GPC-4 KD led to a significant deficit in the synaptogenic activity of LRRTM4 (19) (Fig. S6A and B). This impairment of LRRTM4 activity was rescued by reexpression of GPC-4 WT, but not by expression of GPC-4 351-AISA (Fig. S6A and B), consistent with our pull-down data showing that only cleaved GPC-4 bound to PTP σ (Fig. 3). These results collectively suggest that PTP σ acts via GPCs to function as a presynaptic receptor for LRRTM4.

The HS-Binding Sequence of PTP σ Is Essential for Excitatory Synaptic Transmission in Cultured Neurons. Most of the LAR-RPTP ligands have been demonstrated to cluster presynaptic vesicles and neurotransmitter release machineries by directly interacting with individual LAR-RPTP isoforms in the axons of cocultured neurons when expressed in heterologous cells, suggesting that LAR-RPTPs act as hubs for presynaptic organization (3). This notion, together with the failure of PTP σ -AAAA to restore the synaptogenic activity of LRRTM4 (Fig. 4), prompted us to ask whether the HS-binding property of LAR-RPTPs is also involved in some presynaptic functions (e.g., neurotransmitter release or synaptic transmission). Strikingly, no previous study had examined whether LAR-RPTPs themselves are involved in the presynaptic functions of mammalian neurons. To address these questions, we first monitored the paired-pulse ratio (PPR), a measure that is routinely used to identify changes in the neurotransmitter release probability (30). We first infected cultured hippocampal neurons with control lentiviruses (control) or coinfecting them with lentiviruses expressing sh-LAR/sh-PTP σ and measured the PPR, which was calculated by delivering two stimuli 20 ms apart and then dividing the amplitude of the second excitatory postsynaptic current (EPSC₂) by the amplitude of the first EPSC (EPSC₁). There was no significant change in PPR between control and LAR/PTP σ -deficient neurons over a range of interstimulus intervals (20–200 ms), suggesting that LAR and PTP σ do not directly regulate the probability of neurotransmitter release at excitatory synapses (Fig. S7A and B). We next recorded miniature EPSCs (mEPSCs) in the cultured hippocampal neurons (Fig. 5). We infected neurons with control lentiviruses expressing EGFP (control) only, sh-LAR

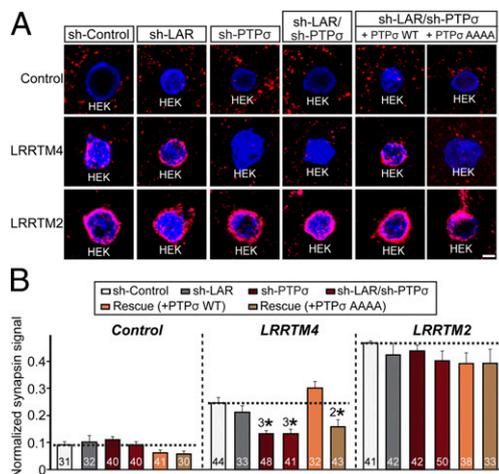


Fig. 4. PTP σ is a functional coreceptor for GPC-4 in mediating LRRTM4-induced presynaptic differentiation. (A) and (B) Representative images (A) and quantification (B) of the heterologous synapse-formation activities of LRRTM4 and LRRTM2. Neurons were infected with lentiviruses expressing sh-Control, -LAR, or -PTP σ only or were coinfecting with lentiviruses expressing PTP σ -KD/LAR-KD (sh-LAR/sh-PTP σ), LAR/PTP σ shRNA plus PTP σ WT (+PTP σ WT rescue), or LAR/PTP σ shRNA plus PTP σ AAAA (+PTP σ AAAA rescue). The infected neurons were then cocultured for 2 d with HEK293T cells expressing EGFP alone (control), LRRTM4-EGFP (LRRTM4), or LRRTM2-mVenus (LRRTM2) and stained with antibodies against EGFP (blue) and synapsin (red). The synapse-forming activity was quantified by measuring the ratio of synapsin staining to EGFP fluorescence. The statistics shown in D were determined by ANOVA Tukey's test. ²* $P < 0.01$; ³* $P < 0.001$. [Scale bar: 25 μ m (applies to all images).] *N* numbers are the number of HEK293T cells as indicated in the bar graphs.

only, sh-PTP σ only, sh-LAR and -PTP σ , or sh-LAR and -PTP σ with coexpression of either PTP σ WT or PTP σ -AAAA, and recorded mEPSCs (Fig. 5). Remarkably, sh-PTP σ , but not sh-LAR, significantly decreased the frequency and amplitude of mEPSCs, strengthening our previous supposition that PTP σ is required for excitatory synapse development (8). This reduction in mEPSC frequency and amplitude among PTP σ - and LAR/PTP σ -deficient neurons was completely reversed by the reexpression of PTP σ WT. Although PTP σ -AAAA rescued mEPSC amplitude, it failed to recover the mEPSC frequency (Fig. 5). To support these electrophysiological data, we used an immunocytochemical approach to determine whether PTP σ KD alters the excitatory synapse structure in cultured neurons. We found that PTP σ KD significantly decreased excitatory synapse density, as determined by VGLUT1 staining, an effect that was completely rescued by reexpression of PTP σ WT, but not PTP σ -AAAA (Fig. S7 E and F). The experimental conditions did not affect the intrinsic properties of the infected neurons, because we observed no change in the membrane capacitance (C_m) or input resistance (R_m) (Fig. S7 C and D). Our data suggest that PTP σ maintains the structure and function of excitatory synapses in a HS-binding-dependent manner.

Discussion

In the present study, we explored the significance of interactions between LAR-RPTP and GPC synaptic proteins in mammalian neurons. It is likely that these interactions are dictated by the availability of HS in neuronal membranes (Fig. 3), but we clearly demonstrated that the HS-binding activity of PTP σ is required for these proteins to act as the presynaptic receptor for a post-synaptic adhesion molecule LRRTM4 and as a key element in excitatory synaptic transmission (Figs. 4 and 5). An unusually large number (>25) of different HSPGs (31) that are expressed in the nervous system have been implicated in many aspects of neural development, including neurogenesis, axon elongation and pathfinding, and synapse formation (32). Most notably,

aggrins identified in neuromuscular synapses have been demonstrated to mediate acetylcholine receptor clustering (33). In addition to aggrins, other neural proteoglycans, such as aggrecan, neurocan, brevican, testicans, SDCs, and GPCs, have been identified and shown to function in the nervous system (32). In recent years, SDCs and GPCs in particular have emerged as crucial regulators of cell migration and axon guidance in flies through binding to LAR (14, 28). However, their roles in mammalian synapses have only begun to be elucidated (19, 20, 34). In the present study, we found that mammalian GPCs, but not SDCs, bind to mammalian LAR-RPTPs (Fig. S5A). This is in stark contrast to the prevailing concept in flies that both Dally-like and SDCs bind to dLAR, suggesting that mammals and flies use a different set of ligand-receptor complexes to regulate nervous system development. Moreover, LRRTM4 exists only in vertebrates and not in invertebrates, strongly supporting the interpretation that mammals use a unique synaptic adhesion complex. Recently, GPC-4 and -6, as astrocyte-secreted signaling molecules, were demonstrated to promote excitatory synapse formation through recruitment of the AMPA receptor subunit, GluA1 (34). It is possible that a PTP σ /GPCs/LRRTM4 complex might control AMPA receptor function. In support of this supposition, LRRTM4 was recently annotated as an AMPA receptor constituent in a multi-epitope proteomic analysis (35). Moreover, presynaptic neuexin-3 was recently reported to control post-synaptic AMPA receptor trafficking through direct binding to LRRTM2 (36); thus, it is probable that presynaptic PTP σ also does so by behaving similarly. Directly exploring the function of PTP σ /GPCs/LRRTM4 synaptic adhesion pathways *in vivo* will ultimately require systematic characterization of conditional knockout mice lacking PTP σ and/or GPCs. However, the involvement of other GPC isoforms in brain functions, particularly synapse development, has not been extensively explored. We examined the expression patterns of mRNAs encoding all six GPCs during several different developmental stages in mice (Fig. S8). We found that GPC-1 and -4 are the major isoforms in the hippocampus (Fig. S8). Intriguingly, GPC-4 mRNA was found in the dentate gyrus, whereas GPC-1 mRNA signals were stronger in the CA3 region of hippocampus, suggesting distinct distribution patterns of individual GPC isoforms in several brain regions (Fig. S8). The functional regulation of synaptic adhesion proteins by carbohydrate molecules, as reported in this work, is not unprecedented. For example, post-translational modification of neural cell adhesion molecule (NCAM) by the addition of polysialic acid (PSA) to the fifth Ig domain

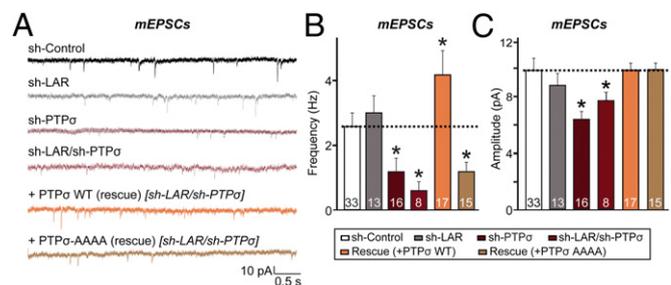


Fig. 5. PTP σ is required for HS-binding-dependent excitatory synaptic transmission in cultured hippocampal neurons. (A) Representative traces of mEPSCs recorded at days *in vitro* (DIV) 14–16 in cultured hippocampal neurons infected at DIV3 with lentiviruses expressing sh-Control, -LAR, or -PTP σ only or were coinfecting with lentiviruses expressing sh-LAR/sh-PTP σ , sh-LAR/sh-PTP σ plus PTP σ WT (+PTP σ WT rescue), or sh-LAR/sh-PTP σ plus PTP σ AAAA (+PTP σ AAAA rescue). (B and C) Summary graphs of the frequencies (B) and amplitudes (C) of mEPSCs from the infected neurons. The data shown in B and C are presented as means \pm SEM. * $P < 0.05$ (Student's *t* test). *N* values indicated in bar graphs correspond to the number of neurons.

abrogates the homophilic binding properties of the protein and reduces cell migration and invasion. Also, removal of PSA from NCAM by enzymatic digestion has been shown to abolish synaptic plasticity (37), suggesting that structural alterations produced by posttranslational modification of synaptic adhesion molecules is crucial for synaptic function. The importance of HS has been directly shown in knockout mice deficient for HS synthesis; these mice exhibit malformations in specific regions of the brain that reflect an altered fibroblast growth factor distribution, decreased cell proliferation, and disrupted axon pathfinding (38). Moreover, multiple signaling pathways involved in axon guidance, such as Slit–Robo and Netrin–Frazzled/DCC (deleted in colorectal cancer), require HS (39). In addition, synaptic transmission at the fly neuromuscular junction is differentially affected by KD of two different enzymes that regulate HSPG sulfation (40), suggesting that HS modifications are important for synapse development. Our findings suggest that the ability of PTP σ to bind to HS initiates multifaceted downstream signaling pathways in presynaptic neurons to control distinct aspects of excitatory synapse development. One major remaining question is how HS-bound PTP σ contributes to organizing general synapse development. HS and its analogs reportedly induce the oligomerization of PTP σ in solution, stabilize PTP σ oligomers via sulfation, and promote neurite extension (23). These findings, together with our present work, suggest that HS-bound presynaptic

PTP σ induces formation of multimeric complexes with various postsynaptic ligands, thereby contributing to dynamic modulation of presynaptic organization. In addition, HS-bound PTP σ may preferentially elicit activation of specific synaptic adhesion pathway(s) via distinct *cis*- and/or *trans*-synaptic ligands.

Methods

Expression constructs and antibodies used in this study are described in detail in *SI Methods*. All cell biological assays were performed as described (27, 41). Generation of lentiviral shRNA plasmids, production, and characterization of recombinant lentiviruses were performed as described (42) and are detailed in *SI Methods*. Electrophysiology recordings in cultured hippocampal neurons were performed as described (43). See *SI Methods* for more details.

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