

# Direct interaction of receptor tyrosine kinases, EphA4 and PDGFR $\beta$ , plays an important role in the proliferation of neural stem cells

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**Abstract:** Receptor tyrosine kinases mediate the extracellular signals and transmit them into the cytoplasm by activating intracellular proteins through tyrosine phosphorylation. Both Ephs and platelet-derived growth factor (PDGF) receptors (PDGFRs) have been implicated in neurogenesis, but the functional interaction between these two pathways is poorly understood. Here, we demonstrated that EphA4 directly interacts with PDGFR $\beta$  and mutually activates each other when expressed in HEK293T cells. H9-derived neural stem cells express Ephs and PDGFRs, and their proliferation is stimulated by ephrin-A1 and PDGF-BB with further augmentation by their combined application. As both EphA4 and PDGFR $\beta$  play important roles in preventing neurodegeneration and promoting neuroprotection, their interaction and transactivation might transduce the signal through the EphA4/PDGFR $\beta$  complex and augment the proliferation of neural stem cells.

**Keywords:** EphA4, PDGFR $\beta$ , neural stem cell, transactivation, proliferation

## Introduction

Receptor tyrosine kinases (RTKs) constitute a distinct family of transmembrane proteins present only in multicellular animals. These proteins transduce extracellular signals into the cytoplasm and are implicated in regulating cell growth, proliferation, migration, differentiation, and apoptosis.<sup>1-4</sup> As the largest RTK subfamily, Eph receptors have type A and B subclasses according to their specificity to bind with their ligands, ephrins.<sup>5</sup> In general, EphAs are bound with ephrin-As and EphBs are bound with ephrin-Bs; however, cross-specificity is also present. The ephrin-A class of ligands has a glycosyl phosphatidylinositol linkage to contact the cell membrane, whereas the ephrin-B class of ligands has a different structure containing a short cytoplasmic and transmembrane domain. Cell-cell contact-dependent signaling pathway from ephrins to Ephs (forward signaling) or from Ephs to ephrins (reverse signaling) regulates many physiological and developmental processes. Bidirectional signaling possesses many functions, including neural stem cell maintenance and plasticity regulation in the proliferation zone of adult brain,<sup>6,7</sup> neuron migration,<sup>8</sup> axon guidance,<sup>9</sup> angiogenesis,<sup>10</sup> bone homeostasis,<sup>11</sup> embryonic patterning,<sup>12</sup> tumorigenesis,<sup>13-18</sup> insulin secretion,<sup>19</sup> and so on. EphA4 expression is very high in the brain, and recently, EphA4 has been proposed to be implicated in Alzheimer's disease (AD),<sup>20,21</sup> Parkinson's disease (PD),<sup>22,23</sup> amyotrophic lateral sclerosis (ALS),<sup>24</sup> and other neurodegenerative diseases. Hence, EphA4 may have functions for protecting neuron loss and reversing the aging cells. To further explore the EphA4-mediated signaling pathways and their biological functions

in the brain, one important thing is to detect the signaling molecules interacting with EphA4.

Platelet-derived growth factor (PDGF) family of RTKs represents another signaling pathway. PDGF growth factors include four distinct subclasses (A–D) that bind to their receptors, PDGFR $\alpha$  and PDGFR $\beta$ , after dimerization.<sup>25–27</sup> PDGF, as a novel factor for neuron protection and neuron growth, plays a key role in regulating neurogenesis and hence is the mutation target of neurodegenerative diseases.<sup>28–31</sup> Bush et al reported that PDGF-BB is implicated in playing key roles in neural stem/progenitor cell (NPC) proliferation and neurogenesis under the condition of HIV-associated neurological disorders. They observed that PDGF-BB could restore the hippocampal NPC proliferation through cognate receptors of HIV Tat-cocaine. PDGF-BB also regulates NPC proliferation and neurogenesis through miR-9/MCPIP1 axis.<sup>29,32</sup> Zachrisson et al<sup>33</sup> found that PDGF-BB is effective in counteracting histological, behavioral, and biochemical changes in the experimental rat model of PD. Treatment with PDGF-BB normalized the rotational behavior, and the effect lasted for 10 weeks. Paul et al<sup>34</sup> found that intracerebroventricular (ICV) injection in PD individuals was tolerated well at all doses tested, supporting PDGF-BB as a proper candidate for further treatment of PD patients.

We have previously reported that ephrin-A1 injection reverses neuronal regeneration and alleviates the symptoms in a 6-OHDA-lesioned PD rat model,<sup>23</sup> and that the interaction of EphA4 and FGFRs promotes mouse embryonic NPC proliferation and neurogenesis via FRS2 $\alpha$  and ERK1/2 downstream of the FGF/FGFR signaling.<sup>35,36</sup> Here, we found that EphA4 and PDGFR $\beta$  have a direct interaction and can transactivate each other when coexpressed in cells. PDGF-BB and ephrin-A1 appear to enhance proliferation of neural stem cells, suggesting that these ligands might be good candidates for curing neurological diseases such as AD and related disorders in human.

## Materials and methods

### Reagents

Recombinant human PDGF-BB (Cat. #220-BB), recombinant human ephrin-A1-Fc (Cat. #6417-A1), and recombinant human IgG(Fc) were purchased from R&D Systems, Inc. (Minneapolis, MN, USA). In this study, we used clustered ephrin-A1-Fc in which 1 mg ephrin-A1 was oligomerized via incubation with 2.4 mg of recombinant human IgG(Fc) for >1 h according to the manufacturer's instructions. PDGFR inhibitor STI571 was purchased from Selleck (Munich, Germany). The following primary antibodies were used in

this study: mouse anti-HA, rat anti-HA (Hoffmann-La Roche Ltd., Basel, Switzerland; 1:4,000); mouse anti-FLAG M2 (Sigma-Aldrich, St Louis, MO, USA; 1:4,000); rabbit anti-EphA4, rabbit anti-PDGFR $\beta$ , and mouse anti-GFP (Santa Cruz Biotechnology Inc., Dallas, TX, USA; 1:2,000); and mouse anti-phosphotyrosine (EMD Millipore, Billerica, MA, USA; 1:4,000).

### Cell culture

Mammalian HEK293T cells (Clontech, Mountain View, CA, USA) were cultured as previously reported.<sup>37</sup> Neural stem cells derived from H9 human embryonic stem cells (H9-NSCs) were obtained from Thermo Fisher Scientific (Waltham, MA, USA) and cultured following the manufacturer's protocols.<sup>38</sup> Cells were passaged to generation 3 for RNA extraction, cell proliferation assay, or immunoprecipitation and immunoblotting.

### Reverse transcription (RT)-polymerase chain reaction (PCR)

H9-NSCs were rinsed with PBS after 3-day culture. The cells were homogenized using TRI Reagent (Sigma-Aldrich; Cat. #T9424), and total RNA was then extracted using standard methods. RT and subsequent PCR were performed using the conditions as previously reported.<sup>36</sup> The product sizes and the forward and reverse primer sequences are presented in Table 1.

### Plasmid transfection

EphA4 and PDGFR $\beta$  eukaryotic expression vectors were constructed as previously reported.<sup>37,39</sup> Mutants of EphA4 and PDGFR $\beta$  plasmids were constructed using QuikChange Lightning Site-Directed Mutagenesis Kit (Stratagene, Santa Clara, CA, USA) following standard instructions. Plasmid transient transfection was performed using PerFectin (Gentantis, San Diego, CA, USA) into HEK293T cells. Before ligand stimulation, HEK293T cells or H9-NSCs were starved in serum-free medium containing 0.5% (m/v) bovine serum albumin (Sigma) for 5 h.

### Immunoprecipitation and immunoblotting

Cells were harvested in lysis A buffer with 50 mM 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid buffer, 1% Triton X-100, 5 mM ethylene diamine tetraacetic acid, 50 mM sodium chloride, protease inhibitors (1  $\mu$ M pepstatin A, 1 mM phenylmethylsulfonyl fluoride, 1  $\mu$ M leupeptin, and 1  $\mu$ M aprotinin), and phosphatase inhibitors (50 mM sodium fluoride, 10 mM sodium pyrophosphate, and 1 mM sodium orthovanadate). Immunoprecipitation was

**Table 1** Primers used in this research

Primer	Sequence (5'-3')	Length (bp)	NCBI code
hEpha1-F	ATGCACTGCAGCCCTGATGG	644	NM_005232
hEpha1-R	CTCGGTTCTTTCTTACCAG		
hEpha2-F	GTTACCAAGATTGACACCA	791	NM_004431
hEpha2-R	TAGTTCATGTGGGGCTCCAG		
hEpha3-F	CAGCCAGCGATGTATGGAGT	463	NM_005233
hEpha3-R	GTGACACCAACCTTTTTCAT		
hEpha4-F	TCGAGGCTCCTGTGTCAACAACTC	642	NM_004438
hEpha4-R	GATGATGGTGCTGCTTGGTTG		
hEpha5-F	CATGTGCAAGGCAGGATATG	623	NM_004439
hEpha5-R	CATTGGGACGATCTGGTTCT		
hEpha6-F	TTCTGACATGGCAGCAGAAC	483	NM_001080448
hEpha6-R	ACAACCCCTTCTAGGCGAAT		
hEpha7-F	GGAAAAATTCCAGTAAGGTG	518	NM_004440
hEpha7-R	ATCCCTAAACTCATCACATC		
hEpha8-F	GCCAGTTCCTCAAATCGAC	608	NM_020526
hEpha8-R	TGTCCATTCACTGGAGA		
hEpha10-F	ATGCCATGATGAAGAGGAG	556	NM_001099439
hEpha10-R	ATCTTGACAGACAAGGTCGCT		
hEphb1-F	TCAGTGGCAAGATGTGCTTC	365	NM_004441
hEphb1-R	CAAACGCCCTTGTACACTT		
hEphb2-F	TGAGTCAAGCCAGAACAAC	542	NM_017449
hEphb2-R	GCCGTCCCCGTTACAGTAGA		
hEphb3-F	ACCCCAATATAATCCGGCTC	463	NM_004443
hEphb3-R	TGGTTGCTCATGTCCAGTA		
hEphb4-F	AAGCAGAGCAATGGGAGAGA	575	NM_004444
hEphb4-R	ACTTTGCAGACGAGGTTGCT		
hEphb6-F	GGGCAGCCCCAGAGGTCATT	473	NM_004445
hEphb6-R	GCTGAGCTGAGCCACATCAC		
hGapdh-F	GAGTCAACGGATTTGGTCGT	512	NM_002046
hGapdh-R	TGTGGTCATGAGTCCTCCA		
hEfna1-F	CCATGACAATCCACAGGAGA	592	NM_004428
hEfna1-R	GGCTTCCAAGCAAGAACTG		
hEfna2-F	TGGAGGTGAGCATCAATGAC	384	NM_001405
hEfna2-R	TATTGCTGGTGAAGATGGGC		
hEfna3-F	TCTGGATATTTACTGCCCGC	414	NM_004952
hEfna3-R	TCCAGCACGTTGATCTTCAC		
hEfna4-F	TGGGCCTCAACGATTACCTA	584	NM_005227
hEfna4-R	AATGCTCCATCTTGTCCGGTC		
hEfna5-F	TACCTGGATGTTTTCTGCCC	546	NM_001962
hEfna5-R	TGTGACAAGTGATGGGAGGA		
hEphexin1-F	ACCAAGAAGCTCTTCCACGA	524	NM_019850
hEphexin1-R	CATTCTTGAGGTTCTGGGA		
hFrs2a-F	ATGAACGAAGAGATGCACCC	502	NM_006654
hFrs2a-R	AGGGGAGTTGTAGGCGTTTT		
hFgfr1-F	ATGGTTGACCGTTCTGGAAG	481	NM_001174066
hFgfr1-R	CTTCACAGCCACTTTGGTCA		
hFgfr2-F	GTCCCATCTGACAAGGGAAA	522	NM_000141
hFgfr2-R	TGTTACCACCATACAGGCGA		
hFgfr3-F	CTGAAAGACGATGCCACTGA	435	NM_000142
hFgfr3-R	GCCGTTGGTTGTCTTCTTGT		
hFgfr4-F	CAAAGACAACGCCTCTGACA	516	NM_002011
hFgfr4-R	ATCCCAAAGACCACACGTC		
hPdgfra-F	AATCTGGACACTGGGAGATTCCG	381	NM_006206
hPdgfra-R	TGGCAGAGGATTAGGCTCAG		
hPdgfrb-F	AGGATCGCTCTGTGAGCAAC	346	NM_002609
hPdgfrb-R	TCCTCCTTACTGCCCTCTCC		

performed with indicated antibodies overnight at 4°C; after a wash for three times in washing buffer, immunoblotting was performed with diluted primary antibodies following the manufacturer's instructions using the standard procedure.<sup>37</sup> To confirm reproducibility, experiments were performed more than once.

## Cell proliferation assay

Cell proliferation was measured using a CellTiter96 Aqueous One Solution Cell Proliferation Assay (MTS) kit (Promega, Madison, WI, USA) according to the manufacturer's protocol. In brief, cells ( $1 \times 10^3$ ) were starved overnight and then seeded on 96-well plastic plates in a normal medium with growth factors. The indicated ligands (PDGF-BB, 20 ng/mL; ephrin-A1, 0.5 µg/mL) were added into the culture wells in a medium free of growth factors. After cultured for 3 days in the new media at 37°C, the cells were further incubated with CellTiter96 Aqueous One Solution Reagent for 1 h. The absorbance was recorded at 490 nm wavelength using a 96-well plate reader (iMark™; Bio-Rad Laboratories Inc., Hercules, CA, USA).

## Statistical analysis

Data are analyzed using Graphpad Prism 6 by two-way ANOVA followed by Dunnett's multiple comparison tests. A value of  $p < 0.0001$  was considered as statistically significant difference. All the values were expressed as mean ± SD.

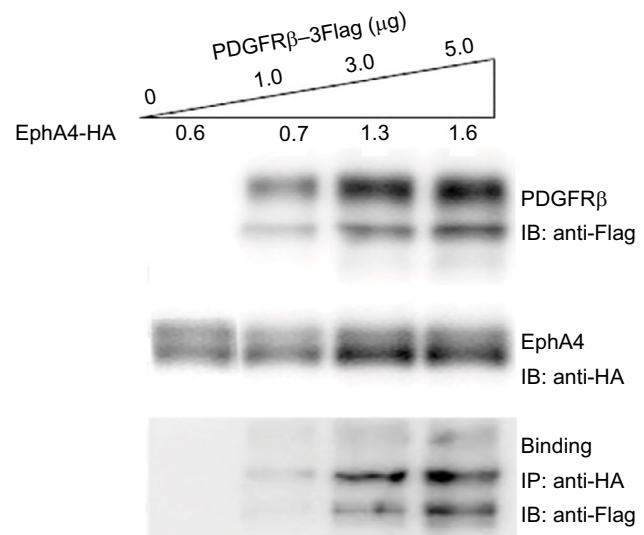
## Results

### Interaction between EphA4 and PDGFRβ

To evaluate the interaction between PDGFRβ and EphA4, both molecules were overexpressed in HEK293T cells, and their binding was examined using the immunoprecipitation and immunoblotting method. pcDNA3.1 plasmid was used to equalize the total amount of DNA in each transfection. As shown in Figure 1, the endogenous PDGFRβ was detected difficultly by immunoblotting with a specific antibody, while PDGFRβ expression level increases strongly under the elevated amount of exogenous PDGFRβ, and a complex formation of EphA4 and PDGFRβ was detected by immunoblotting followed by immunoprecipitation using the antibodies shown. The result also demonstrated that their direct interaction is in their protein dose-dependent fashion.

### Transphosphorylation between EphA4 and PDGFRβ

To investigate the functional consequences of ectopically expressing PDGFRβ and EphA4 and their subsequent complex formation, we next analyzed the transphosphorylation of

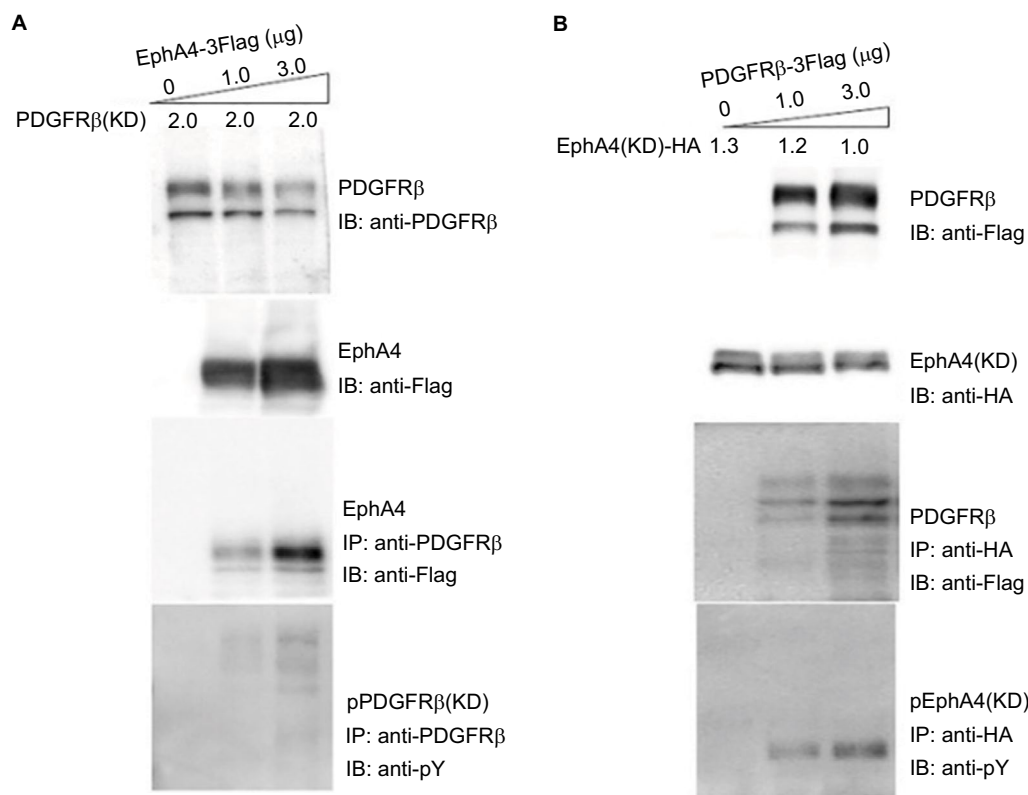


**Figure 1** Complex formation of EphA4 and PDGFRβ in transfected HEK293T cells. **Notes:** HEK293T cells were cotransfected with pcDNA/EphA4-HA (0.6, 0.7, 1.3, and 1.6 µg per 6 cm plate, respectively) and increasing concentrations (0, 1.0, 3.0, and 5.0 µg per 6 cm plate) of pcDNA/PDGFRβ-3Flag. Direct interaction was detected by SDS-PAGE and IB using anti-Flag antibody following IP using anti-HA antibody. **Abbreviations:** IB, immunoblotting; IP, immunoprecipitation; PDGFRβ, platelet-derived growth factor receptor β; SDS-PAGE, sodium dodecyl sulfate polyacrylamide gel electrophoresis.

EphA4 and PDGFRβ when transiently coexpressed in mammalian cells. We overexpressed EphA4 expression vector in HEK293T cells together with expression vector for PDGFRβ(KD), a kinase-inactive mutant of PDGFRβ in which an Ala residue was substituted for Tyr-634 (Figure 2A).<sup>40</sup> Immunoblotting with an antiphosphotyrosine antibody followed by immunoprecipitation with a specific antibody of the kinase-inactive mutant of PDGFRβ in cells coexpressing EphA4(WT) has verified that EphA4 self-phosphorylated by overexpression in HEK293T cells causes the activation of kinase-inactive PDGFRβ mutant through tyrosine phosphorylation. Meanwhile, expression vector for PDGFRβ(WT) was ectopically transfected in HEK293T cells together with the expression vector for EphA4(KD), a kinase-inactive mutant of EphA4 in which a Met residue was substituted for Val-653. The experiment also shows that PDGFRβ in HEK293T cells activated by exogenous transfection induces the kinase-inactive EphA4 mutant tyrosine phosphorylation (Figure 2B).

### Inhibition of the interaction between EphA4 and PDGFRβ by an EphA4 dominant-negative mutant, EphA4 (ΔJM,KD)

EphA4(ΔJM,KD), in which 591–602 amino acids were deleted and a Met residue was substituted for Val-653, was



**Figure 2** Tyrosine phosphorylation of EphA4 and PDGFR $\beta$  in transfected HEK293T cells.

**Notes:** Further direct interaction and tyrosine phosphorylation of kinase-inactive PDGFR $\beta$ (PDGFR $\beta$ (KD)) by EphA4 (**A**) and the kinase-inactive EphA4(EphA4(KD)) by PDGFR $\beta$  (**B**). HEK293T cells were cotransfected with *pcDNA*/PDGFR $\beta$ (KD) (2  $\mu$ g per 6 cm plate) and increasing concentrations (0, 1, and 3  $\mu$ g per 6 cm plate) of *pcDNA*/EphA4(WT) or with *pcDNA*/EphA4(KD)-Flag (1.3, 1.2, and 1.0  $\mu$ g per 6 cm plate, respectively) and increasing concentrations (0, 1, and 3  $\mu$ g per 6 cm plate) of *pcDNA*/PDGFR $\beta$ (WT). Direct interaction was further detected by IB with anti-Flag following IP with anti-PDGFR $\beta$  or anti-HA, respectively. Tyrosine phosphorylation and expression levels of PDGFR $\beta$ (KD) or EphA4(KD) were detected by immunoblotting with anti-pY, and anti-PDGFR $\beta$ , anti-Flag, or anti-HA antibodies, respectively.

**Abbreviations:** IB, immunoblotting; IP, immunoprecipitation; PDGFR $\beta$ , platelet-derived growth factor receptor  $\beta$ .

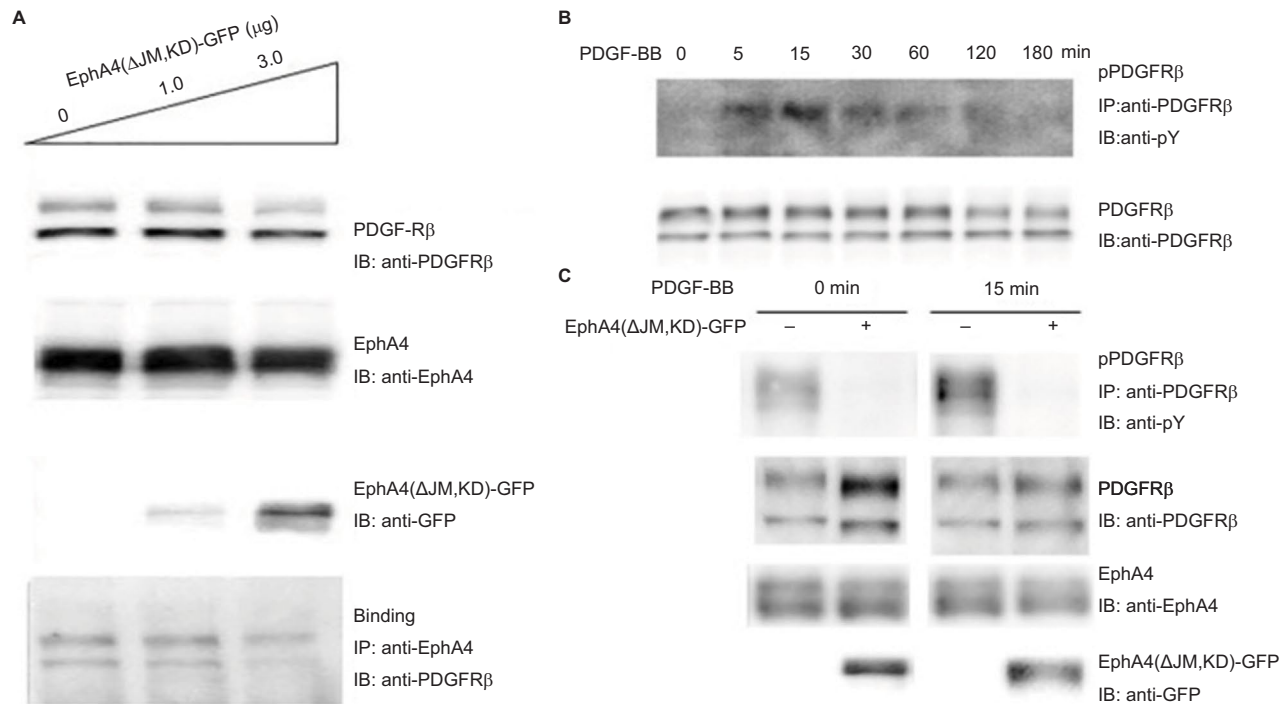
used to inhibit the interaction between EphA4 and FGFR. <sup>36,41</sup> Here, we examined whether EphA4( $\Delta$ JM,KD) could also inhibit binding of EphA4 to PDGFR $\beta$ . Fixed amounts of PDGFR $\beta$  (2  $\mu$ g per 6 cm plate) and EphA4(WT) (1  $\mu$ g per 6 cm plate) were coexpressed with increasing amounts of EphA4( $\Delta$ JM,KD) in HEK293T cells, and the binding of EphA4 to PDGFR $\beta$  was analyzed. We found that EphA4( $\Delta$ JM,KD) inhibited the interaction between EphA4 and PDGFR $\beta$  in a dose-dependent fashion (Figure 3A). Results show that EphA4( $\Delta$ JM,KD) is also a molecule that inhibits the signaling pathway through the Eph–PDGFR $\beta$  complex.

The next step was to analyze whether there is a dominant-negative effect; the expression vector for EphA4( $\Delta$ JM,KD) was transfected into HEK293T cells together with the expression vectors for EphA4 and PDGFR $\beta$ . Time course study shows that the peak of PDGFR $\beta$  tyrosine phosphorylation was at 15 min under PDGF-BB (100 ng/mL)

stimulation (Figure 3B). When cotransfected fixed amounts of EphA4(WT) and PDGFR $\beta$ (WT) in HEK293T cells, as shown in Figure 3C, EphA4( $\Delta$ JM,KD) significantly suppressed PDGF-BB-mediated tyrosine phosphorylation of PDGFR $\beta$ (WT) at either 0 or 15 min (the peak of ligand stimulation). Results show that the binding of EphA4 to PDGFR $\beta$  is important for both EphA4 and PDGFR $\beta$  signaling pathways.

## Interaction of EphA4 and PDGFR $\beta$ in the proliferation of embryonic stem cells deriving neural stem cells

We investigated the expression patterns of EphAs and PDGFRs in the proliferative regulation of H9-NSCs. Almost all EphAs (EphA2, EphA4, EphA6, EphA7, EphA8, and EphA10) and all PDGFR family members (PDGFR $\alpha$  and PDGFR $\beta$ ) were detected in the NSCs by RT-PCR (Figure 4A and B).



**Figure 3** Inhibition of PDGFR $\beta$ -EphA4 binding by a dominant-negative EphA4.

**Notes:** (A) Inhibition of EphA4-PDGFR $\beta$  binding by EphA4( $\Delta$ JM,KD)-green fluorescent protein (GFP). EphA4-Flag and PDGFR $\beta$  were coexpressed with increasing doses of EphA4( $\Delta$ JM,KD)-EGFP in HEK293T cells, and the binding of EphA4-Flag and PDGFR $\beta$  was examined by IB with or without immunoprecipitation (IP) using the antibodies shown following SDS-PAGE. Binding of PDGFR $\beta$  with EphA4-Flag was examined with IP followed by SDS-PAGE and IB using the antibodies shown. (B and C) Inhibition of the ligand-mediated receptor phosphorylation by EphA4( $\Delta$ JM,KD), tagged with GFP. Time course of PDGF-BB mediated PDGFR $\beta$  phosphorylation (B). By using a pcDNA3.1-based transient transfection, EphA4-Flag and PDGFR $\beta$  were coexpressed in HEK293T cells with or without EphA4( $\Delta$ JM,KD)-GFP, the PDGFR $\beta$  phosphorylation was examined with IP by anti-PDGFR $\beta$  followed by IB by anti-pY upon 0 and 15 min stimulation with 100 ng/mL PDGF-BB (C).

**Abbreviations:** IB, immunoblotting; IP, immunoprecipitation; PDGFR $\beta$ , platelet-derived growth factor receptor  $\beta$ ; SDS-PAGE, sodium dodecyl sulfate polyacrylamide gel electrophoresis.

H9-NSCs show an increase in their cell number under PDGF-BB (20 ng/mL) and/or ephrin-A1 (0.5  $\mu$ g/mL) stimulation after a 3-day culture when seeded on a matrigel-coated plate (Figure 4C). We also evaluated the role of these ligands on cell proliferation of H9-NSCs using MTS assay (Figure 4D). Dunnett's multiple comparison test followed by two-way ANOVA depicted that the optical density increased significantly under the stimulation with ephrin-A1-Fc ( $p < 0.05$ ) and PDGF-BB ( $p < 0.0001$ ), respectively, compared with nonstimulation. These results suggest that activation of the cells with endogenous Ephs or PDGFRs promotes proliferation of H9-NSCs. Furthermore, the optical density showed further increase ( $p < 0.0001$ ) under the stimulation with both ephrin-A1-Fc and PDGF-BB, suggesting enhanced proliferation of H9-NSCs by simultaneous stimulation with two ligands. Expression of the dominant-negative EphA4 or administration of STI571 (inhibitor of PDGFRs) strongly inhibited the proliferation of H9-NSCs under both ligands.

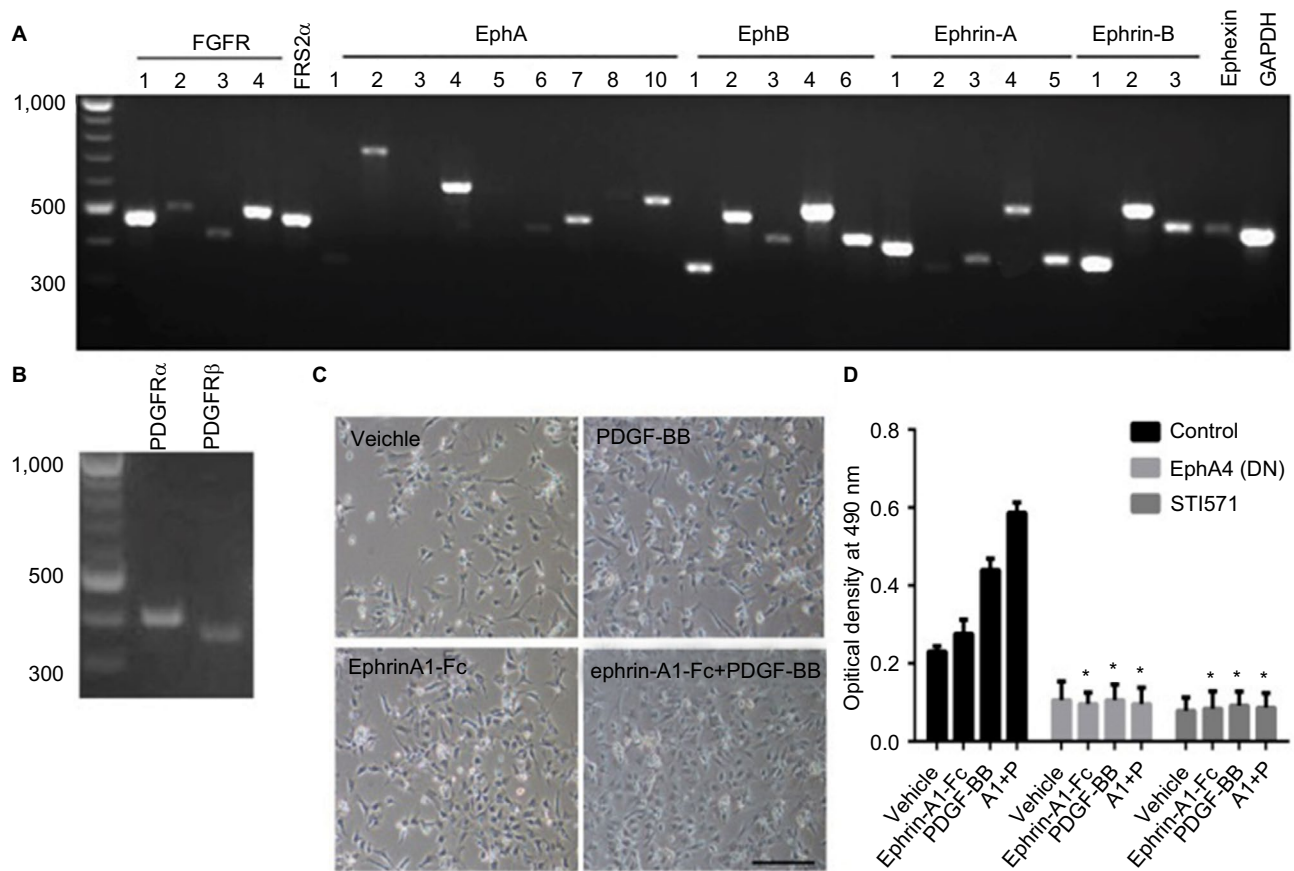
## Discussion

In this report, we found that EphA4 and PDGFR $\beta$  bind to each other in a dose-dependent manner, and EphA4 and PDGFR $\beta$

transphosphorylate each other when transiently coexpressed in the same cells. A dominant-negative molecule of EphA4 can inhibit the interaction of EphA4 with PDGFR $\beta$ . Stimulation with PDGF-BB and ephrin-A1-Fc enhanced neural stem cell proliferation, and the receptor complex involving EphA4 and PDGFR $\beta$  might mediate the signaling pathway.

As reported previously, we found that the cytoplasmic domains of EphA4 and FGFRs interact with each other, and the protein complex can transphosphorylate each other when overexpressed or stimulated with their ligands, which reinforces downstream signaling through activation of FRS2 $\alpha$  and ERK1/2. The receptor complex promotes NSC proliferation in response to combined stimulation with ephrin-A1 and FGF2.<sup>35-37</sup> In this study, we have demonstrated that PDGFR $\beta$  also binds to and phosphorylates EphA4. The signal through the PDGFR $\beta$ /EphA4 complex augments NSC proliferation under the stimulation by PDGF-BB and ephrin-A1.

PDGF-BB is a member of the PDGF family comprising other four ligands (PDGF-AA, -CC, -DD, and -AB) that interact with two RTKs, PDGFR $\alpha$  and PDGFR $\beta$ .<sup>25-27</sup> When PDGFRs are activated with ligands, they interact with and phosphorylate many downstream proteins, including the dock-



**Figure 4** Interaction of Ephs and PDGFRs in the proliferation of human NSCs.

**Notes:** (A and B) Expression of all Eph receptors, ephrin ligands, FGFRs, PDGFRs, and related molecules in H9-NSCs. RT-PCR was performed with equal amounts of total RNA isolated from H9-NSCs. Fragment lengths are indicated on the left in base pairs. (C) Proliferation of H9-NSCs on a matrigel-coated plate. Cells were seeded as single cells onto a 24-well plate coated with matrigel in a normal medium and incubated overnight. The cells were exposed to the indicated reagents (ephrin-A1, 0.5  $\mu$ g/mL; PDGF-BB, 20 ng/mL) in a growth factor-free medium and kept in the same medium for 3 days. The pictures were taken using a phase-contrast microscopy. The bar represents 100  $\mu$ m, N=5. (D) Cell proliferation of H9-NSCs was also quantitated by the 3-(4,5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulfophenyl)-2H-tetrazolium, inner salt assay in the H9-NSCs cultured in normal medium or in medium exposed with ephrin-A1 and/or PDGF-BB. Some H9-NSCs bearing EphA4( $\Delta$ JM,KD) using a retrovirus vector, while some cells were pretreated with STI571 before stimulation. The absorbance at 490 nm of each well was measured as described in experimental procedures. Values were analyzed using two-way ANOVA followed by multiple comparison test; the error bar represents SD. \* $p$ <0.0001 compared to the controls. The optical density of cells incubated with ephrin-A1 and/or PDGF-BB were significantly higher than that of nonstimulated cells. A1: ephrin-A1-Fc; P: PDGF-BB; N=5.

**Abbreviations:** NSCs, neural stem cells; PDGFR, platelet-derived growth factor receptor; RT-PCR, reverse transcription-polymerase chain reaction; ANOVA, analysis of variance.

ing proteins, FRS2 $\alpha$ , which coordinately activates multiple signaling pathways through the protein complex formation.<sup>42</sup> PDGF-BB plays key roles in the *in vitro* proliferation<sup>30</sup> and neuronal differentiation of neural stem cells derived from the embryonic hippocampus.<sup>32</sup> Furthermore, PDGF signaling prevents the cerebral hemisphere from cryogenic injury in adulthood mice.<sup>43</sup> Conditional disruption of PDGFR $\beta$  shows deficits in fear conditioning, prepulse inhibition, spatial memory, social interaction, and forced swimming.<sup>44</sup> EphA4 signaling mediates axon guidance, neuronal boundary formation, cell growth, angiogenesis, and cell migration.<sup>45</sup> Deletion of EphA4 in mice shows deficiency such as hindlimb locomotion, neuron differentiation, and migration during corticogenesis, midline axon guidance, and small body size.<sup>35,46-48</sup> Among the abnormalities during the development, resembling defects in dendritic spine density, impairment in

hippocampus-dependent memory formation, and long-term potentiation are caused by deletion of either PDGFR $\beta$  or EphA4, suggesting neuron development and maturation require the presence of both PDGFR $\beta$  and EphA4.<sup>21,49,50</sup> These findings suggest that the PDGFR $\beta$ /EphA4 receptor complex mediates a variety of signals.

Miao et al<sup>51</sup> reported that ephrin-A1 attenuated ERK activation through PDGF signaling and exerted the antimitogenic functions in a cell-type-specific manner. This is in contrast to our findings. The reason for this difference might be 1) we used clustered ephrin-A1 by pretreating soluble ephrin-A1-Fc with anti-IgG(Fc), and 2) we used neural stem cells in our study, while Miao et al used prostatic epithelial cells and endothelial cells.

Recent reports in animal studies showed that ICV injection of either PDGF-BB for 2 weeks or clustered

ephrin-A1-Fc for 1 week could restore production of dopaminergic neurons and achieve functional improvement in several PD animal models.<sup>23,34</sup> Our current findings might provide molecular evidence for curing PD with PDGF-BB and ephrin-A1. Coinjection of ephrin-A1 and PDGF-BB would be more effective in increasing dopaminergic neurons in the substantia nigra for functional recovery of Parkinsonian rat models. Stem cells may also offer a powerful new approach to model and study PD and AD.<sup>52,53</sup> We studied the effect of transplantation of the induced pluripotent stem cells and the human umbilical blood-derived stem cells to PD or AD animal models in our laboratory and found a significant symptomatic recovery.<sup>54,55</sup> In future, we would also like to combine the transplantation of stem cells and coinjection of ephrin-A1 and PDGF-BB to cure the neurodegenerative disease in PD and AD animal models.

## Conclusion

PDGFR $\beta$  and EphA4 can mutually bind to and transphosphorylate in a dose-dependent manner when cotransfected in HEK293T cells. NSCs express PDGFRs and almost all the Ephs and ephrins. Direct interaction and transphosphorylation of EphA4 and PDGFR $\beta$  may play an important role in the proliferation of H9-derived NSCs. These NSCs appear to integrate the cell contact-dependent ephrin/Eph receptor signal with the humoral signals transduced by PDGF/PDGFR $\beta$ .

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## Disclosure

The authors report no conflicts of interest in this work.

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