Ephrin B1 maintains apical adhesion of neural progenitors

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SUMMARY

Apical neural progenitors are polarized cells for which the apical membrane is the site of cell-cell and cell-extracellular matrix adhesion events that are essential for maintaining the integrity of the developing neuroepithelium. Apical adhesion is important for several aspects of the nervous system development, including morphogenesis and neurogenesis, yet the mechanisms underlying its regulation remain poorly understood. Here, we show that ephrin B1, a cell surface protein that engages in cell signaling upon binding cognate Eph receptors, controls normal morphogenesis of the developing cortex. Efnb1-deficient embryos exhibit morphological alterations of the neuroepithelium that correlate with neural tube closure defects. Using loss-of-function experiments by ex vivo electroporation, we demonstrate that ephrin B1 is required in apical progenitors (APs) to maintain their apical adhesion. Mechanistically, we show that ephrin B1 controls cell-ECM adhesion by promoting apical localization of integrin β1 and we identify ADP-ribosylation factor 6 (Arf6) as an important effector of ephrin B1 reverse signaling in apical adhesion of APs. Our results provide evidence for an important role for ephrin B1 in maintaining the structural integrity of the developing cortex and highlight the importance of tightly controlling apical cell-ECM adhesion for neuroepithelial development.

KEY WORDS: Ephrin, Cell adhesion, Integrin, Arf6, Exencephaly, Radial glia, Mouse

INTRODUCTION

Apical progenitors (APs) in the developing cortex include neuroepithelial cells, radial glia cells and short neural progenitors (Fietz and Huttner, 2011; Götz and Huttner, 2005). Common features of APs are apicobasal polarity and possession of an apical endfoot lining the ventricular surface. Apical processes provide attachment between neighboring cells via the formation of adherens junctions, which are required for cortical integrity (Kadowaki et al., 2007). Adherens junctions, together with bundles of F-actin running parallel to the apical plasma membrane, form the adherens belt, an important structure that imparts rigidity during epithelial morphogenesis (Yonemura, 2011). In addition to cell-cell adhesion via adherens junctions, apical processes of APs also provide adhesion to the extracellular matrix (ECM) present at the ventricular surface (Loulier et al., 2009).

Complete or partial loss of apical adhesion or polarity is necessary at several stages of development of the neural tube. For instance, local alteration in the apical adhesion and polarity of neuroepithelial cells allows for flexibility of the neuroepithelium and is required for hinge-point formation during neurulation (Eom et al., 2011). Furthermore, loss of apical contact by asymmetric division is associated with a change of fate during the neurogenic period (Götz and Huttner, 2005; Shitamukai et al., 2011). Lastly, increased delamination of neural progenitors from the apical ventricular surface could be responsible for the emergence of a class of basal progenitors (BPs) that may have occurred at the beginning of cortical expansion during evolution (Fietz and Huttner, 2011).

The mechanisms by which apical adhesion events are regulated during neural tube development and neurogenesis are under intense scrutiny and a number of studies have identified key molecular effectors that control assembly and/or maintenance of cadherin-based adherens junctions, including cell-fate determinants such as Numb and Numbli, and small GTPases (Chen et al., 2006; Katayama et al., 2011; Rasin et al., 2007). By contrast, how integrin-based adhesion of apical progenitors is regulated is currently unknown.

Eph receptors and ephrins form a large family of cell surface proteins that regulate various aspects of development (Niewergall et al., 2012). A distinctive feature of the Eph/ephrin signaling pathway is the ability of both Eph receptors and ephrins to activate signal transduction cascades (respectively called forward and reverse signaling) and its extensive cross-talk with other cell surface receptors, including cadherins and integrins (Arvanitis and Davy, 2008). Although Eph/ephrin signaling is commonly associated with cell repulsion, a number of studies have shown that this signaling cascade might also promote cell-cell and cell-ECM adhesion in certain cellular contexts (Halloran and Wolman, 2006). We are particularly interested in ephrin B1 as it is encoded by an X-linked gene mutation of which causes the human craniofrontonasal syndrome (CFNS) (Twigg et al., 2004; Wieland et al., 2004). CFNS is an unusual congenital disorder in which heterozygote female patients exhibit a number of defects that are not observed in hemizygote male carriers. We and others have shown that this is due to the formation of ectopic Eph-ephrin boundaries within developing tissues of heterozygote individuals (Compagni et al., 2003; Davy et al., 2006). In the developing cortex, ephrin B1 is expressed in APs from the neuroepithelial stage in a ventricular-high to pial-low gradient (Stuckmann et al., 2001). Ephrin B1 is required to maintain the neural progenitor fate at later stages of cortical development (Murai et al., 2010; Qiu et al., 2008) and we have shown recently that ephrin B1 reverse signaling controls the switch between progenitor maintenance and neuronal differentiation by engaging in a feedback loop involving miR-124, a pro-neuronal miRNA (Arvanitis et al., 2010).
Here, we report that a fraction of Ephb1<sup>−/+ </sup> and Ephb1<sup>+/+</sup> embryos display exencephaly, which led us to consider a potential role for Ephb1 in neuroepithelial morphogenesis. We show that Ephb1 mutants exhibit neuroepithelial morphological defects that appear before the onset of neurogenesis and persist throughout cortical development. These morphological alterations are characterized by an irregular appearance of the apical surface of the neuroepithelium and formation of micro-invaginations at the apical surface of the ventricular zone (VZ). These morphological alterations are accompanied by a misplacement of mitotic nuclei within the cortical wall without changes in apicobasal polarity of APs. Using <i>ex vivo</i> embryonic studies, we demonstrate that Ephb1 B1 at E13.5 is required to maintain apical adhesion of APs. Furthermore, we show that ephrin B1 reverse signaling inhibits the ADP-ribosylation factor 6 (Arf6) in APs and controls integrin-based cell-ECM apical adhesion.

**MATERIALS AND METHODS**

**Animals**

Wild-type (Ephb1<sup>+/+</sup>), Ephb1<sup>−/+ </sup>, female and Ephb1<sup>−/−</sup> male mice were generated as described (Davy et al., 2004) and kept in a mixed 129S4/C57BL/6J genetic background. For clarity in embryonic studies, mice were generated as described (Davy et al., 2004) and kept in a mixed 129S4/C57BL/6J genetic background. Animal procedures were pre-approved by the Animal Care Committee of Région Midi-Pyrénées (MP/07/21/04/11).

**Brain sample preparation**

Timed-pregnant mice were sacrificed by cervical dislocation; embryos were removed and dissected in ice-cold PBS. For immunohistochemistry, embryonic brain tissues were collected and placed in 4% paraformaldehyde (PFA) at 4°C. All brain samples were removed from PFA and either equilibrated in 70% ethanol and embedded in paraffin or immediately sectioned on a vibratome. Coronal paraffin sections (7 μm) were placed on Superfrost microscope slides (Fisher Scientific) and stored at room temperature until use. For quantitative RT-PCR, E13.5 cortices were dissected and total RNAs were extracted with TRI Reagent (Molecular Research Center).

**Quantitative RT-PCR (qRT-PCR)**

Reverse transcription (RT) was performed with 1 μg of total RNA per reaction. For the qRT-PCR reaction, the resultant cDNA was diluted 1:50. Each RT step was performed in duplicate and the qRT-PCR in triplicate for each RT reaction. RT-PCR was performed using Quantitech SYBR Green Master Mix (Qiagen) and amplified on a Bio-Rad cycler. Relative values for each RT reaction were calculated by the 2ΔΔCT method. For the qRT-PCR reaction, the resultant cDNA was diluted 1:50. Each RT step was performed in duplicate and the qRT-PCR in triplicate for each RT reaction. RT-PCR was performed using Quantitech SYBR Green Master Mix (Qiagen) and amplified on a Bio-Rad cycler. Relative values for each RT reaction were calculated by the 2ΔΔCT method.

**Adhesion assay**

Twenty-four-well tissue culture plates were coated overnight at 4°C with solutions containing either PBS, PBS + 4 μg/ml Ephb2-Fc, PBS + 4 μg/ml EphA4-Fc or laminin (10 μg/ml). Alternatively, plates were coated with PBS + 1 μg/ml laminin in presence or absence of 4 μg/ml of Ephb2-Fc or EphA4-Fc. NPCs were trypsinized, washed, re-suspended in full media and 10<sup>4</sup> cells were plated in triplicate in the coated wells. Plates were incubated (37°C, 15 minutes) and unattached cells were removed by aspiration. Attached cells were fixed in 4% PFA for 10 minutes at room temperature, washed and stained with Crystal Violet. After extensive rinsing, Crystal Violet was extracted in 1 ml 2% SDS and optical density of the resulting solution was measured at 550 nm. Alternatively, NPCs were incubated for 5 minutes with a control IgG or a function-blocking antibody to integrin β1 (3.5 μg; BD Pharmingen) prior to the adhesion assay.

**Pull down and western blotting analysis**

Cortices from E13.5 embryos were lysed in 0.5 ml ice cold lysis buffer (20 mM Tris, pH 8.0), 100 mM NaCl, 1 mM MgCl<sub>2</sub>, 1% Triton X-100, 0.05% cholate, 0.01% SDS, 1 mM dithiothreitol, 1 mM phenylmethylsulfonyl fluoride, 5 μg/ml aprotinin, 5 μg/ml leupeptin, 1 mM NaF, 1 mM vanadate). Protein lysates were clarified by centrifugation at 14,000 rpm (16,000 g) for 10 minutes at 4°C. For the detection of integrin β1, 25 μg of total lysate was subject to SDS-PAGE. Proteins were transferred onto nitrocellulose membrane, incubated with primary antibodies to integrin β1 (BD Biosciences) and Grb2 (Millipore). For Arf6 activity assays, lysates were immediately incubated with 10 μg of GST-MT2 fusion protein conjugated with glutathione beads, in the presence of 2 mM ZnCl<sub>2</sub> for 2 hours at 4°C with rocking, as previously described (Bégé et al., 2009). The beads were collected and washed with PBS containing 2 mM ZnCl<sub>2</sub>, 1 mM phenylmethylsulfonyl fluoride, 5 μg/ml aprotinin,
5 µg/ml leupeptin, 1 mM NaF and 1 mM vanadate. Bound proteins were dissociated and denatured by heating to 100°C for 10 minutes in 100 µl SDS loading buffer. Aliquots were subject to SDS-PAGE on a 12% gel. Western blots were carried out with anti-ARF6 antibodies. Alternatively, NPCs were dissociated and 10×10⁶ cells were incubated for 15 or 60 minutes with 4 µg/ml pre-clustered EphB2-Fc at 37°C. Control samples were incubated with 4 µg/ml pre-clustered IgG-Fc. NPCs were lysed and lysates were processed as described above for Arf6 activity.

**Ex vivo electroporations and organotypic slice cultures**

E14.5 embryos were decapitated and electroporations were performed as described (Arvanitis et al., 2010). Briefly, solutions containing 5 µg/µl expression vectors were mixed with 0.01% Fast Green and injected into the telencephalon ventricles using pulled 3.5-NanoLTR needles. Five electrical pulses were applied (50 V, 50 mseconds duration, 1-second intervals) using a BTX ECM-830 electroporator (BTX, Gentronic). Electroporated heads were kept in ice-cold PBS with 5% glucose, dissected and embedded in 3% agarose. Vibratome sections (250 µm) corresponding to the dorsolateral region of the cortex were cultured for 20-24 hours in neurobasal medium supplemented with N2 (Invitrogen), B27 (Invitrogen), 0.1% penicillin-streptomycin and 2 mM l-glutamine. Slices were then fixed with 4% PFA and processed for immunostaining with rhodamine phalloidin (1:500) or 5 µg/ml leupeptin, 1 mM NaF and 1 mM vanadate. Bound proteins were processed as described above for Arf6 activity.

**RESULTS**

**Neuroepithelial morphological defects in Efnb1 mutants**

A significant fraction of Efnb1+/+ and a small number of Efnb1−/− mutant embryos exhibit exencephaly (Efnb1+/+: 0/57 embryos; Efnb1−/−: 11/49 embryos (22.4%); Efnb1+/±: 9/117 embryos (7.69%); supplementary material Fig. S1), suggesting that ephrin B1 might be required for morphogenesis of the neural tube. Accordingly, ephrin B1 is expressed in nestin-positive neuroepithelial cells at early stages of development, where it is enriched in the apical region (Fig. 1A). To understand how ephrin B1 could influence neuroepithelial morphogenesis, we performed an immunohistochemical analysis of Efnb1 mutants; however, to circumvent secondary effects that could be caused by neural tube closure defects, we selected only mutant embryos that had undergone neural tube closure. At E10.5, we observed that the gross morphology of the forebrain neuroepithelium was normal in Efnb1 mutants, yet the neuroepithelial apical surface appeared abnormally folded in Efnb1−/− and Efnb1+/− embryos compared with wild-type (WT) embryos (n=3) (Fig. 1A-F; supplementary material Fig. S1). In keeping with a higher penetrance of the exencephaly phenotype in Efnb1−/− embryos, we observed a more drastic morphological phenotype in these embryos (Fig. 1B). Owing to random X-inactivation, Efnb1−/− embryos are mosaic for ephrin B1 expression and, as has been shown in other tissues (Compagni et al., 2003; Davy et al., 2004; Davy et al., 2006), ephrin B1-positive cells and ephrin B1-negative cells segregate in different territories in the neuroepithelium (Fig. 1G). We noted the appearance of abnormal gaps between nuclei in ephrin B1-negative domains (arrowhead).
unaffected by the loss of ephrin B1 (Fig. 2A,B). However, we observed that 
\( \text{Efnb1}^{+/–} \) mutant embryos exhibited micro-invaginations 
of the ventricular surface that were not observed in WT embryos 
(Fig. 2A,B; \( \text{Efnb1}^{+/–} \): 7/9 embryos; \( \text{Efnb1}^{–/–} \): 7/11 embryos). Similar 
micro-invaginations, visible at high magnification, were also present 
at E16.5 (\( \text{Efnb1}^{+/–} \): 6/7 embryos; \( \text{Efnb1}^{–/–} \): 3/4 embryos). Altogether, 
these results indicate that ephrin B1 is required for normal structure 
of the apical surface of the neuroepithelium.

Epithelial integrity requires local control of apical cell adhesion 
and polarity, two processes that could be impacted by the loss of 
ephrin B1. Immunostaining for N-cadherin (cadherin 2) indicated 
that this protein was normally expressed and localized in 
\( \text{Efnb1}^{mutant} \) embryos (Fig. 2C,D). To test whether cell polarity was affected 
by the loss of ephrin B1, we used \( \beta \)-catenin as a marker of apicobasal 
polarity and observed that apical distribution of \( \beta \)-catenin was also 
normal in \( \text{Efnb1}^{mutant} \) embryos (Fig. 2E,F). These results indicate that 
 morphological defects observed in \( \text{Efnb1}^{mutant} \) embryos were not 
correlated with a loss of apicobasal polarity or cadherin-based cell-cell 
adhesion.

**Apical distribution of integrin \( \beta 1 \) at the ventricular surface is impaired in \( \text{Efnb1}^{mutant} \) mutants**

In addition to cell-cell adhesion, cell-ECM adhesion also takes 
place at the apical surface of the VZ. Indeed, integrin \( \beta 1 \) localizes 
at the apical surface of the VZ, where it engages laminin to 
maintain apical adhesion of APs (Loulier et al., 2009). To test 
whether loss of ephrin B1 impacts integrin-based adhesion, we 
performed immunostaining for integrin \( \beta 1 \) on sections of E13.5 
\( \text{Efnb1}^{+/–} \) and \( \text{Efnb1}^{–/–} \) forebrain. We observed a marked decrease 
of integrin \( \beta 1 \) apical localization concomitant with the appearance 
of diffuse intracellular staining in a subset of cells in the VZ of 
\( \text{Efnb1}^{mutant} \) embryos (Fig. 3A-F). This decrease in apical staining was not due to 
an overall decrease in integrin \( \beta 1 \) protein levels (Fig. 3G) or 

![Fig. 2. Morphological defects do not correlate with changes in cell polarity in \( \text{Efnb1}^{mutant} \) embryos.](image)

(A,B) E13.5 coronal sections of WT or \( \text{Efnb1}^{–/–} \) forebrain were stained for acetylated tubulin (red) and Draq5 (blue, nuclei). Ectopic invaginations of the apical surface of the VZ (arrowhead) are detected in \( \text{Efnb1}^{–/–} \) embryos. (C,D) Coronal sections of E13.5 WT or \( \text{Efnb1}^{+/–} \) forebrain were stained for N-cadherin (green) and Draq5 (blue, nuclei). (E,F) Coronal sections of E16.5 WT and \( \text{Efnb1}^{–/–} \) embryos were stained with an antibody to \( \beta \)-catenin (red) to assess apicobasal polarity.

![Fig. 3. Ephrin B1 regulates the apical distribution of integrin \( \beta 1 \) in APs.](image)

(A–F) Coronal sections of E13.5 WT (A,C,E) or \( \text{Efnb1}^{–/–} \) (B,D,F) forebrain were stained for integrin \( \beta 1 \) and nuclei were labeled with Draq5. (C,D) High-magnification images showing decreased localization of integrin \( \beta 1 \) at the apical surface of the VZ in \( \text{Efnb1}^{mutant} \) embryos (arrowheads) compared with WT (D). (E,F) High-magnification images corresponding to the boxed areas in A and B showing ectopic cytoplasmic staining in a subset of cells 
in the VZ of \( \text{Efnb1}^{mutant} \) embryos (F) compared with WT (E). Red arrowheads indicate diffuse intracellular staining. (G) Western blotting for integrin \( \beta 1 \) from E13.5 WT, \( \text{Efnb1}^{+/–} \) and \( \text{Efnb1}^{–/–} \) cortical homogenates shows no change in the level of integrin \( \beta 1 \) in mutant cortices compared with WT. Grb2 was used as a loading control. (H) Expression of \( \text{Itgb1} \) in the cortex of E13.5 WT (gray bars) and \( \text{Efnb1}^{–/–} \) (black bars) embryos was analyzed by quantitative RT-PCR. No difference in \( \text{Itgb1} \) mRNA levels was detected in \( \text{Efnb1}^{–/–} \) compared with WT samples.
mRNA levels (Fig. 3H), indicating that subcellular localization of integrin β1, but not expression, is modified in Efnb1-deficient APs.

One of the phenotypes observed following transient abrogation of integrin signaling at the ventricular surface was an increase in the number of mitotic nuclei positioned away from the ventricular surface (Loulier et al., 2009). Because we observed a decrease in integrin β1 apical localization in Efnb1 mutants, we decided to test whether loss of ephrin B1 also affects the position of mitotic nuclei. Mitotic nuclei were labeled with phospho-histone H3 (P-H3) and the distribution of these nuclei was analyzed in E13.5 WT and Efnb1−/− VZ (Fig. 4A,B; supplementary material Fig. S2). Measurement of the distance between P-H3-positive nuclei and the ventricular surface showed that P-H3-positive mitotic nuclei were positioned further away from the apical surface in Efnb1−/− VZ compared with WT (Fig. 4A-C). We next quantified the number of P-H3-positive nuclei according to their position in the VZ (apical: nuclei lining the ventricle; displaced: nuclei at least one nuclei diameter away from the ventricle; basal: nuclei adjacent to the cortical plate). Quantifications were performed on at least 500 P-H3-positive cells from five embryos per genotype. (E) Total number of cells in E13.5 WT (n=3) and Efnb1−/− (n=3) embryos determined by nuclear counting. For C-E, statistical analysis was performed using Student’s t-test. *P<0.05. Error bars represent s.d. (F-K) Coronal sections of E13.5 WT (F-H) and Efnb1−/− (I-K) embryos were stained for MPM-2 (F,I, red) and Pax6 (G,J, green); nuclei were labeled with Draq5 (blue in H,K). The majority of displaced mitotic nuclei in Efnb1 mutants (arrows) express Pax6.

Acute loss of ephrin B1 leads to dispersion of APs
These results prompted us to test the short-term consequences of a loss of ephrin B1 in APs. Acute loss of ephrin B1 was obtained by electroporating an expression vector for Cre recombinase into the developing cortex of Efnb1flox/flox embryos and cultivating organotypic slices of electroporated brains. Twenty hours after electroporation, cells electroporated with a control vector and GFP exhibited a typical distribution in the cortical wall with the majority of electroporated cells located in the VZ (Fig. 5A,D,E). By contrast, cells co-electroporated with GFP and Cre recombinase exhibited a dispersed distribution in the cortex, with a significant fraction of these cells displaced away from the VZ (Fig. 5B,D,E). At the cellular level, the majority of control-
electroporated cells exhibited an elongated morphology with their apical processes attached to the ventricular surface (Fig. 5F,I; supplementary material Fig. S4). This elongated morphology and contact to the ventricular surface was lost in Cre-electroporated cells located in the VZ (Fig. 5G,I; supplementary material Fig. S4). Co-expression of Cre recombinase and ephrin B1-GFP restored normal elongated morphology of APs and attachment to the ventricular surface (Fig. 5H,I; supplementary material Fig. S4). Importantly, these modifications in cell distribution and morphology were not due to apoptosis (supplementary material Fig. S5). Furthermore, electroporation of Cre recombinase did not change the proportion of GFP-positive cells expressing either Pax6, Tbr2 or β3 tubulin, a marker of neurons (supplementary material Fig. S5), indicating that dispersion of APs in Cre-electroporated slices does not correlate with a change of fate in this short time window. Altogether, these results suggest that ephrin B1 is required to maintain AP adhesion at the apical surface of the ventricle.

Although Eph/ephrin signaling is better known for its role in promoting cell repulsion, interaction between Eph receptors and ephrins can result in increased integrin-mediated adhesion of ephrin-expressing cells in certain cellular contexts (Davy and Robbins, 2000; Huai and Drescher, 2001). To test whether Eph/ephrin B1 signaling directly promoted adhesion of APs, we isolated primary NPCs, which express ephrin B1 (supplementary material Fig. S6), and performed adhesion assays on substrates coated with Eph receptors. We chose EphA4 and EphB2, two of the ephrin B1 cognate receptors that are expressed in the developing E13.5 neocortex in a pattern overlapping with that of ephrin B1 (supplementary material Fig. S7). Quantitative RT-PCR experiments showed that EphA4 is more highly expressed than EphB2 in the developing neocortex (supplementary material Fig. S7), yet EphB2 is the preferred interacting receptor for ephrin B1 (supplementary material Fig. S8) (Noberini et al., 2012). First, we tested the ability of NPCs to directly bind to EphB2-, EphA4- or laminin-coated culture plates. NPCs exhibited a slight, but not significant, decrease in adhesion to plates coated with EphB2-Fc or EphA4-Fc, compared with plates coated with PBS or laminin (Fig. 6A). Next, we tested whether Eph-ephrin B1 interaction could modulate integrin-mediated adhesion. Culture plates were coated with a solution containing either laminin, laminin + EphB2-Fc, or laminin + EphA4-Fc, and adhesion of NPCs to these substrates was evaluated. NPCs exhibited a preferential adhesion to plates coated with laminin + EphB2-Fc compared with plates coated with laminin

**Fig. 5. Acute loss of ephrin B1 leads to detachment of APs from the ventricular surface.**

(A-C) Ex vivo electroporation of the developing cortex of Efnb1flox/flox E14.5 embryos with GFP (A), pGK-CRE+GFP (B) or pGK-CRE+ephrinB1-GFP (C). Position of electroporated cells was assessed by indirect immunofluorescence detecting GFP on slice cultures (green). The overall organization of the cortex was visualized by staining for F-actin (red). (D) Dot plot of the distance between GFP+ cells and the ventricular surface relative to cortical width. Each dot corresponds to measurements for one electroporated cell from one representative brain for each electroporation condition. (E) The mean distance between GFP+ cells and the ventricular surface relative to cortical width in the three electroporation conditions (GFP, n=9; pGK-CRE+GFP, n=10; pGK-CRE+ephrinB1-GFP, n=10). (F-H) High-magnification images of Efnb1flox/flox E14.5 cortices electroporated with GFP (F), pGK-CRE+GFP (G) and pGK-CRE+ephrinB1-GFP (H). Low-magnification (A-C) and high-magnification (F-H) images are from independent electroporated cortices. Images are representative of a minimum of three independent electroporated brains. (I) Quantification of the percentage of electroporated cells possessing an apical process contacting the ventricular surface (n=5 per condition). Statistical analysis was performed using Student’s t-test. ***P<0.001; ns, non-significant. Error bars represent s.d.
adhesion of NPCs on laminin + EphB2-Fc was blocked in presence alone or laminin + EphA4-Fc (Fig. 6B). Importantly, increased adhesion of NPCs on laminin + EphB2-Fc was blocked in presence of an integrin β1 function-blocking antibody (Fig. 6C), indicating that EphB2-ephrin B1 interaction promoted integrin-mediated adhesion of NPCs.

Altogether, these results suggest that ephrin B1, via an interaction with EphB2 on neighboring cells, maintains morphology and distribution of APs in the VZ by promoting apical integrin-based adhesion.

SH2- and PDZ-dependent reverse signaling is dispensable for apical adhesion of APs

To characterize the molecular mechanisms by which ephrin B1 controls integrin-based adhesion of APs, we tested the requirement of the ephrin B1 signaling domains for cortical morphogenesis. Two signaling modules have been identified in the cytoplasmic tail of ephrin B1: tyrosines that are phosphorylated in response to activation of the pathway and a binding domain for PDZ-containing proteins. Tyrosine phosphorylation of ephrinBs could be detected in the VZ and in the cortical plate of WT embryos (Fig. 7A) where it colocalized with ephrin B1 in the VZ (Fig. 7A-C). Because ephrin B1 is the most highly expressed ephrinB in the neo-cortex and in NPCs (supplementary material Figs S6, S7), these results strongly suggest that ephrin B1 is tyrosine phosphorylated in APs.

To test whether tyrosine phosphorylation or binding to PDZ-containing proteins are required for VZ morphogenesis, we analyzed embryos expressing mutant versions of ephrin B1 that are lacking these signaling modules either individually or in combination (Bush and Soriano, 2009). No structural abnormality was detected in the cortex of these mutant embryos and integrin β1 alone or laminin + EphA4-Fc (Fig. 6B). Importantly, increased adhesion of NPCs on laminin + EphB2-Fc was blocked in presence of an integrin β1 function-blocking antibody (Fig. 6C), indicating that EphB2-ephrin B1 interaction promoted integrin-mediated adhesion of NPCs.

Altogether, these results suggest that ephrin B1, via an interaction with EphB2 on neighboring cells, maintains morphology and distribution of APs in the VZ by promoting apical integrin-based adhesion.

Ephrin B1 regulates adhesion of APs via inhibition of Arf6

The small GTPase Arf6 has been shown to influence cell-ECM interactions by regulating recycling of integrins in migratory cells (Pellinen and Ivaska, 2006). Furthermore, Arf6 has recently been identified as an effector of EphA2-mediated adhesion in cultured epithelial cells (Miura et al., 2009). This prompted us to test whether this cytosolic protein could play a role downstream of ephrin B1 in APs. Immunohistochemistry for Arf6 revealed that this GTPase is expressed in APs, where it is enriched at the apical surface similar to ephrin B1 (Fig. 8A,B). We next set out to investigate whether Arf6 activity was modified in Efnb1 mutants. Metallotheonin 2 has been shown to interact specifically with Arf6-GTP, the active form of Arf6 (Schweitzer and D’Souza-Schorey, 2002); we thus performed pull-down assays using a GST-metallotheonin 2 fusion protein to specifically pull down active Arf6-GTP from E13.5 cortical protein lysates. These experiments revealed that Arf6 activity was dramatically increased in the cortex of Efnb1 adviser- (Fig. 8C), suggesting that ephrin B1 normally restrains Arf6 activity. To test this hypothesis directly, we stimulated cultured NPCs with EphB2-Fc and monitored Arf6 activity using GST-metallotheonin 2 pull down. EphB2-Fc stimulation for 15 minutes led to a decrease in the level of Arf6-GTP (Fig. 8D,E), indicating that ephrin reverse signaling directly inhibits Arf6 activity in NPCs. We next evaluated the consequences of increased Arf6 activity on APs, by expressing a constitutively active form of Arf6 (Arf6Q67L) in these cells. Constitutive activation of Arf6 led to cell dispersion and the appearance of cells that did not attach to the ventricular surface (Fig. 9A-F). In addition, the constitutively activated form of Arf6 blocked adhesion and spreading of HeLa cells in response to ephrin B1 reverse signaling (supplementary material Fig. S10). Conversely, co-expression of a dominant-negative form of Arf6 (Arf6T27N) was able to rescue the dispersion phenotype induced by acute loss of ephrin B1 (Fig. 9G-J). These results suggest that inhibition of Arf6 activity downstream of ephrin B1 reverse signaling is necessary to maintain apical adhesion of APs.

DISCUSSION

Ephrin B1 and cortical development

Ephrin B1 controls a number of processes in the developing cortex, including maintenance of progenitor fate, guidance of callosal axons...
and migration of projection neurons in a reelin-dependent manner (Arvanitis et al., 2010; Bush and Soriano, 2009; Qiu et al., 2008; Sentürk et al., 2011). Here, we demonstrate that ephrin B1 is also implicated in neural tube morphogenesis by promoting adhesion of APs to the ventricular surface. Importantly, our data show that ephrin B1 exerts this function as early as the neuroepithelial stage, before its implication in neurogenesis, which has been shown to take place at later stages of development (Qiu et al., 2008). Specifically, a decrease in the number of P-H3-positive cells was observed in the VZ of Efnb1 mutants at E16.5 but not at E13.5 (Qiu et al., 2008).

Fig. 7. The cytoplasmic domain of ephrin B1 is dispensable for apical adhesion of APs. (A-C) Coronal sections of a WT E13.5 embryo were stained with an antibody specific to tyrosine phosphorylated ephrinBs (P-ephrinB; A, green) and with an antibody specific to ephrin B1 (B, red). (D-F) Coronal sections from Efnb1 mutant embryos in which tyrosine phosphorylation is prevented (Efnb1F65;D) or mutants in which binding to PDZ-domain-containing proteins is prevented (Efnb1DV; E) were stained for ephrin B1. (F) Coronal sections of E13.5 Efnb1F65 embryos were stained for integrin B1 (green) and nuclei were labeled with Draq5 (blue). Dashed lines highlight the pial surface of the cortex. (G-I) Efnb1fl/fl E14.5 embryos were co-electroporated with either pGK-CRE + GFP + empty vector (G) or with pGK-CRE + GFP + ephrin-B1deltaC (H). Distribution of electroporated cells was assessed by indirect immunofluorescence detecting GFP on slice cultures (green). The overall organization of the cortex was visualized by staining for F-actin (red). (I) Quantification of the mean distance between GFP+ cells and the ventricular surface relative to cortical width (pGK-CRE + GFP + empty vector, n=10; pGK-CRE + GFP + ephrin-B1deltaC, n=9). Statistical analysis was performed using Student’s t-test. ***P<0.001. Error bars represent s.d.

Fig. 8. Ephrin B1 reverse signaling inhibits Arf6 activity. (A,B) Coronal sections of E13.5 embryos were stained for Arf6 (A, green) and for ephrin B1 (B, red). Dashed lines highlight the pial surface of the cortex. (C) Arf6 activity is increased in the cortex of Efnb1 mutants (Efnb1−/−) compared with wild-type (WT) E13.5 embryos. Active Arf6 (Arf6-GTP) was pulled down from protein lysates obtained from the cortex of three independent embryos of each genotype using metallothionein 2 (Mt2)-GST beads. Total Arf6 levels in the lysates are shown. (D,E) Cultured NPCs were stimulated with IgG-Fc or with EphB2-Fc and Arf6 activity was monitored using GST-metallothionein 2 pull-down. Total Arf6 levels in the lysates are shown. (E) Quantification of Arf6-GTP compared with total Arf6 protein is shown for IgG-Fc and EphB2-Fc stimulation. Error bars represent s.d.
et al., 2008) (data not shown). Although the PDZ domain of ephrin B1 is required for its role in neurogenesis (Qiu et al., 2008), we showed here that it is dispensable for adhesion of APs, supporting the notion that both functions are distinct.

Despite a well-known role for Eph/ephrin signaling in promoting cell repulsion, our data show that in APs, ephrin B1 promotes integrin-based cell adhesion. EphA4 and EphB2 are expressed in the developing cortex, where EphA4/ephrin B1 signaling has been implicated in neurogenesis (North et al., 2009). We propose here that EphB2-ephrin B1 interaction may preferentially control adhesion of APs to the apical surface of the VZ. Promotion of cell adhesion has been described previously for the EphA7-ephrin A5 pair and, interestingly, neural tube closure defects (NTDs) are observed in a fraction of EfnA5−/− embryos (Holmberg et al., 2000). However, the mechanisms causing NTDs in EfnA5−/− and Efnb1−/− are different. In the former study, it was shown that EphA7 and ephrin A5 are expressed at the edge of the dorsal neural folds and that lack of interaction between these proteins led to a failure of the neural folds to fuse at the midline (Holmberg et al., 2000). Here, we show that ephrin B1 plays a structural role at the apical surface of the neuroepithelium. In absence of ephrin B1, local alterations of the apical surface might weaken the rigidity and cohesion of the neuroepithelium and thus perturb the complex morphogenetic processes taking place during neurulation. Our exencephaly data indicate that Efnb1+/− are more severely affected than Efnb1−/− embryos, which has been reported for other phenotypes observed in mice and humans carrying mutations in Efnb1 (Compagni et al., 2003; Davy et al., 2004; Twigg et al., 2004; Wieland et al., 2004). Our interpretation for neuroepithelial morphogenesis is that in Efnb1+/− embryos, sorting between ephrin B1-positive and ephrin B1-negative cells leads to discontinuous rigidity of the neuroepithelium, which is more detrimental to morphogenesis of this tissue than a homogenous decrease in rigidity. One of the phenotypes we observed that could be linked to a decrease in rigidity of the cortical tissue in Efnb1−/− mutants is the mis-positioning of mitotic nuclei of both APs and BPs. Indeed, it has long been proposed that apical-to-basal migration of nuclei could be a passive mechanism driven by cell crowding (Sauer, 1935). More recently, it has been shown that weakening the apical acto-myosin cortex in APs leads to defects in apical-to-basal nuclear migration of both APs and BPs (Schenk et al., 2009). Lastly, blocking integrin β1 function at the apical surface of the cortex leads to mis-positioning of mitotic nuclei (Loulier et al., 2009).
Mechanisms of ephrin-induced adhesion

We showed that ephrin B1 controls apical adhesion of APs by an indirect mechanism involving integrin β1. Indeed, in cultured NPCs, Eph-ephrin interaction promoted cell adhesion only in presence of laminin. Furthermore, acute loss of ephrin B1 led to the dispersion of APs in the cortical wall, a phenotype reminiscent of that observed when apical integrin β1 is specifically targeted using function-blocking antibodies or in laminin α2-deficient embryos (Loulier et al., 2009). Lastly, we observed that the distribution of integrin β1 at the apical membrane of APs was perturbed in Ephb2−/− embryos. A number of studies have reported regulation of integrin-based adhesion by Eph/ephrin signaling (Arvanitis and Davy, 2008; Davy and Robbins, 2000; Huai and Drescher, 2001). Although most of these studies were based on in vitro data, a crosstalk between Eph/ephrin and integrins has previously been demonstrated in vivo during somitogenesis in the zebrafish embryo (Jülich et al., 2009).

Interestingly, the latter study showed that ephrin reverse signaling was sufficient to induce clustering of integrin along tissue boundaries.

Our results with ephrin-B1ΔC showed that the extracellular domain of ephrin B1 was able to rescue cell adhesion independently of the cytoplasmic domain. One possible explanation for these results is that this truncated form of ephrin B1 might retain signaling activity, similar to glycosylphosphatidylinositol (GPI)-linked ephrins. Indeed, we have shown previously that reverse signaling via the GPI-linked ephrin A5 led to increased cell-ECM adhesion that was mediated by the inside-out activation of integrin β1 (Davy and Robbins, 2000). Regardless of how ephrin-B1ΔC modulates cell adhesion, our results call for caution in interpreting in vivo data using truncated versions of ephrins, which are widely used to discriminate between forward or reverse signaling (Davy and Soriano, 2005).

Arf6 and cell adhesion

We identified Arf6 as an effector of ephrin B1-induced adhesion of APs. We showed that Arf6 activity was increased in Ephb1 mutant cortex and demonstrated that EphB2/ephrinB1 signaling suppresses Arf6 activity in NPCs. Whether this inhibition involves the engagement or recruitment of the ArfGAP Git1 as was shown previously for EphA2 (Miura et al., 2009) will have to be explored further but is likely to involve a mechanism not described thus far.

Indeed, engagement of Git1 by ephrinB reverse signaling has been reported previously; however, this recruitment required binding of Git1 to Grb4 (Nck2 – Mouse Genome Informatics), which is known to interact with phosphorylated residues on the cytoplasmic tail of ephrinBs (Segura et al., 2007). Here, our findings indicate that engagement of Git1, or any other negative regulator of Arf6, in response to EphB2-ephrin B1 interaction would be achieved independently of the cytoplasmic domain of ephrin B1.

Arf6 is a small GTPase involved in membrane trafficking, plasma membrane protrusions and invaginations, peripheral actin assembly and Ca2+-dependent exocytosis in a number of cell types (D’Souza-Schorey and Chavrier, 2006). Owing to its important bearing on plasma membrane remodeling, Arf6 activity influences morphology, adhesion and migration of numerous cell types. For instance, in epithelial cells, increased Arf6 activity correlated with scattering and the acquisition of a migratory phenotype (Palacios and D’Souza-Schorey, 2003). Arf6 is known to play various roles in neurons, including recycling of integrin β1 to the neuronal surface (Eva et al., 2012), yet a possible function for this small GTPase in the developing cortex has not been reported to date. Our results demonstrate that limiting Arf6 activity is essential for maintaining apical adhesion of APs and ensuring cortical integrity. Our results suggest that low Arf6 activity is required to maintain apical localization of integrin β1 in APs (Fig. 10).

In conclusion, we uncovered an important function for ephrin B1 in maintaining the apical adhesion of APs during cortical development, a function that is essential for appropriate morphogenesis of the neural tube.

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Competing interests statement

The authors declare no competing financial interests.

Supplementary material

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