RESEARCH REPORT

Vangl-dependent planar cell polarity signalling is not required for neural crest migration in mammals

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ABSTRACT

The role of planar cell polarity (PCP) signalling in neural crest (NC) development is unclear. The PCP dependence of NC cell migration has been reported in Xenopus and zebrafish, but NC migration has not been studied in mammalian PCP mutants. Vangl²¹ᵖ¹ᵖ mouse embryos lack PCP signalling and undergo almost complete failure of neural tube closure. Here we show, however, that NC specification, migration and derivative formation occur normally in Vangl²¹ᵖ¹ᵖ embryos. The gene family member Vangl1 was not expressed in NC nor ectopically expressed in Vangl²¹ᵖ¹ᵖ embryos, and doubly homozygous Vangl1/Vangl2 mutants exhibited normal NC migration. Acute downregulation of Vangl2 in the NC lineage did not prevent NC migration. In vitro, Vangl²¹ᵖ¹ᵖ neural tube explants generated emigrating NC cells, as in wild type. Hence, PCP signalling is not essential for NC migration in mammals, in contrast to its essential role in neural tube closure. PCP mutations are thus unlikely to mediate NC-related birth defects in humans.

KEY WORDS: Cell migration, Embryo, Mouse, Neural crest, Neural tube, Planar cell polarity

INTRODUCTION

The neural crest (NC) is a transient cell population that delaminates from the dorsal neural tube and migrates extensively, generating a variety of cell types (Kulesa et al., 2010; Sauka-Spengler and Bronner-Fraser, 2008). NC emigration is closely coordinated spatiotemporally with closure of the neural tube, and some genes [e.g. AP2e (Tfap2a), Cecr2, Pax3, Zic2] (Harris and Juriloff, 2007) are necessary for both embryonic events. Signalling via the planar cell polarity (PCP) pathway is required for neural tube closure in vertebrates, and recently PCP mutations were reported in human neural tube defects (Juriloff and Harris, 2012). However, the role of PCP signalling in NC migration, particularly in mammals, remains unresolved.

The PCP pathway is an evolutionarily conserved, non-canonical Wnt-frizzled-dishevelled signalling cascade. The vertebrate homologues of Drosophila ‘core’ PCP genes regulate many developmental processes, including convergent extension (CE) cell movements in embryonic axis elongation, orientation of mechanosensory hair cells in the cochlea, and the arrangement of fur, feathers and scales (Seifert and Mlodzik, 2007).

In Xenopus embryos, disruption of PCP signalling (Dsh-DEP+ or dominant-negative Wnt11 mRNA) inhibited cranial NC migration in vivo and in vitro (De Calisto et al., 2005). Similar findings were reported with the PCP-associated gene PTK7 (Shnitsar and Borchers, 2008), and NC migration defects were also observed in zebrafish treated with Dsh-DEP+ or wnt3 morpholino (Matthews et al., 2008). Knockdown of Strabismus (Vangl2 orthologue) inhibited Xenopus NC migration similarly to Dsh-DEP+ (Carmona-Fontaine et al., 2008), whereas a milder NC migration phenotype was observed in the trilobite (vangl2) zebrafish mutant (Matthews et al., 2008).

It is unclear whether PCP signalling is essential for mammalian NC migration. NC-related anomalies comprise up to 20% of clinically important human birth defects (Bolande, 1974; Dolk et al., 2010), so it is important to ascertain whether PCP mutations are a likely cause. Here, we examined NC migration in mice lacking Vangl1/2 function. Loop-tail (Lp) is a dominant-negative allele of the core PCP gene Vangl2 that abrogates PCP signalling (Kibar et al., 2001; Murdoch et al., 2001; Song et al., 2010; Yin et al., 2012). Vangl2¹ᵖ homozygotes fail almost completely in neural tube closure due to defective CE in midline neural plate and axial mesoderm (Ybot-Gonzalez et al., 2007). They also display defects of cochlea organisation, heart morphogenesis, lung and kidney branching and reproductive system development – all attributed to severely disrupted PCP function (Montcouquiol et al., 2003; Torban et al., 2007; vandenBerg and Sassoon, 2009; Yates et al., 2010a, b). We find no defects in NC migration in Vangl1/2 mutant embryos, either in vivo or in vitro, arguing strongly that PCP signalling is not essential for early NC development in mammals.

RESULTS

NC specification and migration are normal in Vangl2¹ᵖ¹ᵖ embryos

The specification of NC cells was detected by whole-mount hybridisation (WISH) for Sox9, a marker of premigratory NC (Cheung and Briscoe, 2003). Sox9-positive NC cells were visible along the mid-dorsal aspect of the embryonic day (E) 9.5 wild-type neural tube and, similarly, on the tips of the open neural folds in stage-matched Vangl2¹ᵖ¹ᵖ embryos (supplementary material Fig. S1A-F).

Migrating NC cells were detected by WISH for ErbB3, a neuregulin receptor tyrosine kinase (Garratt et al., 2000). Both wild-type and stage-matched Vangl2¹ᵖ¹ᵖ embryos at E9.5 showed streams of cranial NC cells migrating from the hindbrain towards branchial arches 1 and 2, and around the optic vesicles (Fig. 1A,B,D,E). ErbB3-positive trunk NC cells were delaminating from the neuroepithelium and migrating ventrally (Fig. 1C,F). In later development, NC cell...
emigration from the trunk neural tube also appeared closely comparable in wild-type and Vangl2Lp/Lp embryos (supplementary material Fig. S1G-T).

A similar NC migration pattern was detected by fluorescent lineage labelling in both Vangl2+/+; Wnt1-Cre/YFP and Vangl2Lp/Lp; Wnt1-Cre/YFP embryos. At E8.5, YFP-positive NC cells had colonised the forebrain, peri-ocular region and branchial arches 1 and 2 (Fig. 1G-I,K-M), and migrating NC cells were present at heart-level in both genotypes (Fig. 1J,N). Closely comparable patterns of NC cell distribution were present later in development at different axial levels (supplementary material Fig. S2A-H). No significant differences were found in the number of migrating YFP-positive NC cells in Vangl2+/+ and Vangl2Lp/Lp embryos at E9, E9.5 or E10.5 (supplementary material Fig. S2I). Analysis of embryos at E10.5, both by Erbb3 WISH (supplementary material Fig. S1U-BB) and Wnt1-Cre/YFP labelling (supplementary material Fig. S2J-Y), also revealed very similar NC cell distribution and patterning of NC-derived structures. We conclude that specification, migration and tissue colonisation by NC is normal in Vangl2Lp/Lp mutants that fail in neural tube closure.

**Vangl1 does not compensate for loss of Vangl2 during NC migration**

We examined whether the gene family member Vangl1 could compensate for loss of Vangl2, thereby ensuring normal NC migration. Vangl1 is a highly conserved, structurally similar parologue of Vangl2 (Torban et al., 2004) and the only other known mammalian orthologue of Drosophila Strabismus (Van Gogh). Both Vangl1 and Vangl2 proteins interact physically with mammalian dishevelled (Torban et al., 2004). Moreover, Vangl1 interacts genetically with Vangl2 during neurulation (Torban et al., 2008), with a more severe phenotype in Vangl1/Vangl2 double homozygotes than in Vangl2Lp/Lp (Song et al., 2010).

Vangl1 expression was detected solely in the ventral neuroepithelium of E8.5 Vangl2+/+ and Vangl2Lp/Lp embryos, from the level of hindbrain to low spine (Fig. 2A,E). In both genotypes, Vangl1 transcripts could not be detected in the upper hindbrain, midbrain (Fig. 2B,F) or edges of the trunk neural folds (Fig. 2C,D,G,H), which are all sites of Erbb3-positive NC cell origin (Fig. 2I,L). Vangl2 expression also showed no overlap with Erbb3, but rather exhibited generalised neural tube expression, overlapping with Vangl1 only at the ventral midline (Fig. 2M-P). Later in neurulation, Vangl1 expression remained distinct from Erbb3 along the body axis, with no evidence of ectopic expression in Vangl2Lp/Lp embryos (supplementary material Fig. S3).

To test experimentally whether Vangl1 may compensate for Vangl2 disruption in NC migration, we bred mice doubly homozygous for Vangl1 and Vangl2 loss of function (Song et al., 2010). The pattern of Erbb3-positive NC cell migration was very similar at both E8.5 and E9.5 in normally developing controls (Vangl1+/+; Vangl2+/+; Fig. 3A,C,E) and in doubly homozygous mutants (Vangl1Lp/Lp; Vangl2Lp/Lp; Fig. 3B,F-H), despite the entirely open neural tube in the latter embryos. We conclude that Vangl gene function is not required for mouse NC migration in vivo.
Acute ablation of Vangl2 function in the NC lineage

Constitutional absence of Vangl2-dependent PCP signalling in loop-tail embryos could stimulate a compensatory mechanism (e.g. activation of a Vangl2-independent pathway) in the NC or surrounding tissue, allowing normal NC migration (Fig. 3I, i). To address this, we produced Vangl2Lp/flox; Wnt1-Cre/YFP embryos in which Vangl2 expression was ablated specifically in the NC lineage. We reasoned that acute ablation of Vangl2 should prevent any compensatory mechanism from arising, and so lead to NC migration defects (Fig. 3I, ii). Fluorescently labelled NC cells were detected in E9.5 Vangl2Lp/flox; Wnt1-Cre/YFP embryos in a pattern indistinguishable from that of controls (Fig. 3J-O). WISH for Erbb3 revealed no difference between conditional mutants and controls (data not shown). We conclude that the normal pattern of NC migration observed in Vangl2Lp/Lp embryos is unlikely to arise from a compensatory mechanism masking a role for Vangl2 in NC migration.

Vangl2Lp/Lp NC cells migrate normally in vitro

Migration of Xenopus NC was inhibited after disruption of PCP signalling (De Calisto et al., 2005). By contrast, we observed comparable in vitro outgrowth of migratory cells from Vangl2+/+ and Vangl2Lp+/+ neural tube explants (supplementary material Fig. S4A,B). YFP-positive premigratory NC cells were initially detected along the dorsal margin of neural tube/fold explants from Vangl2+/+ and Vangl2Lp+/+ embryos expressing Wnt1-Cre/R26R-YFP. After 24 h, similar numbers of YFP-positive migratory cells had emerged from the explants of both genotypes (Fig. 4A). The percentage increase in outgrowth area did not differ between Vangl2+/+, Vangl2Lp+/+ and Vangl2Lp/Lp genotypes at either 24 or 48 h (Fig. 4B). Double immunostaining confirmed that the majority of YFP-positive NC cells also expressed the NC cell marker p75 (Ngfr – Mouse Genome Informatics) (supplementary material Fig. S4D,E).

In Xenopus NC outgrowths, leading edge cells extended large, polarised lamellipodia whereas those with defective PCP signalling failed to polarise (Carmona-Fontaine et al., 2008; Matthews et al., 2008). In mouse Vangl2+/+ and Vangl2Lp/Lp explants, we observed both highly polarised YFP-expressing cells at the leading edge as well as non-polarised cells (Fig. 4C; supplementary material Fig. S4C). The proportion of cells polarised in the direction of migration did not differ significantly between genotypes (Fig. 4D,E), nor did the distance migrated by leading edge NC cells from the central explant (Fig. 4F). Together, these data demonstrate that loss of function of the core PCP gene Vangl2 does not impair NC cell migration in vitro.

DISCUSSION

In contrast to Xenopus and zebrafish, where Wnt/PCP signalling is required for NC migration (Carmona-Fontaine et al., 2008; Matthews et al., 2008), we could detect no abnormality of NC development in Vangl1/2 mouse mutants with severe PCP defects. NC migration disorders are typically associated with anomalies of craniofacial development and cardiac outflow tract (OFT) septation, but neither defect is observed in Vangl2Lp/Lp fetuses (Henderson et al., 2001). Pairwise loss of mouse dishevelled genes Dvl1/2 and Dvl2/3 does cause cardiac OFT defects but cardiac NC migration...
has been described in these mice as either normal (Etheridge et al., 2002) or disrupted via a disorder of Wnt/β-catenin signalling (Hamblet et al., 2002). Canonical Wnt/β-Vangl2Lp/Lp is universal among vertebrates. We conclude that the PCP dependence of NC development is not known to be required for NC migration in mice (Ikeya et al., 1997).

Several lines of evidence indicate that PCP signalling is abrogated in Vangl2Δ/Δ mice. Vangl2 recruits all three dishevelled family members to the plasma membrane (Torban et al., 2004) as part of the asymmetric localisation of PCP protein complexes needed for signal transduction. Membrane localisation is lost in Vangl2Δ/Δ embryos (Torban et al., 2007). Moreover, the Vangl2Δ/Δ allele acts as a dominant negative in the female reproductive tract and brain ependymal cells (Guirao et al., 2010; vandenBerg and Sassoon, 2009). Stronger neural tube and inner ear phenotypes occur in Vangl2Δ/Δ knockouts, supporting a dominant-negative allele (Song et al., 2010; Yin et al., 2012).

This is likely to result from disrupted trafficking from endoplasmic reticulum to plasma membrane, which affects the Vangl2Δ/Δ protein (Merte et al., 2010) and other PCP proteins in Vangl2Δ/Δ mice (Yin et al., 2012).

We could not detect functional redundancy between Vangl1 and Vangl2 in relation to NC migration. Moreover, acute downregulation of Vangl2 in the NC lineage did not suggest a compensatory mechanism in mice with constitutional lack of Vangl2. Vangl2 is expressed at the mRNA level in the mouse neural tube but not in migrating NC cells. Similarly, mRNAs for other core PCP components, including Celsr1 (Formstone and Little, 2001; Shima et al., 2002) and Dvl1 (Gray et al., 2009), are not detected in NC. Hence, our finding of normal NC migration in loop-tail mice is consistent with the absence of PCP signalling in NC cells after emigration from the neural tube.

Neurocristopathies are congenital malformations involving defective NC development (Bolande, 1974). These include craniofacial abnormalities, gut innervation defects and disorders of cardiac OFT septation, which occur in ~5 per 1000 births (Dolk et al., 2010). Environmental factors (e.g. alcohol, retinoic acid) are relatively minor causes of birth defects [0.12 cases per 1000 births (Dolk et al., 2010)] and genetic factors are likely to be quantitatively more significant. Core PCP genes have been implicated in human neural tube closure defects (Juriloff and Harris, 2012) and, given the close spatiotemporal relationship between neurulation and NC development, PCP genes might be considered as strong candidates for congenital neurocristopathies. Our findings, however, argue that PCP genes are an unlikely cause of NC-related birth defects. Instead, attention should be focused on other groups of genes, such as those regulating the guidance of migrating NC cells and the differentiation of NC derivatives.

Fig. 3. Normal NC migration in Vangl1/2 double mutants and after acute Vangl2 downregulation in the NC lineage. (A-H) Control (A,C,E; Vangl1Δ/Δ; Vangl2Δ/Δ) and double-mutant (B,F-H; Vangl1Δ/Δ; Vangl2Δ/Δ) embryos exhibit normal migration of Eribb-positive cranial NC (E8.5; A,B) and cranial/trunk NC (E9.5; C-H). Acute NC downregulation of Vangl2 to test for a possible compensatory mechanism in Vangl2Δ/Δ mice (I) reveals identical YFP-positive NC migration in control (J-L; Vangl2Δ/Δ; Wnt1-Cre) and downregulation (M-O; Vangl2Δ/Δ; Wnt1-Cre) E9.5 embryos. Arrows indicate comparable streams of NC cells migrating from the trunk neural tube in both genotypes. Scale bars: 200 µm in A; 500 µm in C,F; 100 µm in J-O.

Materials and Methods

Mouse strains and embryos

Animal studies were performed according to the UK Animals (Scientific Procedures) Act 1986 and the Medical Research Council’s Responsibility in the Use of Animals for Medical Research (July 1993). Experimental embryos were generated from strains: Vangl2Δ/Δ (CBA/Ca background) (Ybot-Gonzalez et al., 2007), Wnt1-Cre (Jiang et al., 2000) crossed with R26R-EYFP (Srinivas et al., 2001), doubly heterozygous Vangl1Δ/Δ; Vangl2Δ/Δ mice (Song et al., 2010) and Vangl2Δ/Δ; Erbb3Δ/Δ (gift from Deborah Henderson, Institute of Genetic Medicine, Newcastle University, UK). See supplementary material methods for breeding schemes and genotyping. Noon after overnight mating was designated E0.5. Embryos were dissected at E8.5-10.5 in Dulbecco’s Modified Eagle’s Medium (DMEM) containing 10% fetal calf serum (FCS). Whole-mount YFP expression was visualised by direct fluorescence. Embryos for WISH or immunohistochemistry were fixed in 4% paraformaldehyde (PFA) in PBS at 4°C overnight.
WISH, immunohistochemistry and immunocytochemistry

WISH was performed on a minimum of five embryos per probe and per genotype. Digoxygenin-labelled RNA probes for Erbb3, Vangl1 and Vangl2 were as described (Doudney et al., 2005; Henderson et al., 2001). Hybridised embryos were embedded in 2% agarose in PBS and vibratome-sectioned at 50 µm thickness before mounting in Mowiol (Sigma). Immunohistochemistry utilised 7 µm wax sections; primary and secondary antibodies are listed in supplementary material methods. Sections and explants were mounted using Vectashield medium with DAPI (Vector Labs).

Neural tube explant culture

Embryo trunks were digested in 2% pancreatin (Sigma) in PBS at 37°C for 15 min, and the neural tube adjacent to the caudalmost five somites was plated onto fibronectin- and poly-D lysine-coated cover-glasses. Explants were cultured at 37°C (5% CO₂/95% air): from 0-24 h in Phenol Red-free DMEM containing 10% FCS plus 1% penicillin and streptomycin; and from 24-48 h in serum-free DMEM containing supplements for neural cell culture (N2 and B27; Invitrogen) and growth factors (EGF and FGF). After culture, explants were fixed for 10 min in 4% PFA. See supplementary material methods for details of NC cell counts and migration analysis.

Statistical analysis

Statistical tests were performed using SigmaStat (Systat) version 3.5.

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Competing interests

The authors declare no competing financial interests.

Author contributions

S.E.P., N.D.E.G. and A.J.C. designed the experiments; S.E.P. and V.M. performed the experiments; D.S., P.A. and Y.Y. performed the mouse crosses; S.E.P., N.D.E.G. and A.J.C. analysed the data and wrote the manuscript.

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Supplementary material

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