Sequential and combinatorial inputs from Nodal, Delta2/Notch and FGF/MEK/ERK signalling pathways establish a grid-like organisation of distinct cell identities in the ascidian neural plate

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The ascidian neural plate has a grid-like organisation, with six rows and eight columns of aligned cells, generated by a series of stereotypical cell divisions. We have defined unique molecular signatures for each of the eight cells in the posterior-most two rows of the neural plate – rows I and II. Using a combination of morpholino gene knockdown, dominant-negative forms and pharmacological inhibitors, we tested the role of three signalling pathways in defining these distinct cell identities. Nodal signalling at the 64-cell stage was found to be required to define two different neural plate domains – medial and lateral – with Nodal inducing lateral and repressing medial identities. Delta2, an early Nodal target, was found to then subdivide each of the lateral and medial domains to generate four columns. Finally, a separate signalling system along the anteroposterior axis, involving restricted ERK1/2 activation, was found to promote row I fates and repress row II fates. Our results reveal how the sequential integration of three signalling pathways – Nodal, Delta2/Notch and FGF/MEK/ERK – defines eight different sub-domains that characterise the ascidian caudal neural plate. Most remarkably, the distinct fates of the eight neural precursors are each determined by a unique combination of inputs from these three signalling pathways.

KEY WORDS: Ciona, Ascidian, Neural patterning, Nodal, Delta, Notch, FGF, MEK, ERK

INTRODUCTION

The central nervous system (CNS) of the Ciona intestinalis larva is remarkably similar in overall organisation to, but much simpler than, its vertebrate counterpart. It consists of an anterior sensory vesicle, followed by a narrow neck region, trunk ganglion and tail nerve cord, which are thought to correspond to the forebrain/midbrain (sensory vesicle), hindbrain (neck) and spinal cord (trunk ganglion), respectively (reviewed in Lemaire et al., 2002) [see Dufour et al. for recent advances (Dufour et al., 2006)]. Furthermore, it exhibits gene expression profiles along the anteroposterior and dorsoventral axes that are comparable to the vertebrate neural tube (reviewed in Lemaire et al., 2002). One of the advantages of studying early ascidian development is its relative morphological simplicity. Embryos develop with a fixed cell-cleavage pattern and embryonic blastomeres undergo early fate restriction. This has resulted in well-described cell lineages and fate maps (Cole and Meinertzhagen, 2004; Nicol and Meinertzhagen, 1998a; Nicol and Meinertzhagen, 1988b; Nishida, 1987), which allow the precise identification of cells and the study of cell fate specification events at the level of individual blastomeres; a level of precision not currently accessible in any other chordate model. The recent surge in interest in the Ciona model has resulted in the availability of the draft genome (Dehal et al., 2002), extensive EST collections (Satou et al., 2005), a ‘virtual’ 3D-embryo (Tassy et al., 2006) and the unravelling of the first draft whole-embryo gene regulatory network of a chordate (Imai et al., 2006).

We are exploiting the advantages of the Ciona embryo to study the generation of cell diversity in the CNS at neural plate stages, when cells are precisely aligned in a grid-like organisation and each cell can be identified (Cole and Meinertzhagen, 2004; Nicol and Meinertzhagen, 1988b; Nishida, 1987). The CNS derives from three of the four blastomere types present at the eight-cell stage, the a-, b- and A-blastomeres. This study concerns the patterning of the A-blastomere-derived part of the nervous system, which emerges at the 64-cell stage following a cell division that generates four notochord and four neural precursors (Fig. 1A). The medial pair of A-line neural precursors (A7.4) form the posterior part of the sensory vesicle and the ventral-most row of cells in the trunk ganglion and tail nerve cord, whereas the lateral cells (A7.8) form the lateral part of the trunk ganglion and tail nerve cord. At the next division, these four neural precursor cells divide along the mediolateral axis to generate one row of eight cells at the early gastrula stage (Fig. 1A). The next division, along the anteroposterior axis, generates two rows of eight cells occupying the posterior-most part of the neural plate. At this time the a- and A-derived neural plate consists of 40 cells aligned in six rows and eight columns (Fig. 1A). Rows of cells are named as rows I to VI, with row I the posterior-most row; columns are named as 1 to 4, with column 4 the most lateral and column 1 the most medial in this bilaterally symmetrical neural plate. The A-neuronal lineage contributes rows I and II (Fig. 1A). One muscle precursor is also generated from the lateral neural plate at the row I/column 4 position – the A9.31 blastomere (Fig. 1A). This muscle cell forms part of the so-called secondary muscle lineages, which generate the posterior-most larval muscle in the tail (Nicol and Meinertzhagen, 1988a; Nishida, 1990).

We have previously shown that laterally localised Nodal signalling sources participate in patterning the A-line neural plate of Ciona embryos across its mediolateral axis (Hudson and Yasuo, 2005). In the absence of Nodal signalling, all lateral neural plate
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**MATERIALS AND METHODS**

Embryo culture, manipulation, morpholinos and injection/electroporation constructs

Adult *Ciona intestinalis* were purchased from the Roscoff Marine Biological Station (Roscoff, France). Blastomere names, lineages and fate mapping are as described (Conklin, 1905; Cole and Meinertzhagen, 2004; Nicol and Meinertzhagen, 1988a; Nicol and Meinertzhagen, 1988b; Nishida, 1987). Embryo culture, microinjection and the dnDel2 injection construct have been described previously (Hudson et al., 2003; Hudson and Yasuo, 2006). *Nodal-MO* (morphorphino oligonucleotide) and Delta2-MO were purchased from GeneTools LLC and have been described elsewhere (Hudson and Yasuo, 2005; Hudson and Yasuo, 2006), except that Delta2-MO was injected in a slightly higher concentration of 0.2 mM, rather than 0.125 mM, in some experiments. pRN3-dnFGFR was generated from the EST clone ciib040h06. A DNA fragment encoding the extracellular and transmembrane domains was PCR-amplified with a primer set, 5′-GGCCAGATCTACCATGATA-CAACTACAAAATACG-3′ and 5′-GGCCGGGGGCCGCACGATGCATGGAAGTCTTATTT-3′, and subcloned into the BglII and NotI sites of pRN3. *dnFGFR* mRNA was injected at a concentration of 1 μg/μl. Electroporations were carried out as previously described (Corbo et al., 1997; Bertrand et al., 2003). The FOG-Delta2 construct is similar to that described previously (Pasini et al., 2006) except that the construct we used, which was a gift from A. Pasini (IBDML, Marseille, France), lacks the UTRs of the Delta2 gene of *Ciona intestinalis* (Ci-Delta2).

In situ hybridisation and immunohistochemistry
dpERK1/2 immunohistochemistry, in situ hybridisation and Hoechst staining were carried out as previously described (Hudson and Yasuo, 2005; Hudson and Yasuo, 2006; Picco et al., 2007; Wada et al., 1995). Dig-labelled RNA probes were synthesised from the following CDNA clones derived from the Kyoto Gene Collection plates or previously described: *Ci-Actin*, *Ci-Chordin*, *Ci-Delta2*, *Ci-FGF8/17/18*, *Ci-FGF9/16/20*, *Ci-HB9/Mnx* (renamed *Ci-Mnx* [Imai et al., 2006]), *Ci-Hesb* and *Ci-Snail* (Hudson and Yasuo, 2005); *Ci-Cdx*, *Ci-COE*, *Ci-FoxB* and *Ci-Ngn* (Imai et al., 2006); *Ci-ephrinAb* (Imai et al., 2004); *cic007j15* (Fugiwara et al., 2002; Satou et al., 2005); *Ci-MRF* (Mcedel et al., 2007); *Ci-Tbx6* (Takatori et al., 2004); and *Ci-Otx* (Hudson and Lemaire, 2001).

Inhibitor treatments and establishing the approximate timing of penetration

SB431542 (Tocris), U0126 (Calbiochem) and DAPT (Calbiochem) treatments in *Ciona* have been described previously (Hudson and Yasuo, 2005; Hudson and Yasuo, 2006). Prior to carrying out the experiments described in this study, we wanted to have some idea of how long these chemical inhibitors take to penetrate and act upon the expression of the target genes. *Ci-Otx* expression in a6.5 and b6.5 blastomeres at the 44-cell stage has been identified as a direct target of FGF9/16/20 acting via MEK/ERK (Bertrand et al., 2003; Hudson et al., 2003). *Ci-FGF9/16/20* is expressed from the 16-cell stage, ERK1/2 is activated in the a6.5 and b6.5 blastomeres during the latter half of the 32-cell stage and *Ci-Otx* is expressed in these cells at the 44-cell stage, approximately 20-30 minutes after the onset of ERK1/2 activation (Bertrand et al., 2003; Hudson et al., 2003). Thus, there is a lag between transcription of the ligand gene (*FGF9/16/20*), detectable activation of the pathway (dpERK1/2) and the readout in target gene expression (*Ci-Otx*), which should be considered when trying to establish how long a pharmacological reagent takes to penetrate and act. We found that embryos need to be placed in the MEK/ERK inhibitor, UO126 (Duncia et al., 1998; Favata et al., 1998), 20-30 minutes prior to fixation at the 44-cell stage, which corresponds to the early 32-cell stage, in order to completely inhibit detectable *Ci-Otx* expression (see Fig. S1 in the supplementary material). This is just prior to detectable ERK1/2 activation and suggests that UO126 can penetrate the embryo and act very quickly.

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Similarly, we placed embryos in an inhibitor of gamma-secretase, DAPT (Geling et al., 2002), at different time points starting from the 44-cell stage and analysed expression of a potential direct target of Delta2/Notch signalling, Ci-Hesb, at the early gastrula stage. DAPT treatment strongly downregulated Ci-Hesb expression when applied 30–40 minutes prior to fixation (see Fig. S1 in the supplementary material). Finally, we tested how long SB431542, a pharmacological inhibitor of ALK4/5/7 (Inman et al., 2002), might take to block Ci-Delta2 expression, which is the earliest identified target of Nodal signals. SB431542 had to be applied to embryos approximately 40 minutes prior to fixation in order to downregulate Ci-Delta2 expression at the 64-cell stage. We conclude, given that there should be a time lag between expression of the ligand and onset of target gene transcription, that all of these inhibitors penetrate and act in a reasonably short period of time.

RESULTS
Gene expression profiles in the ascidian neural plate

We have previously described a collection of gene expression profiles that we used as molecular markers to study neural plate patterning (Fig. 1B) (Hudson and Yasuo, 2005). In this study, additional genes were included, which were found by searching the EST/in situ data banks ‘Ghost’ and ‘ANISEED’ (e.g. Imai et al., 2004; Tassy et al., 2006; Satou et al., 2005). The Ciona intestinalis Neurogenin gene (Ci-Neurogenin; Ci-Ngn) encodes a basic helix-loop-helix (bHLH) transcription factor and its expression was restricted to the lateral-most A-line neural blastomere, A8.16, at the early gastrula stage (Fig. 1B, Fig. 2) (Imai et al., 2004; Imai et al., 2006). cicl007j15 encodes a protein with similarity to a regulator of G-protein signalling. Expression was restricted at the early gastrula stage to the medial four cells (columns 1 and 2) of the A-line neural lineage (Fig. 1B, Fig. 2). This supports previous evidence that medial and lateral cells are undergoing different developmental programs by the early gastrula stage, with Ci-SnaIl and Ci-Delta2 only in the lateral cells (Fig. 1B) (Hudson and Yasuo, 2005). This gene expression profiling further revealed that, by the early gastrula stage, column 3 (A8.15) and column 4 (A8.16) precursors become distinguishable, with expression of Ci-Ngn and Ci-Hesb only in A8.16 (Fig. 1B, Fig. 2) (Hudson and Yasuo, 2006; Imai et al., 2006). Thus, by the early gastrula stage the A-line neural cells can be divided into three domains in terms of gene expression (Fig. 1B).

At the neural plate stage, cicl007j15 is expressed in the medial cells of row II (Fig. 1B, Fig. 2) (Fujiwara et al., 2002). Ci-ephrinAb encodes a GPI-anchored ephrin ligand (Satou et al., 2003a) and we detected expression in row I/column 3 (A9.29) of the neural plate (Fig. 1B, Fig. 2). Ci-COE encodes a transcription factor of the Collier/Olf/EBF family (Satou et al., 2003b) and its expression was detected in row II/column 4 (A9.32) (Fig. 1B, Fig. 2) (Imai et al., 2006). We also included two markers of muscle fate, Ci-Tbx6b and Ci-MRF, encoding transcription factors of the T-box and bHLH classes, respectively; these are detectable in row I/column 4 (A9.31) (Fig. 1B, Fig. 2) (Meeel et al., 2007; Takatori et al., 2004). These expression profiles indicate that in the neural plate, soon after each division, individual blastomeres undergo different developmental programmes. In the posterior two rows of the neural plate, we can thus define eight expression domains corresponding to the eight different cells (Fig. 1B). In row I, the expression domains are as follows: column 1 (Mnx), column 2 (Mnx, Hesb and Cdx), column 3 (Hesb, Cdx, Chordin and ephrinAb), of which ephrinAb is specific to this cell) and column 4 (Hesb, Cdx, Chordin, MRF and Tbx6b, of which MRF and Tbx6b are specific to this cell). In row II, the expression domains are as follows: column 1 (FGF9/16/20, cicl007j15 and FoxB, of which FoxB is specific to this cell), column 2 (FGF9/16/20, cicl007j15 and Hesb), column 3 (Hesb, Chordin and FGF8/17/18, of which FGF8/17/18 is specific to this cell) and column 4 (Hesb, Chordin and COE, of which COE is specific for this cell). Thus, each of the eight blastomeres in the posterior neural plate exhibits a unique combination of gene expression profiles, which can be used as a molecular signature for each cell identity and, in particular, a cell-specific marker has been identified for each of
the lateral four cells: COE, FGF8/17/18, MRF/Tbx6b and ephrinAb (Fig. 1B). We next addressed how each cell identity in the posterior neural plate, characterised by these distinct profiles of gene expression, is generated.

**Lateral versus medial neural plate fate specification**

Each of these additional molecular markers behaved as predicted from previous work when Nodal signalling was inhibited: medial markers were expanded at the expense of lateral markers (Hudson and Yasuo, 2005; Imai et al., 2006). Nodal signalling was blocked by treatment with a pharmacological inhibitor of ALK4/5/7, SB431542, or by injecting a morpholino oligonucleotide against Ci-Nodal (Fig. 2). Expression of the lateral neural plate markers Ci-Ngn, Ci-ephrinAb, Ci-COE, Ci-MRF and Ci-Tbx6b was inhibited, whereas that of the medial marker cici007j15 was expanded into the lateral cells both at the early gastrula and neural plate stages. A reduction in Ci-COE and Ci-Ngn expression at the late gastrula stage has previously been reported by quantitative reverse transcriptase (RT)-PCR or in situ hybridisation analysis following Nodal inhibition (Imai et al., 2006). These data provide further evidence that Nodal signalling is required for the formation of all lateral A-line neural plate fates of columns 3 and 4, and shows that expansion of medial fates into the lateral A-line neural precursors occurs as early as the early gastrula stage.

We next addressed the timing of Nodal signalling required for lateral versus medial neural plate fates by placing embryos in SB431542 at different developmental time points. We analysed, at the early gastrula stage, Ci-Snail expression as a general lateral marker, Ci-Ngn expression as an A8.16 marker, and cici007j15 as a medial marker. We found that at around the 64- to 76-cell stage of development, expression of all three genes became insensitive to SB431542 treatment (Fig. 3). SB431542 can penetrate embryos and act within at least 40 minutes (see Fig. S1C in the supplementary material and see Materials and methods), indicating that, by the early gastrula stage at the latest, Nodal-mediated lateral versus medial fates are determined. It has been proposed previously that the lateral-most cell, A8.16, might adopt a distinct fate to its more medial sister cell, A8.15, due to its prolonged contact with Nodal-expressing b-line cells (Hudson and Yasuo, 2005; Imai et al., 2006). However, because Ci-Snail and Ci-Ngn exhibit a similar temporal dependency to Nodal signals, it is unlikely that this is the case and rather suggests that Nodal mediates only medial versus lateral fate specification and that other mechanisms subsequently act to further pattern the lateral columns.

**Delta2 is required for column 4 gene expression**

We have shown previously that Delta2/Notch signalling acts in a relay of Nodal signalling during the induction of the secondary notochord fate (Hudson and Yasuo, 2006). Ci-Delta2 is expressed from the late 64-cell stage in A7.6, b7.9 and b7.10, with weak expression also observed occasionally in A7.8 (Fig. 4A) (Hudson and Yasuo, 2006). A7.6 and b7.10 blastomeres are in direct contact with the A7.8 blastomere, the founder of neural plate columns 3 and 4 (Fig. 1A). This expression of Ci-Delta2 persists during the cell division of A7.8 into A8.15 and A8.16 at the 76-cell stage, with the Ci-Delta2-expressing cells remaining in contact only with A8.16, the column 4 precursor (Fig. 4A). We investigated whether Delta2/Notch signalling plays a role during patterning of the A-line-derived neural plate using a morpholino oligonucleotide against Delta2 (Del2-MO), a dominant-negative version of Delta2 lacking the intracellular domain (dnDel2) and DAPT, a pharmacological inhibitor of gamma-secretase, an enzyme required for Notch receptor processing. These reagents have previously been shown to inhibit Delta2/Notch signalling in *Ciona* embryos (Hudson and Yasuo, 2006).

We first analysed the effect on A-line neural patterning at the early gastrula stage (Fig. 4B). Expression of the general lateral markers Ci-Snail and Ci-Delta2 in A8.15 and A8.16 cells was not affected by inhibition of Delta2/Notch signalling. Similarly, the medial marker cici007j15 was not expanded. Thus, Delta2/Notch signalling is not required for medial versus lateral neural plate fates. However, expression of Ci-Ngn in the most-lateral cell, A8.16, was lost. This is consistent with our previous observation that Ci-Hesb expression in A8.16 is Delta2/Notch-dependent (Hudson and Yasuo, 2006) and suggests that Delta2 might be required specifically for column 4 fates during the patterning of the A-line neural plate.

The role of Delta2/Notch was further addressed by analysing gene expression at the neural plate stage (Fig. 5; Fig. S2 in the supplementary material). As expected, expression of Ci-Hesb, which is a target of Delta2/Notch at early gastrula stages, was lost following Delta2/Notch inhibition. However, Ci-Chordin, which is also broadly expressed in the lateral neural plate, was not
affected. Similarly, Ci-FGF8/17/18 and Ci-ephrinAb, which are specifically expressed in column 3, were still expressed in the majority of embryos following Delta2/Notch inhibition. This shows that Delta2/Notch signalling is not generally required for lateral neural plate fates. Consistently, Ci-Mnx and Ci-FGF9/16/20 were not expanded into the lateral neural plate following Delta2/Notch inhibition. However, genes that are specifically expressed in column 4, such as Ci-COE in row II/column 4 (A9.32), and Ci-MRF and Ci-Thx6b in row I/column 4 (A9.31), were Delta2/Notch-dependent (Fig. 5; Fig. S2 in the supplementary material). Loss of secondary muscle fate was confirmed by analysing Ci-Actin expression in the A8.16 lineage at the neurula stage in embryos treated with cytochalasin B from the early gastrula stage, a treatment that allows analysis of late marker expression in terms of lineages (e.g. Hudson and Yasuo, 2005). Thus, inhibition of Delta2/Notch results in the specific loss of column 4 identity.

Delta2/Notch signalling is acting upon the column 4 precursor (A8.16)

Loss of column 4 fates following inhibition of Delta2/Notch signalling became apparent at the early gastrula stage with loss of Ci-Hesb and Ci-Ngn in A8.16. In order to address when Delta2/Notch signalling was required to establish column 4 fates, we placed embryos in DAPT inhibitor at different developmental time points and analysed Ci-COE and Ci-MRF expression at the neural plate stage (Fig. 6). Expression of Ci-MRF, Ci-Actin and Ci-COE at neural plate stages was not affected by DAPT treatment from the 76-cell stage onwards, coinciding with the stage at which the column 4 precursor (A8.16) is formed. Because DAPT can penetrate and block target gene expression within 30-40 minutes (see Fig. S1B in the supplementary material), well within the cell cycle of A8.16, we conclude that Delta2/Notch is acting upon A8.16 and that, once specified, A8.16 generates two distinct daughter cells (marked by Ci-COE and Ci-MRF) along the anteroposterior axis in a Notch-independent manner.

Overexpression of Delta2 can promote ectopic column 4 identity

We have shown that Delta2/Notch signalling is required for column 4 fates. In order to address whether Delta2 is sufficient to promote column 4 fates, we overexpressed Ci-Delta2. This was carried out using an electroporation construct, FOG::Delta2, in which the FOG promoter is placed upstream of Ci-Delta2, driving its expression in all animal cells from the 16-cell stage onwards (Pasini et al., 2006). Animal cells are in contact with all the A-line neural precursors up to and including gastrula stages. At the early gastrula stage, we analysed expression of Ci-Hesb, Ci-Ngn and Ci-Snail (Fig. 4C). Following FOG::Delta2 electroporation, expression of Ci-Hesb was observed throughout the A-line neural cells in all columns (column 4, 98%; column 3, 93%; column 2, 89%; column 1, 89%), suggesting that all A-line neural cells received a Delta2/Notch signal
under these experimental conditions. Similarly, ectopic Ci-Ngn expression was observed, although expression appeared more readily in column 3 compared with columns 1 and 2 (column 4, 100%; column 3, 84.5%; column 2, 30%; column 1, 35%). Consistent with the specific requirement of Delta2 for column 4 fates, the general lateral neural marker, Ci-Snail, was not ectopically
expressed following Delta2 overexpression, showing that Delta2 cannot promote general lateral fates.

We next analysed markers of column 3 (Ci-Fgf8/17/18 and Ci-ephrinAb) and column 4 (Ci-MRF and Ci-COE) at neural plate stages in FOG:Delta2-electroporated embryos. We found that Ci-COE was expressed ectopically in row II/column 3 (A9.30; 71%), with expression in columns 2 or 1 rarely observed (4 and 7%, respectively). Under these conditions, a row I/column 4 marker, Ci-MRF, was also ectopically expressed in row I/column 3 (A9.29) in 56% of embryos and never in columns 1 and 2. On the other hand, the column 3 markers Ci-Fgf8/17/18 and Ci-ephrinAb appeared slightly downregulated compared with control embryos (Fig. 5).

These data show that Delta2 specifically promotes column 4 identity. It also shows that, at neural plate stages, the competence to express column 4 markers in response to Delta2 is restricted to columns 3 and 4, which previously received a Nodal signal.

Later Delta2/Notch activity is involved in distinguishing column 1 versus column 2 fates

From the 110-cell stage, Ci-Delta2 is expressed in column 3 and 4 precursors (A8.15 and A8.16, respectively), with column 3 precursors being in direct contact with column 2 precursors (Fig. 4B) (Hudson and Yasuo, 2005). We therefore addressed whether Delta2/Notch might be playing an additional patterning role; in particular, patterning between column 1 and 2. At the neural plate stage, Ci-Hesb is expressed in columns 2-4, but not in column 1 (Fig. 5) (Hudson and Yasuo, 2005). On the other hand, Ci-FoxB specifically marks the row II/column 1 blastomere (A9.14) (Moret et al., 2005). Both of these markers were found to be sensitive to Delta2/Notch signal inhibition, with Ci-Hesb expression being lost and Ci-FoxB expression expanded into row II/column 2 (A9.16) (Fig. 5). Conversely, overexpression of Ci-Delta2 suppressed Ci-FoxB expression (Fig. 5). Treatment of embryos with DAPT at different developmental time points revealed that this Delta2/Notch-mediated patterning event takes place later than that for column 4 specification (Fig. 6). This suggests that a later Delta2/Notch signal is required to promote column 2 (Ci-Hesb expression) and repress column 1 (Ci-FoxB expression) identity in column 2 cells, at least in row II.

Taken together, our results suggest that Delta2/Notch acts to subdivide the neural plate into four columns, with early Delta2/Notch involved in subdividing column 3 and 4 fates in the lateral domain and later Delta2/Notch subdividing column 1 and 2 fates in the medial domain.

Differential FGF/MEK/ERK signals between row I and row II neural plate cells are required for their differential fate specification

Nodal and Delta2/Notch signalling can explain fate differences along the mediolateral axis of the neural plate, but not those along the anteroposterior axis. We therefore considered other candidate signalling pathways. Extracellular-signal-regulated kinase 1/2 (ERK1/2) is a part of an evolutionary conserved signalling cascade acting downstream of receptor tyrosine kinases (RTKs), which are activated by ligands such as FGF. Antibodies against the dual phosphorylated form of ERK1/2 (dpERK1/2) can be used to visualise the pattern of ERK1/2 activation during Ciona development (e.g. Yasuo and Hudson, 2007). During neural plate stages, we found that ERK1/2 was differentially activated between row I and row II. Soon after the division of A-line neural plate precursors into row I and row II, at the stage when the entire neural plate consists of four rows of cells, ERK1/2 activation was detected in row I cells, but not in row II cells, and this pattern was maintained until the neural plate consisted of six rows of cells (Fig. 7A). Activation of ERK1/2 was also observed in the a-line precursors of row III. These data are consistent with observations in Halocynthia (Nishida, 2003) and suggest that differential ERK1/2 activation between row I and row II cells might be playing a role during patterning of the neural plate along the anteroposterior axis.

In order to address this possibility, we placed embryos in UO126, a pharmacological inhibitor of MEK, which is a kinase required for ERK1/2 activation, at the early gastrula stage. The early gastrula stage is approximately 30 minutes before A-line neural precursors divide into rows I and II. We found that all markers of row I, including Ci-MRF, Ci-Tbx6b, Ci-Actin, Ci-ephrinAb, Ci-Mnx and Ci-Cdx, were lost following inhibition of the MEK/ERK pathway (Fig. 7B, Table 1). By contrast, row II markers were expanded into row I (Fig. 7C; Table 1). This was particularly striking in the lateral cells with an almost complete transformation of row I cells into a row II-like fate, as judged by ectopic expression of Ci-Fgf8/17/18 in row I/column 3 (A9.29) and Ci-COE in row I/column 4 (A9.31). A similar transformation took place in the medial cells, although the ectopic expression of row II markers in row I was sometimes weaker than in row II. Importantly, ectopic expression of row II markers in
row I was observed only in the same column as the expression normally observed in row II. This indicates that inhibition of MEK/ERK from the early gastrula stage affects only anteroposterior patterning and that mediolateral positional information remains intact in these embryos. Finally, by placing embryos in UO126 at different developmental time points and analysing Ci-COE and Ci-MRF expression, we found that segregation of these cell types became refractory to MEK inhibition at around the time that A-line neural precursors had divided into row I and row II (Fig. 8).

FGF9/16/20 is expressed in the A-line neural precursors from the 64-cell stage until the mid-gastrula stages, making it a good candidate for the signal responsible for ERK activation in row I (Imai et al., 2002) (our unpublished data). However, we could not address the role of FGF9/16/20 during posterior neural plate patterning because this ligand is required earlier in development for the induction of Ci-Nodal expression in the lateral b-line cells at the 32-cell stage and Ci-Nodal is required for mediolateral patterning (Hudson and Yasuo, 2005). In order to address whether FGF signals were required for the differential specification of row I and row II, we injected a dominant-negative FGF receptor (dnFGFRc) into A5.2 at the 16-cell stage. This blastomere generates columns 3 and 4 of the A-line neural plate as well as one quarter of the A-line notochord, a trunk lateral cell and an endoderm precursor. This procedure resulted in the loss of Ci-MRF expression and ectopic Ci-COE expression in row I, phenocopying UO126 treatment from the early gastrula stage (Fig. 7D). Although we cannot rule out that the transformation of neural plate cells is a secondary effect of mis-specification of the other tissue precursors derived from A5.2, these data support a role for FGF signalling during the differential specification of row I and row II cells.

Taken together, these results suggest that an FGF signal is required for ERK activation in row I cells, which acts to promote row I fates and repress row II fates, patterning the caudal neural plate along the anteroposterior axis.
DISCUSSION

We have shown that three distinct signalling pathways are integrated during patterning of the A-line neural plate and play a major role in establishing a grid-like pattern of gene expression domains (Fig. 9). Nodal signals are required for all lateral neural plate fates and to restrict medial fates, early Delta2/Notch is required for column 4 fates, late Delta2/Notch is required for column 2 fates, and FGF/MEK/ERK is required to promote row I fates and restrict row II fates. Each neural plate precursor receives a distinct combination of the three signalling pathways, which are required to define each of the eight cell types (Fig. 9). For example, the formation of the secondary muscle precursor in the row I/column 4 position requires positive input from all three signalling pathways. These signalling pathways appear to be acting sequentially. Nodal expression begins at the 32-cell stage and the Nodal-mediated medial versus lateral fate choice is achieved around the 64- to 76-cell stage. Nodal signalling is required for the specification of all derivatives of A7.8 (founder cell of columns 3 and 4), which emerges at the 64-cell stage. Delta2, a transcriptional target of Nodal signalling, is expressed from the late 64-cell stage and is required for fate specification of A8.16 (precursor of column 4), which forms at the 76-cell stage. Later, at around the 110-cell stage, Ci-Delta2 is expressed in cells adjacent to column 2 precursors and is required to promote column 2 and repress column 1 identity. Finally, FGF/ERK activation in row I but not in row II cells at neural plate stages is required for the differential fate specification between these two rows of cells. It is likely that the molecules used as markers in this study are also interacting with each other. For example, it has been shown that Ci-Snail, which is expressed in the lateral neural cells and is activated by Nodal, is required for repression of the medial marker Ci-Mnx (Imai et al., 2006).

We previously noted that mediolateral patterning of the A-line neural plate appeared to be independent of anteroposterior patterning, because the expansion of medial marker expression observed following Nodal inhibition remained in the correct row of cells (Fig. 2) (Hudson and Yasuo, 2005). In support of this, here we show that disruption of anteroposterior patterning by FGF/MEK/ERK inhibition from the early gastrula stage resulted in adaption of row II-like fates in row I in a manner respecting columnar position (Fig. 7). Thus, mediolateral and anteroposterior patterning of the neural plate are uncoupled, independent events.

Nodal, Delta2 and FGF/MEK/ERK signalling during neural tube patterning of Ciona

LATERALLY LOCALISED NODAL SIGNALS PROVIDE A POSITIONAL CUE, WHICH INITIATES PATTERNING ALONG THE MEDIOLATERAL AXIS OF THE POSTERIOR NEURAL PLATE. This pattern is achieved through an alternative fate choice, with Nodal promoting lateral and repressing medial identity, and results in the subdivision of the neural plate precursors into two domains, a Ci-Snail/Ci-Delta2-positive lateral domain and a cicl007j15-positive medial domain (this study) (Hudson and Yasuo, 2005). Nodal signalling is also required for lateral neural plate fates in the anterior (a-line) neural plate and for expression of markers in b-line neural precursors (Hudson and Yasuo, 2005; Imai et al., 2006). Further work will be required to understand whether these anterior neural cells adopt alternative fates in the absence of Nodal signals.

In the posterior neural plate, Delta2 redefines the initial pattern established by Nodal. During the specification of column 4 fates, Delta2/Notch signals do not appear to be driving a binary cell fate switch, because column 4 cells do not adopt their column 3 sister cell

Table 1. Expression of row I and row II markers following UO126 treatment from the early gastrula stage

<table>
<thead>
<tr>
<th>Marker</th>
<th>Control %</th>
<th>Control Mean</th>
<th>Control n</th>
<th>UO126 %</th>
<th>UO126 Mean</th>
<th>UO126 n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ci-MRF</td>
<td>99</td>
<td>1.9</td>
<td>159</td>
<td>2</td>
<td>0</td>
<td>64</td>
</tr>
<tr>
<td>Ci-Tbx6b</td>
<td>84</td>
<td>1.5</td>
<td>57</td>
<td>0</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Ci-Actin</td>
<td>98</td>
<td>1.7</td>
<td>54</td>
<td>0</td>
<td>0</td>
<td>59</td>
</tr>
<tr>
<td>Ci-ephrinAb</td>
<td>92</td>
<td>1.6</td>
<td>103</td>
<td>2.5</td>
<td>0</td>
<td>119</td>
</tr>
<tr>
<td>Ci-Mnx</td>
<td>99</td>
<td>3.9</td>
<td>130</td>
<td>3</td>
<td>0</td>
<td>115</td>
</tr>
<tr>
<td>Ci-Cdx</td>
<td>100</td>
<td>5.3</td>
<td>79</td>
<td>0</td>
<td>0</td>
<td>110</td>
</tr>
<tr>
<td>Ci-COE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row I</td>
<td>13</td>
<td>0.2</td>
<td>108</td>
<td>99</td>
<td>1.9</td>
<td>69</td>
</tr>
<tr>
<td>Row II</td>
<td>98</td>
<td>1.6</td>
<td>100</td>
<td>1.8</td>
<td>95</td>
<td>1.9</td>
</tr>
<tr>
<td>Ci-FGF9/17/18</td>
<td>93</td>
<td>1.8</td>
<td>135</td>
<td>99</td>
<td>1.8</td>
<td>110</td>
</tr>
<tr>
<td>Ci-FGF9/16/20</td>
<td>0</td>
<td>0.0</td>
<td>129</td>
<td>80</td>
<td>3.0</td>
<td>127</td>
</tr>
<tr>
<td>Row I</td>
<td>99</td>
<td>3.7</td>
<td>100</td>
<td>4</td>
<td>100</td>
<td>3.5</td>
</tr>
<tr>
<td>Row II</td>
<td>5</td>
<td>0.1</td>
<td>66</td>
<td>1.8</td>
<td>100</td>
<td>3.5</td>
</tr>
<tr>
<td>cicl007j15</td>
<td>100</td>
<td>3.6</td>
<td>137</td>
<td>100</td>
<td>3.5</td>
<td>86</td>
</tr>
</tbody>
</table>

Expression in row I was counted for row I markers (Ci-MRF, Ci-Tbx6b, Ci-Actin, Ci-ephrinAb, Ci-Mnx, Ci-Cdx), and in row I and row II for row II markers (Ci-COE, Ci-FGF9/17/18, Ci-FGF9/16/20, cicl007j15). %, percentage of embryos showing any expression; Mean, mean number of neural plate cells positive for each marker; n, total number of embryos analysed.
identity following Delta2/Notch signal inhibition. Continued expression of general lateral neural plate markers (Ci-Snail, Ci-Delta2, Ci-Chordin) throughout the lateral neural plate indicates that column 4 cells retain lateral neural identity (Figs 4, 5). However, only rarely was ectopic expression of the column 3 markers Ci-ephrinAb and Ci-FGF8/17/18 observed in column 4 (Fig. 5). This suggests that other mechanisms might operate in the embryo to repress column 3 fates in column 4. Alternatively, there might be additional signals required to induce column 3 fates in column 3. One possible candidate is BMP2/4, which has been shown in Halocynthia to be required for specification of motoneurons, which are column 3 derivatives (Katsuyama et al., 2005). In addition to column 4 specification, we have found that later Delta2/Notch signals are implicated in the formation of column 2 versus column 1 identity. In this case, the Delta2/Notch signal might act as a binary switch, because column 1 fates are ectopically expressed in column 2 following Delta2/Notch signal disruption.

Superimposed on this mediolateral pattern is a difference in anteroposterior identities established by the differential activation of ERK1/2 between rows I and II (Fig. 7). We show that this differential fate specification requires FGF-signalling within the A5.2 lineage. Within the a-line neural plate, ERK1/2 is also differentially activated between the row III (active) and row IV (inactive) sister rows (Fig. 7). Thus, in both A- and a-lineages, ERK1/2 activity is associated with the posterior-most row of cells. Further studies will be required to establish whether row III fates adopt row IV fates in the absence of FGF/MEK/ERK activity.

It will be important in future studies to reveal the ultimate fates of each of these neural plate cells by precise fate mapping coupled with marker analysis, and to verify whether the early changes in neural plate patterning described in this study manifest as terminal fate changes in the CNS.

Nodal, Notch and MEK/ERK signalling during vertebrate neural patterning

All three of these signalling pathways are involved in a myriad of cell fate specification events during vertebrate development. Within the vertebral neural tube, Nodal is required for induction of the floor plate, the ventral-most structure of the neural tube, at least in zebrafish (reviewed in Strähle et al., 2004). This is at odds with the role for Nodal in promoting lateral fates at the expense of medial (including floor plate) fates in ascidians and suggests that the role of Nodal in neural tube patterning is not conserved among chordates. By contrast, in the vertebrate neural tube, Delta/Notch signalling has been implicated in the formation of both extreme dorsal (neural crest) and ventral (floor plate) cell types (Cornell and Eisen, 2005; Latimer and Appel, 2006). In Ciona, Delta2/Notch is involved in both the specification of lateral and medial fates within the neural plate. Interestingly, there are some differences in the mode of action of Delta/Notch signalling in Ciona, because Ci-MRF, Ci-COE and Ci-Ngn, which all encode HLH proteins, are activated by Delta2/Notch, whereas expression of these transcription factors is generally negatively regulated by Notch signals (e.g. Dubois and Vincent, 2001; Hansson et al., 2004; Kuroda et al., 1999; Ma et al., 1996; Umbhauer et al., 2001; Wittenberger et al., 1999). Later, during neurogenesis, Notch signalling is involved in the selection of neurones in neurogenic regions of the developing neural plate, a process known as lateral inhibition (reviewed in Lai, 2004). Although this role has not been addressed in the CNS of Ciona, it is involved in the selection of epidermal sensory neurones within the dorsal and ventral midline neurogenic regions of the larval tail epidermis (Pasini et al., 2006). In vertebrates, FGF, together with Wnt, signalling is required during late gastrula stages to impose a posterior identity on neural tissue (e.g. Gamse and Sive, 2000; Nordström et al., 2006). This is reminiscent of the situation in ascidians, in which we have shown that FGF/MEK/ERK signalling is required for posterior identities in the neural plate. Thus, the role of this signalling pathway during posteriorisation might represent a core evolutionary strategy to generate posterior cell types within neural tissue.

Concluding remarks

The simple organisation of the ascidian neural plate allows us to understand cell fate diversification at the level of individual cells. Our studies have enabled us to superimpose the activity of three overlapping signalling pathways onto the grid-like organisation of cells and gene expression patterns in the neural plate (Fig. 9). It will be imperative in future studies to try to understand how these signalling pathways are integrated at the level of transcriptional control of cell-type-specific gene markers, particularly in the lateral neural plate, in which a specific marker for each individual cell has been identified. Taken together with recent advances in establishing gene regulatory networks during early Ciona development (Imai et al., 2006), it is not unreasonable to expect that it will ultimately be possible to establish a gene regulatory network, integrating cell signalling and transcription factor inputs, for each individual cell of the neural plate.

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Supplementary material

Supplementary material for this article is available at http://dev.biologists.org/cgi/content/full/134/19/3527/DC1

References


