RESEARCH ARTICLE

Retinoic acid regulates size, pattern and alignment of tissues at the head-trunk transition

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ABSTRACT

At the head-trunk transition, hindbrain and spinal cord alignment to occipital and vertebral bones is crucial for coherent neural and skeletal system organization. Changes in neural or mesodermal tissue configuration arising from defects in the specification, patterning or relative axial placement of territories can severely compromise their integration and function. Here, we show that coordination of neural and mesodermal tissue at the zebrafish head-trunk transition crucially depends on two novel activities of the signaling factor retinoic acid (RA): one specifying the size and the other specifying the axis position relative to mesodermal structures of the hindbrain territory. These activities are each independent but coordinated with the well-established function of RA in hindbrain patterning. Using neural and mesodermal landmarks we demonstrate that the functions of RA in aligning neural and mesodermal tissues temporally precede the specification of hindbrain and spinal cord territories and the activation of hox transcription. Using cell transplantation assays we show that RA activity in the neuroepithelium regulates hindbrain patterning directly and territory size specification indirectly. This indirect function is partially dependent on Wnts but independent of FGFs. Importantly, RA specifies and patterns the hindbrain territory by antagonizing the activity of the spinal cord specification gene cdx4; loss of Cdx4 rescues the defects associated with the loss of RA, including the reduction in hindbrain size and the loss of posterior rhombomeres. We propose that at the head-trunk transition, RA coordinates specification, patterning and alignment of neural and mesodermal tissues that are essential for the organization and function of the neural and skeletal systems.

KEY WORDS: Retinoic acid, cdx, Hindbrain, Spinal cord, Patterning, Head-trunk transition, Craniovertebral junction, Zebrafish

INTRODUCTION

The coherent organization of the neural and skeletal systems requires that the respective neuroectodermal and mesodermal precursor tissues align accurately along the vertebrate rostrocaudal axis. Changes in the axial position of precursor tissues can result in structural malformations and compromised function. Alignment is particularly crucial at the head-trunk transition, where the basal opening of the occipital bone, the foramen magnum, must align with the caudal hindbrain to allow the nerve cord safe passage into the vertebral canal. Both misalignments and structural abnormalities have long been known to result in severe neurological syndromes (List, 1941; Marin-Padilla, 1991). Although significant progress has been made in understanding neural and mesodermal regionalization (reviewed by Stern et al., 2006), the mechanisms specifying the relative position of neural and mesodermal territories within the vertebrate rostrocaudal axis remain unknown. Here, we set out to study the earliest processes involved in neural and skeletal system integration by investigating the signaling events that specify the rostrocaudal position and relative alignment of hindbrain/spinal cord (HB/SC) territories to the somitic precursors of the head and trunk bones and muscles.

Specification events that regionally restrict the identity of neural progenitor cells to a hindbrain or spinal cord fate would necessarily specify the rostrocaudal position of the HB/SC transition. The hindbrain and spinal cord are specified from a common progenitor tissue, the caudal neural plate (Schoenwolf, 1992; Muhr et al., 1997, 1999; Brown and Storey, 2000), through the binary activity of Cdx transcription factors (Skromne et al., 2007). Transcription of cdx genes in the caudal neural plate is initially broad, but is quickly turned off rostrally to allow hindbrain segmentation and patterning. While it is maintained in the ‘on’ state caudally to specify spinal cord (Skromne et al., 2007; Sturgeon et al., 2011). These events take place from mid-gastrulation to early segmentation (Muhr et al., 1997, 1999; Woo and Fraser, 1998; Nordström et al., 2006; Skromne et al., 2007; Sturgeon et al., 2011) and are crucial for proper cell fate allocation. In mouse and zebrafish, changes in the expression domain of cdx changes the size of the hindbrain and spinal cord territories in a reciprocal manner; a rostral expansion of cdx transcriptional domain reduces the hindbrain and expands the spinal cord, whereas a caudal reduction in cdx transcriptional domain expands the hindbrain and reduces the spinal cord (Charite et al., 1998; Shimizu et al., 2006; Skromne et al., 2007; van Rooijen et al., 2012). Thus, in order to understand the processes that establish the position of the HB/SC transition, it is important to understand the mechanisms of cdx regulation.

Regulation of cdx genes is complex, with several signaling factors influencing transcription. All three members of the cdx family of transcription factors, cdx1, cdx2 and cdx4, are transcribed in the caudal region of embryos (Frumkin et al., 1991; Gamer and Wright, 1993; Meyer and Gruss, 1993; Beck et al., 1995; Skromne et al., 2007). This restricted caudal expression is controlled by the activity of the signaling factors FGF, Wnt and retinoic acid (RA) (reviewed by Lohnes, 2003; Deschamps and van Nes, 2005). Whereas the regulatory function of these signals on cdx transcription has been extensively studied in the context of mesoderm anterior-posterior patterning (reviewed by Deschamps and van Nes, 2005), the regulation of cdx in nervous system regionalization has not been characterized.

RA is a suitable candidate to regulate both cdx expression in neural tissue and the axial placement of the HB/SC transition relative to the paraxial mesoderm. In all species examined, RA is synthesized at the right place and time, the paraxial mesoderm adjacent to the HB/SC transition (Niederreither et al., 1997;
Swindell et al., 1999; Begemann et al., 2001; Grandel et al., 2002), during the hindbrain and spinal cord specification period (Woo and Fraser, 1998; Muhr et al., 1999). Importantly, RA can induce caudal neural plate explants fated to become posterior spinal cord to change their hox expression profile to that of more anterior regions (Nordström et al., 2006). Whereas changes in spinal cord gene expression from posterior to anterior could be attributed to the well-known function of RA in hox patterning gene regulation (Sockanathan and Jessell, 1998; Liu et al., 2001; reviewed by Glover et al., 2006; Rhinn and Dolle, 2012), patterning processes alone cannot explain the transformation of spinal cord to hindbrain identities. Instead, the transformation suggests that, in addition to its patterning functions, RA is also involved in hindbrain and spinal cord specification.

In this study we demonstrate a novel role for RA in specifying the axial position and alignment of the HB/SC transition relative to mesodermal tissues in zebrafish. These activities depend on Cdx4 and can be distinguished from RA patterning functions temporally and mechanistically. Temporally, inhibition of RA activity demonstrates that RA aligns the neural and mesodermal tissue early during gastrulation, before the specification of hindbrain and spinal cord territories, and the expression of hox patterning genes. Mechanistically, cell transplantation approaches show that RA induces posterior patterning genes in the hindbrain directly, but functions in regulating cdx4 spatial expression domain indirectly. The indirect regulation of cdx4 through RA is FGF-independent, but requires Wnt activity. Together, these findings identify RA as a key component in the signaling network regulating the specification, alignment and patterning of hindbrain, spinal cord and mesodermal tissues that are essential for the functional organization of nervous and skeletal systems at the head-trunk transition.

RESULTS

RA regulates hindbrain size specification and neural-to-mesodermal alignment at the head-trunk transition

To investigate the processes aligning neural to mesodermal tissues at the head-trunk transition, we analyzed the axial position of hindbrain, spinal cord and mesodermal landmarks in zebrafish embryos lacking RA. RA is a suitable candidate to mediate tissue alignment, as changes in RA levels cause hindbrain defects and spinal cord mis-patterning (Begemann et al., 2001; Grandel et al., 2002; Emoto et al., 2005). In considering landmarks for analysis, we focused on two commonly used markers to analyze changes in hindbrain specification (Begemann et al., 2001; Grandel et al., 2002; Emoto et al., 2005; Maves and Kimmel, 2005): the rostral border of rhombomere 3 (r2/r3), as identified by expression of krx20 (Oxtoby and Jowett, 1993), and the somites identified by expression of myoD (Weinberg et al., 1996). With these landmarks we compared the location of the HB/SC transition, identified by the expression of the spinal cord marker cdx4 (Skromne et al., 2007). In wild-type embryos, cdx4 expression domain during early segmentation stages extends caudally from the somite 2/3 border (s2/s3) (Fig. 1A), which in zebrafish corresponds to occipital to vertebral somite transition (Morin-Kensicki et al., 2002). By contrast, embryos exposed at the onset of gastrulation to the RA-synthesis inhibitor DEAB, referred to hereafter as RA-deficient embryos, had both spinal cord and somites shifted rostrally closer to the r2/r3 boundary (Fig. 1B). Importantly, however, the spinal cord shifted rostrally to a greater extent than the paraxial mesoderm (Fig. 1B). This spinal cord expansion was accompanied by an equivalent hindbrain reduction, determined by the relative position of the most posterior rhombomere in these embryos, r4, to the r2/r3 landmark (Fig. 1C–F). Thus, in addition to its role in rhombomere specification (Begemann et al., 2001; Grandel et al., 2002; Linville et al., 2004; Emoto et al., 2005), RA is also involved in hindbrain size specification, and in the accurate alignment of the HB/SC transition to the craniovertebral junction.

Rostrocaudal specification of hindbrain/spinal cord transition and its alignment to the craniovertebral junction are temporally distinct processes

To begin understanding the relationship between the positioning and alignment functions of RA, we asked whether these two processes require RA at the same critical period. Differences in critical periods would suggest that regulation of tissue position and
RA is required early in gastrulation for neural and mesodermal tissue alignment. (A–C) Control embryos showing the expression domain of cdx4 (purple) relative to r2/r3 boundary (krx20, red) and somites (myoD, red) early (A), and the position of branchial motor neurons (BMN, Tg Isl1::GFP, magenta; B) and spinal motor neurons (SMN, Tg olig2:dsRed, yellow; C) relative to trunk musculature (cyan) late. (D–F) RA inhibition during gastrulation (50-100% epiboly) shifts cdx4 expression domain rostrally relative to r2/r3 and s2/s3 (D), severely reducing BMN size (E) and rostrally shifting the position of the first SMN (F). (G–I) RA inhibition during the first half of gastrulation (50-75% epiboly) shifts cdx4 expression domain rostrally relative to r2/r3 and s2/s3 (G), severely reducing BMN size (H) and rostrally shifting the position of the first SMN (I). (J–L) RA inhibition during the second half of gastrulation (75-100% epiboly) shifts cdx4 expression domain rostrally relative to r2/r3 while maintaining s2/s3 alignment (J), reducing BMN size (K) without affecting the first SMN position (L). Embryos in A, D, G and J are at 12-somite stage, dorsal view and anterior to the left, shown under bright-field and epifluorescent illumination to highlight somites. In these embryos, arrows indicate the distance from r2/r3 to cdx4 expression domain, and arrowheads indicate the somites (s) 2/3 border. The remaining embryos are at 50 h post fertilization (hpf), lateral view, anterior to the left. In these embryos arrowheads indicate BMN posterior extent; small arrows, first SMN axons; asterisks, rostrally shifted SMN; large arrow, an abnormally small first somite. Numbers correspond to somites. Scale bars: 50 µm.

We next investigated whether the changes in gene expression observed in RA-deficient embryos caused anatomical defects by analyzing the position of branchial and spinal motor neuron populations (BMN and SMN) relative to trunk musculature (Fig. 3) and bone structures (Fig. 4). In wild-type embryos, the last BMN population localizes as far posterior as the s2/s3 border, and the first SMN localizes at s2 (Fig. 3B,C). By contrast, loss of RA during the first half or throughout gastrulation shifts the position of both populations anteriorly by one somite (Fig. 3F,H,I), consistent with the rostral shifts in cdx4 expression observed earlier in development (Fig. 3D,G). Significantly, RA inhibition late in gastrulation does not change cdx4 expression domain or the position of motor neuron populations (Fig. 3J-L). Together, change in motor neuron position further supports the role of RA in neural and mesodermal tissue alignment.

We also analyzed the relationship between BMN and skeletal tissues by monitoring ossification events in live specimens over time, using calcein as indicator of calcium deposits (Du et al., 2001). Embryos expressing an RFP transgene in BMN (Tg(zCREST1(isl1)::membRFP; Mapp et al., 2010) were exposed to RA synthesis inhibitor during the first half of gastrulation, as this treatment results in neural and mesodermal tissue misalignment without causing severe hindbrain patterning defects (Fig. 3G-I). Then, from day 7 to day 14 post fertilization (dpf), we monitored changes in two bone-related parameters. First, we measured the distance along the axis from the vagal foramen in the neurocranium (identified in confocal images as the site where vagal axons cross the calcifying otic capsule; Fig. 4, white arrowheads), to the cleithrum in the pectoral girdle (Fig. 4, black arrowheads). At 10 and 12 dpf, this distance was not statistically different in wild-type (53.83±6.28 µm, n=4)
and RA-deficient embryos (53.14±6.96 µm, n=4), suggesting preservation of the skull-to-trunk skeletal organization. We also measured the angle at which the vagal nerve enters and then exits the vagal foramen (e.g. Fig. 4E,F), as changes in this angle would suggest a shift in the position of neural populations relative to skeletal structures. At 10 and 12 dpf, this angle in wild-type embryos was 86.59° ±7.33°, whereas in RA-deficient embryos it was 99.69° ±6.5° (n=6 per condition, t-test, P<0.0015), suggesting a relative displacement of neural and skeletal elements. These late morphological changes are consistent with the early gene expression changes, further supporting the role of RA in head-trunk tissue alignment.

The rostrocaudal position of the hindbrain/spinal cord transition regulates rhombomere size and number

The observation that RA specifies the axial position of the HB/SC transition (Figs 2 and 3) and rhombomere identities (Begemann et al., 2001; Grandel et al., 2002; Maves and Kimmel, 2005) over the same critical period raises the possibility that these two processes are developmentally related. There are three distinct ways in which these processes could be related. First, rhombomere specification determines the axial position of the HB/SC transition. Second, axial specification of the HB/SC transition determines the size of the hindbrain primordium and, consequently, the number and size of the rhombomeres. A final possibility is that RA regulates these processes independently but in a coordinated manner.

To test the possibility that rhombomere specification determines the axial position of the transition, we analyzed the expression domain of the spinal cord marker cdx4 in embryos lacking hnf1ba (vhnf1, tcf2), a direct, early RA target gene that is essential for r5-r7/8 development (Fig. 5A-D; Sun and Hopkins, 2001; Wiellette and Sive, 2003; Hernandez et al., 2004; Pouilhe et al., 2007). If the axial position of the HB/SC transition is dependent on the formation of posterior rhombomeres, then their loss in hnf1ba embryos should shift the HB/SC transition rostrally. This, however, was not the case; cdx4 was expressed in the same spatial pattern in wild-type and hnf1ba mutants (Fig. 5E,F). Thus, rhombomere specification does not regulate the positioning of the HB/SC transition along the embryonic axis.

We next tested the possibility that the axial position of the transition determines the size of the hindbrain primordium and, consequently, rhombomere number and size, by examining whether the loss of posterior rhombomeres in RA-deficient embryos could be rescued by caudally shifting the axial position of the HB/SC transition. To caudally shift the HB/SC transition we eliminated the activity of the spinal cord specification gene cdx4 (Skromne et al., 2007). Because in these embryos the expression of cdx4 cannot be used to locate the HB/SC transition, we used instead the position of the last BMN (vagus, nX) in r7/8 and the first SMN in s2. Compared with control siblings, Cdx4-deficient embryos had a hindbrain that appeared to be patterned normally (Fig. 6D), but which was larger in size due to a caudal expansion of r7/8 (nX; Fig. 6E,F). These embryos also had a caudally shifted spinal cord, as indicated by the localization of the first SMN to s3 (Fig. 6F). By contrast, loss of RA early in gastrulation caused an overall reduction in hindbrain size, a reduction in the size of the last BMN population and a rostral shift in the position of the first SMN to s1 (Fig. 6G-I). Remarkably, loss of Cdx4 in an RA-deficient embryo greatly expanded the hindbrain, rescuing posterior rhombomeres and BMN (Fig. 6J,K), suggesting that posterior rhombomeres can develop in the absence of RA when the hindbrain territory is enlarged. In addition, loss of Cdx4 in an RA-deficient embryo restored the position of the first SMN to s2, suggesting antagonistic effects of Cdx4 and RA in SMN positioning. Together, these results show that Cdx4 and RA regulate the axial position of the HB/SC transition, which constrains the size of the hindbrain primordium that can subsequently be specified into rhombomeres.
RA regulates hindbrain patterning directly and rostrocaudal position of the hindbrain/spinal cord transition indirectly

The function of RA in positioning and aligning the HB/SC transition relative to other tissues could be direct or indirect. Whereas RA is known to regulate rhombomere specification genes directly (e.g. vhnf1, hox; Serpente et al., 2005; Pouilhe et al., 2007), it can also regulate mesodermal gene expression, particularly secreted factors that can pattern the neuroectoderm, indirectly (e.g. FGF and Wnt; Muhr et al., 1997; Ensini et al., 1998; Muhr et al., 1999; Nordström et al., 2002; Nordström et al., 2006; Zhao and Duester, 2009). To distinguish between direct and indirect functions, we combined gene overexpression and cell transplantation approaches to inactivate RA signaling exclusively in presumptive hindbrain cells while leaving RA signaling in other tissues intact. Cells from donor embryos labeled with GFP and made unresponsive to RA by overexpressing the RA-metabolizing enzyme Cyp26c1 (supplementary material Fig. S1; Kudoh et al., 2002; Taimi et al., 2004) were transplanted into the prospective hindbrain of wild-type hosts and then analyzed for changes in gene expression. Because regulation of posterior rhombomere genes requires RA (Hernandez et al., 2004; Serpente et al., 2005; Pouilhe et al., 2007), RA-unresponsive cells should not express posterior rhombomere genes and instead express anterior rhombomere genes, similar to RA-deficient embryos (Fig. 1). Transplanted wild-type and RA-unresponsive cells populated the host neural tube to the same extent (Fig. 7D-F,K), indicating that neither transplantation nor mRNA injection procedures affected their development. However, whereas wild-type cells expressed genes appropriate to their location (Fig. 7A,D,G), RA-unresponsive cells located in posterior rhombomeres expressed genes of more anterior rhombomeres (Fig. 7C,F,I). These changes in expression were only seen in clusters of cells and not in isolated cells (95% of clones, 2% of isolated cells), presumably because only clustered cells can effectively degrade RA and prevent pathway activation. For example, transplanted wild-type cells only expressed the r5/r6 marker mafB when located in r5/r6 (Fig. 7A,D,G). By contrast, transplanted RA-unresponsive cells located in r5/r6 never expressed mafB (Fig. 7B,E,H) and instead expressed the r4 gene hoxb1a (Fig. 7C,F,I), a rostral transformation similar to the ones observed in RA-deficient embryos (Fig. 1; supplementary material Fig. S1). These results show that in the posterior hindbrain, RA regulates rhombomere identity directly.

The effect of RA in regulating hindbrain and spinal cord specification was then tested by analyzing the expression of the spinal cord marker cdx4 in RA-unresponsive cells. If RA directly regulates the axial position where the hindbrain ends and the spinal cord begins, then local RA pathway inactivation should transform the identity of neural cells in one territory to the identity of the other territory, thus altering cdx4 expression profile. Significantly, cdx4 expression did not change in RA-unresponsive cells irrespective of clone size or location; RA-unresponsive cells did not express cdx4 in the hindbrain and continued to express cdx4 in the spinal cord (100% clones in 20 embryos, Fig. 7J-L). These observations indicate that RA function in cdx4 regulation and in hindbrain and spinal cord specification is indirect.

RA is necessary but insufficient for the alignment of the hindbrain/spinal cord transition to the mesoderm

Thus far our results suggest that RA acting indirectly is necessary for hindbrain and spinal cord specification, and presumably for their alignment to the mesoderm. To test whether RA is sufficient for neural and mesodermal alignment, we increased RA levels by exposing embryos at 50% epiboly to either a pan-inhibitor of RA degradation enzyme Cyp26 or to RA and analyzed the expression of krx20 in r3/r5, hoxb4a in r7/8 and cdx4 in spinal cord. Consistent with previous reports, increasing RA transformed the hindbrain anterior identities to posterior fates (Fig. 8A,B; Hill et al., 1995;
Fig. 7. Retinoic acid regulates hindbrain patterning directly and axial position indirectly. Expression analysis of hindbrain and spinal cord markers (magenta) in wild-type (A,D,G) or RA-deficient (Cyp26c1-overexpressing; B,C,E,F,H,L), GFP-positive cells transplanted into wild-type host. (A,D,G) Wild-type clones express mouse when located in r5/r6 (arrow, n=5/6 clones, n=5 embryos). (B,E,H) RA-deficient clones do not express mouse when located in r5/r6 (arrow, n=3/3 clones, n=3 embryos). (C,F,I) RA-deficient clones express the r4 marker hoxb1a when located in r5/r6 (arrow, n=4/3 clones, n=4 embryos). (J,K,L) RA-deficient clones express cdx4 in the spinal cord (black arrow, n=35/35 clones, n=20 embryos) and not in the hindbrain (white arrow; n=32/32 clones, n=20 embryos). Embryos in J-L were counterstained with knx20 (black) to visualize rhombomere 5 (r5), and with DAPI to visualize somite (s) boundaries (not shown; white lines). Embryos are 12-somite stage, dorsal side up, anterior to the left. Scale bars: 50 µm.

Begemann et al., 2001; Linville et al., 2004; Hernandez et al., 2007) and, importantly, reduced the hindbrain territory size (Hernandez et al., 2007; data not shown). Significantly, however, excess RA did not change the axial position of the HB/SC transition relative to somites 2/3 (Fig. 8C,D). These results suggest that factors other than RA are required for the alignment of the HB/SC transition relative to the mesoderm and further support the idea that hindbrain territory size specification and alignment are separate processes.

RA interacts with FGF and Wnt pathways to regulate the rostrocaudal position of the hindbrain/spinal cord transition

To investigate the molecular mechanism by which RA indirectly regulates the HB/SC transition, we analyzed the epistatic relationship between the RA pathway and two other signaling pathways, FGF and Wnt, as they regulate neuroectoderm patterning in amniotes (Muhr et al., 1997, 1999; Ensini et al., 1998; Nordström et al., 2002; Nordström et al., 2006) and are regulated by RA (Zhao and Duester, 2009). We found that RA in zebrafish also regulates the expression of the FGF and Wnt pathway components etv4 (pea3), wnt3a and wnt11, but not fgf8 (Fig. 9), making them probable candidates to mediate the indirect activity of RA.

We first investigated the epistatic relationship between FGF and RA, uncovering that they interact in different ways in different processes. With respect to patterning, exposure of gastrula (shield stage) embryos to the FGF receptor inhibitor SU5402 (Mohammadi et al., 1997) caused a reduction in rhombomere size (Fig. 10C; Maves et al., 2002). This phenotype was also observed in FGF/RA-deficient embryos, the only difference being that these embryos also lacked posterior rhombomeres (Fig. 10A-D). Thus, with respect to hindbrain patterning, FGF and RA pathways have additive functions. With respect to the axial position of the HB/SC transition relative to neural landmarks, loss of FGF caused the HB/SC transition to shift caudally, a phenotype that is opposite to that seen in RA-deficient embryos (Fig. 10A-D). Significantly, simultaneous loss of FGF and RA restored the HB/SC transition to an axial position similar to that seen in wild-type embryos (Fig. 10A-D), suggesting that FGF and RA have antagonistic effects in positioning the HB/SC transition. With respect to mesodermal landmarks, however, loss of FGF in wild-type and RA-deficient embryos caused the s2/s3 junction to be situated anterior to the HB/SC transition. Thus, with respect to hindbrain patterning, FGF and RA interactions are different in each process: additive in hindbrain patterning, antagonistic in hindbrain size specification and epistatic in neural-mesodermal tissue alignment.

We next investigated the epistatic relationship between Wnt and RA, uncovering strong interactions between the two pathways. Loss of Wnt activity due to the activation of a dkk1-GFP transgene at gastrulation caused minor rhombomere expansion and caudal shift in the axial position of the HB/SC transition, but did not affect neural-to-mesoderm alignment (Fig. 10E). Strikingly, however, the simultaneous loss of Wnt and RA severely disrupted hindbrain organization and shifted cdx4 expression caudally (Fig. 10F), suggesting that Wnt and RA act together to regulate cdx4 and, consequently, the axial positioning of the HB/SC transition. With respect to alignment of tissues, somites in RA/Wnt-deficient
DISCUSSION

RA aligns the hindbrain/spinal cord transition to the craniovertebral junction

The alignment of neural and mesodermal tissues at the head-trunk transition requires their development to be coordinated. The present study provides evidence that RA is essential for the accurate alignment of the HB/SC transition to the craniovertebral junction (summarized in Table 1), and that this function is independent from the well-characterized function of RA in hindbrain patterning (Niederreither et al., 1997; Muhr et al., 1999; Begemann et al., 2001; Sakai et al., 2001; Grandel et al., 2002; Emoto et al., 2005; Sirbu et al., 2005; Nordström et al., 2006; Lloret-Vilaspasa et al., 2010). Specification of head and trunk territories in zebrafish is completed by mid to late gastrulation (Kim et al., 2002), shortly after prospective hindbrain cells become committed to their fate (Woo and Fraser, 1998) and prospective paraxial mesoderm cells ingress into the embryo, contributing to occipital and anterior vertebral somites (Muller et al., 1996). This is also the critical period during which RA aligns the HB/SC transition to occipital and vertebral somites (Figs 2 and 3). The culmination of this critical period at mid-gastrulation precedes the wave of hox gene transcriptional activation that takes place during the second half of gastrulation (Prince et al., 1998; Maves and Kimmel, 2005), thus distinguishing early global and late local neural-to-mesodermal aligning processes. Notably, the novel function of RA in tissue alignment is independent of previously described RA functions in tissue patterning (Muhr et al., 1999; Niederreither et al., 1999; Begemann et al., 2001; Sakai et al., 2001; Grandel et al., 2002; Kudoh et al., 2002; Emoto et al., 2005; Sirbu et al., 2005; Nordström et al., 2006; Lloret-Vilaspasa et al., 2010), as patterning and alignment utilize different genetic cascades (e.g. hnf1ba in patterning but not alignment; Fig. 5) and operate in different tissues (autonomous for patterning, non-autonomous for alignment; Fig. 7). In addition, excess RA has different effects on patterning and alignment processes. Whereas excess of RA causes hindbrain patterning defects (Grandel et al., 2002; Maves and Kimmel, 2005), it does not change the alignment of tissues (Fig. 8). We propose that one of the earliest functions of RA at the head-trunk junction is to align the HB/SC transition to occipital and vertebral somites in a Hox-independent manner, but that this function requires additional signals, as RA is necessary but insufficient for the alignment of neural and mesodermal tissues.

RA specifies the size of the hindbrain territory by negatively regulating Cdx4

A second novel function of RA is in hindbrain size specification, an activity that is distinct from its functions in tissue alignment and patterning. RA function in territory specification can be distinguished from its function in tissue alignment temporally, with RA being required during the first half of gastrulation for alignment and throughout gastrulation for territory specification (Fig. 2). RA functions in territory specification and patterning can also be distinguished genetically; hindbrain patterning requires Hnf1ba, whereas territory specification does not (Fig. 5). Furthermore, territory specification crucially depends on RA restricting the cdx4 expression domain, as loss of RA reduces the spinal cord territory in a Cdx4-dependent manner (Fig. 4). Based on this dependency, we propose that RA regulates the size of the hindbrain territory by establishing in the caudal neural plate an anterior cdx4-negative region that can then segment, and a posterior cdx4-positive region that will form the spinal cord.

Although the mechanism by which RA negatively regulates cdx4 is currently unknown, several lines of evidence support the notion of this activity as indirect. In mouse, comparative transcriptome analysis of wild-type and RA-deficient embryos failed to identify cdx4 as an RA target (Paschaki et al., 2013), whereas in zebrafish,
our transplants show that RA is not required in the nervous system for cdx4 transcription (Fig. 7). Probable candidates to mediate RA activity are Wnts, which in zebrafish and mouse are under RA regulation (Fig. 9; Zhao and Duester, 2009; Paschaki et al., 2013) and are direct positive regulators of cdx4 (Shimizu et al., 2005, 2006; Pilone et al., 2006; Lengerke et al., 2011; Ro and Dawid, 2011). RA regulation of Wnts has previously been reported in other developmental contexts, particularly in the mesoderm (reviewed by Motz and Pourquié, 2011). We propose that during normal development a double morphogenetic gradient is required to pattern the hindbrain as a result of Cdx specifying the spinal cord and constraining the hindbrain primordium. Thus, by preventing the specification of spinal cord identities from overtaking the hindbrain territory, aligning the hindbrain territory to mesodermal tissues and patterning the hindbrain, RA functions as a primary regulator of neural and mesodermal tissue organization at the head-trunk transition.

**RA and hindbrain patterning**

RA is required for hindbrain patterning (Muhr et al., 1999; Niederreither et al., 1999; Begemann et al., 2001; Sakai et al., 2001; Grandel et al., 2002; Kudoh et al., 2002; Emoto et al., 2005; Sirbu et al., 2005; Nordström et al., 2006; Lloret-Vilaspa et al., 2010); yet, as our experiments show, posterior rhombomeres can develop independently of RA when the hindbrain territory is expanded caudally due to loss of Cdx4 (Fig. 6). Given that specification of posterior rhombomeres requires RA-dependent activation of hnf1b and hox genes (Marshall et al., 1994; Gould et al., 1998; Packer et al., 1998; Studer et al., 1998; Zhang et al., 2000; Serpente et al., 2005; Pouilhe et al., 2007), how are posterior rhombomeres in RA/Cdx4-deficient embryos being specified? The time at which Cdx4 specifies the hindbrain and spinal cord territories during gastrulation (Figs 2 and 3) is also the time when the hindbrain is patterned by opposing but partially overlapping FGF and RA gradients (Maves et al., 2002; Sagerstrom, 2004; Hernandez et al., 2007; Pouilhe et al., 2007; Labalette et al., 2011). Both signals are morphogens (White et al., 2007; Nowak et al., 2011), and each one alone is sufficient for the induction of several rhombomere fates when exogenously applied (Roy and Sagerstrom, 2004). We propose that Cdx4 constraining the size of the hindbrain territory forces the use of two opposing morphogens for rhombomere patterning. When Cdx4 is lost, the hindbrain primordium becomes enlarged and the two-morphogen system is no longer necessary for hindbrain patterning. Under these circumstances, the field of hindbrain cells is large enough for a single morphogen, FGF in RA-deficient embryos, to convey to cells their positional information. Whereas further work is needed to demonstrate that a gradient of FGF alone is sufficient for patterning when the hindbrain territory is expanded, this is a viable possibility, given the small size of the hindbrain primordium during gastrulation (Prince et al., 1998; Maves et al., 2002) and the relatively large diffusion coefficient and morphogenetic activity of FGF (Nowak et al., 2011). We propose that during normal development a double morphogenetic gradient is required to pattern the hindbrain as a result of Cdx4 specifying the spinal cord and constraining the hindbrain primordium. Thus, by preventing the specification of spinal cord identities from overtaking the hindbrain territory, aligning the hindbrain territory to mesodermal tissues and patterning the hindbrain, RA functions as a primary regulator of neural and mesodermal tissue organization at the head-trunk transition.

**MATERIALS AND METHODS**

Zebrafish embryos of stock *AB* (wild type), *hhba*<sub>1b</sub> (Viala et al., 2007), *kkq<sup>206</sup>* (cdx4; Davidson et al., 2003), Tg(CREST<sub>1</sub>:tlid); membf<sub>FP</sub> (Mapp et al., 2010), Tg(isl1:GFp) (Kim et al., 2008) and Tg(hsp<sub>70</sub>:dkk1b-GFP) (Perls et al., 2000), Tg(olig2:DsRed) (Kim et al., 2008) and Tg(hsp<sub>70</sub>:dkk1b-GFP) (Stoick-Cooper et al., 2007) were obtained from natural crosses of adult fish raised and handled according to standard protocols and animal care guidelines (Westerfield, 1994). Embryos were grown at 28°C and staged as previously described (Kimmel et al., 1995). Pharmacological treatments were carried out in embryo media containing 0.1% DMSO (Mallinkrodt) in the dark. To block pigmentation, embryos older than 24 h were treated with 0.003% 1-phenyl-2-thiourea (Sigma-Aldrich) (Westerfield, 1994). Inactivation of FGF and Wnt signaling was performed at shield stage by exposing embryos to 2×10<sup>-4</sup> M SU5402 (EMD Millipore) (Mohammadi et al., 1997), or by inducing dkk1 from an hsp<sub>70</sub>:dkk1b-GFP transgene at 37°C for 1 h (Stoick-Cooper et al., 2007), respectively. To activate the RA pathway, embryos at 50% epiboly were exposed to 1×10<sup>-7</sup> M all-trans RA (Sigma-Aldrich) or to 1 μM of the Cyp26 inhibitor R115866 (Janssen

**Table 1. Summary functions of RA at the head-trunk transition**

<table>
<thead>
<tr>
<th>Process</th>
<th>Time of activity (Figs 2 and 3)</th>
<th>Mechanism of activity (Figs 7 and 8)</th>
<th>Activity requirement (Figs 5 and 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neural-mesodermal alignment</td>
<td>50-75% epiboly (beginning to mid gastrulation)</td>
<td>Indirect</td>
<td>Wnt (downstream or parallel), FGF (upstream)</td>
</tr>
<tr>
<td>Hindbrain territory size specification</td>
<td>50-100% epiboly (gastrulation)</td>
<td>Indirect</td>
<td>Wnt (downstream or parallel), FGF (antagonistic)</td>
</tr>
<tr>
<td>Hindbrain patterning</td>
<td>50-100% epiboly (gastrulation)</td>
<td>Direct</td>
<td>Hnf1b-dependent, FGF (additive)</td>
</tr>
</tbody>
</table>
Pharmaceuticals) (Hernandez et al., 2007). To inactivate the RA pathways, embryos were exposed to the RA synthesis inhibitor 4-(Dimethylamino)-benzaldehyde (DEAB; Sigma-Aldrich) at 1×10^{-5} M, or by overexpressing the RA-metabolizing enzyme Cyp26c1 (Kudoh et al., 2002; Taiini et al., 2004). For overexpression, embryos were injected at the one-cell stage with capped sense mRNA (SP6 mMessage mMACHINE Kit; Ambion) at 15 pg egfp and 375 pg cyg26c1, a concentration determined experimentally to induce RA-deficient phenotypes (supplementary material Fig. S1; and data not shown). Bone mineralization analysis was performed by submerging larvae in 0.2% calcium solution as described (Du et al., 2001). Embryos at the appropriate stage were fixed with 4% paraformaldehyde in 1× PBS pH 7.2 for 3-24 h at 4°C before processing. Specimens for in situ hybridization were transferred to 100% methanol and stored at −20°C.

Cell transplantation approaches were carried out as previously described (Ho and Kane, 1990). About 30 cells from a 30% epiboly stage donor embryo injected with either egfp or egfp/cyp26c1 mRNA were transplanted five cell diameters away from the blastula margin of a stage-matched, and 375 pg 488, mouse IgG2b-Alexa 568 and rabbit-Alexa 633 (Life Technologies; 1:500), followed by goat secondary antibodies against mouse IgG2a-Alexa Fluor 594, mouse embryo and placenta: possible role in patterning of the extra-embryonic membranes. Dev. Dyn. 204, 219-227.


**SUPPLEMENTARY FIGURE LEGEND**

**Figure S1.** Overexpression of the Retinoic Acid-degrading enzyme Cyp26c1 recapitulates defects associated with loss of Retinoic Acid synthesis. (A) Frequency distribution of morphological defects caused by RA loss due to exposure to the RA synthesis inhibitor DEAB at 50% epiboly (black bars), overexpression of RA-degrading enzyme Cyp26c1 (gray bars) and both (hatched bars). Embryos were scored at 32 hpf using a four-class scale of increase severity. Class 1 had blood pooling. Class 2 had hindbrain size reduction, tail defects, lack of fin buds and edema. Class 3 had severe tail bending. Class 4 had a severely reduced axis and small somites. For each condition, n=80 embryos from three independent trials. Cyp26c1 treatments were statistically significant from mock control (white bar), but not DEAB treatments by pairwise chi square analysis (mock versus cyp26c1 treatment, χ²=63, df=1, P=0; DEAB versus cyp26c1 treatment, χ²=1.01, df=1, P≤0.314). Embryos are mounted laterally, anterior to the left. Scale bar: 250 µm. (B-G) Expression analysis of *hoxb1a* (r4; B,E), *mafb* (r5/r6; C,F) and *cdx4*
(spinal cord; D,G) (purple) relative to r2/r3 (krx20, red) and somites 2/3 (myoD, red) boundaries, in Cyp26c1-overexpressing embryos that were not exposed (Cyp26c1; B-D) or exposed (Double; E-G) to the RA synthesis inhibitor DEAB. Similar changes were observed in DEAB-treated embryos (Fig. 1). Embryos at 12-somite stage are shown in dorsal view, anterior to the left. Arrows, distance from r2/r3 to the expression domain of the indicated gene; arrowheads, s2/s3 border. Scale bars: 50 µm.