Zebrafish and fly Nkx6 proteins have similar CNS expression patterns and regulate motoneuron formation

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Accepted 12 August 2004

Summary

Genes belonging to the Nkx, Gsh and Msx families are expressed in similar dorsoventral spatial domains of the insect and vertebrate central nervous system (CNS), suggesting the bilaterian ancestor used this genetic program during CNS development. We have investigated the significance of these similar expression patterns by testing whether Nkx6 proteins expressed in ventral CNS of zebrafish and flies have similar functions. In zebrafish, Nkx6.1 is expressed in early-born primary and later-born secondary motoneurons. In the absence of Nkx6.1, there are fewer secondary motoneurons and supernumerary motoneuron and suppresses interneuron formation. Overexpression of fish or fly Nkx6 is sufficient to generate supernumerary motoneurons in both zebrafish and flies. These results suggest that one ancestral function of Nkx6 proteins was to promote motoneuron development.

Key words: nkh6.1, Danio rerio, Drosophila melanogaster, Hedgehog, Primary motoneurons, Secondary motoneurons, Interneurons, Eve, HB9, Islet

Introduction

The growing number of genes expressed in similar patterns during axis formation and early central nervous system (CNS) patterning in arthropods and vertebrates has revived an old hypothesis (St.-Hilaire, 1822) postulating conservation of dorsoventral patterning in these phyla (reviewed by Sasai and De Robertis, 1997) (Arendt and Nubler-Jung, 1999; Cornell and Von Ohlen, 2000). Arthropods and vertebrates have been evolving away from a common ancestor for over 800 million years (Hedges, 2002) and their CNSs arise on opposite sides of the body, dorsal in vertebrates and ventral in arthropods (Fig. 1). Thus, it is not surprising that their CNSs are architecturally distinct, suggesting they are patterned by different mechanisms (Romer and Parsons, 1977). What is surprising is that despite these differences, corresponding spatial domains within the arthropod and vertebrate CNS express homologous genes (reviewed by Cornell and Von Ohlen, 2000).

The cell types that arise from corresponding CNS domains differ between vertebrates and flies. For example, in vertebrates all motoneurons arise from ventral CNS, whereas in flies motoneurons are generated from neuroblasts (NBs) at all dorsoventral levels (Bossing et al., 1996; Schmidt et al., 1999). Despite these differences, the arthropod and vertebrate neur ectoderm exhibit similar patterns of gene expression. For example, fly neur ectoderm expresses three transcription factor genes, vnd, ind and msh, in precise, longitudinal, ventral-to-dorsal domains (Isshiki et al., 1997; McDonald et al., 1998; Weiss et al., 1998). Mouse orthologs belonging respectively to the Nkx, Gsh, and Msx gene families are similarly expressed in a ventral-to-dorsal orientation in longitudinal spinal cord domains, raising the possibility that these genes are a phylogenetically ancient mechanism to direct dorsoventral CNS patterning (reviewed by Cornell and Von Ohlen, 2000) (Arendt and Nubler-Jung, 1999).

Although these genes are expressed in strikingly similar spatial patterns in flies and mice, not all of them are expressed at corresponding developmental stages. All three fly genes are expressed early during CNS development (Chu et al., 1998; Isshiki et al., 1997; McDonald et al., 1998; Weiss et al., 1998), whereas only Msx genes are expressed at a corresponding stage in the mouse (Satokata and Maas, 1994; Wang et al., 1996). Thus, the hypothesis that similar mechanisms underlie dorsoventral patterning of arthropod and vertebrate neur ectoderm predicts that vertebrates should have as yet uncharacterized, early-expressed paralogs of the fly genes.

Nkx genes are expressed in ventral spinal cord in mouse, chick and zebrafish. Nkx2.2, an ortholog of fly vnd, is required to establish a ventral interneuron precursor domain in the mouse (Briscoe et al., 1999). However, zebrafish nkh2.2 is expressed relatively late in ventral spinal cord (Barth and Wilson, 1995), precluding involvement in early neural patterning. Nkx6.1, a family member that might fulfill an earlier patterning role has been described in the mouse and chick (Qiu et al., 1998). This gene is expressed early in medial neural plate and later in ventral spinal cord. Nkx6.1 is sufficient for motoneuron formation in the chick and required for formation...
of a subset of motoneurons and interneurons in the mouse (Briscoe et al., 2000; Sander et al., 2000). However, a dramatic reduction in spinal motoneurons is only seen in mice lacking Nkx6.1 and a related gene, Nkx6.2, suggesting their functions overlap (Vallstedt et al., 2001). Flies also have an Nkx6 gene that is expressed early in a subset of ventral neuroblasts and later in CNS neurons (Uhler et al., 2002). Thus, Nkx6 genes in flies and vertebrates represent another pair of orthologs expressed in similar CNS domains.

To determine whether Nkx6 genes play similar roles in specifying ventral CNS identity in vertebrates and arthropods, we investigated Nkx6 function in zebrafish and flies. We cloned and characterized a zebrafish nkd6.1 gene that is expressed initially in ventral CNS and later in motoneurons and some interneurons. Like other anamniote vertebrates, zebrafish have two distinct types of spinal motoneurons. Primary motoneurons (PMNs) are individually identifiable, born early, and have axons that pioneer motor nerves (Eisen et al., 1986). Secondary motoneurons (SMNs) are more numerous, born later (Myers, 1985), and have axons that follow primary motor axons (Pike et al., 1992). The ventral spinal cord domain that generates PMNs and SMNs also generates oligodendrocytes and at least three types of interneurons; Komer-Agduhr (KA), Ventral Longitudinal Descending (VeLD) and Circumferential Descending (CiD), each of which can be identified by some position and axonal trajectory (Appel et al., 2001; Bernhart et al., 1992; Park et al., 2002) (H. C. Park and B. Appel, personal communication).

Here we show that ectopic expression of Nkx6 genes in zebrafish or flies results in embryos with supernumerary motoneurons, suggesting that at least one function of Nkx6 genes has been preserved over the last 800 million years. Surprisingly, knocking down Nkx6.1 protein in zebrafish reduces the number of SMNs, but not PMNs, raising the possibility of additional nkd6 genes. Nkx6.1 knockdown also increases the number of VeLD interneurons, suggesting that Nkx6.1 protein regulates a decision between motoneuron and interneuron fate, consistent with our finding that there are fewer VeLDs and supernumerary motoneurons in embryos ectopically expressing Nkx6.1. Fly embryos ectopically expressing either fish or fly Nkx6 show a similar phenotype.

The apparent conservation of Nkx6 expression and function in flies and fish suggested these genes might be similarly regulated. As in other vertebrates, Hedgehog (Hh) signaling is necessary for expression of zebrafish nkd6.1. However, expression of fly Nkx6 is unaffected by lack of Hh. These data suggest that although the signals establishing Nkx6 expression have diverged, Nkx6 proteins function as an ancient patterning mechanism to establish motoneurons within the CNS.

Materials and methods

Embryos

Zebrafish (Danio rerio) embryos were collected from natural crosses of adults, reared at 28.5°C, and staged according to hours postfertilization (hpf) and gross morphology (Kimmel et al., 1995). Wild-type embryos are genotype AB, the syaD allele is a deletion of the shh locus (Schauerte et al., 1998); slow muscle omitted (smo) encodes Smoothened, a component of the Hh signaling pathway (Chen et al., 2001; Varga et al., 2001) GATA-2::GFP fish are described by Meng et al. (Meng et al., 1997).

Drosophila melanogaster embryos were gathered from staged collections. Adults of the following genotypes were induced to lay embryos on a grape agar pad coated with yeast paste; yw, sca>Nkd6 (fly gene), sca>nkd6.1 (zebrafish gene), egsp>Nkd6 (fly gene), w[1118];hh ts2 eTM3 fs lacZ, hh w[1118] eTM3 fs lacZ.

Zebrafish nkd6.1 cDNA isolation

The following degenerate primers amplified an approximately 730 base fragment from 10 hpf cDNA (Ambion RETROScript Kit), forward 5’-TGCACCTCCAGGCGGCGARATAC-3’, reverse 5’-CGCCGGTCTGGAACCACNYT-3’. We designed specific primers and screened a gastrula stage cDNA library (Faucourt et al., 2001) to isolate a full-length clone; forward 5’-GCCTACCCTTAACGTCACT-3’, reverse 5’-GACTTGTGGCCTGCTGCTCCT-3’. Zebrafish nk6.1 GenBank Accession number is AY437556.

The Fly EST database (http://flybase.bio.indiana.edu) contains four identical clones with high similarity to the zebrafish nkd6.1 homeodomain and NK domain, indicating the fly genome probably contains a single Nk6 gene, designated conceptual gene CG13475, also known as Nk6 (Uhler et al., 2002).

Zebrafish nkd6.1 and fly Nk6 (ResGen EST clone RE66661) ORFs trimmed of UTRs were inserted into the pCS2+ MT expression vector (Rupp et al., 1994) for use in overexpression experiments.

Phylogenetic analysis

MacVector software, utilizing the Clustal W algorithm, created a maximum likelihood tree. Sequences included in the tree were gathered from GenBank.
In situ hybridization
Zebrafish RNA in situ hybridization was performed as described by Appel and Eisen (Appel and Eisen, 1998). RNA probes include islet1 and islet2 (Appel et al., 1995). RNA in situ hybridization on fly embryos was performed as described by Tautz and Pfeifle (Tautz and Pfeifle, 1989).

Immunochemistry
Zebrafish
The following antibodies were used: monoclonal mouse anti-Islet (Korzh et al., 1993) recognizes the Islet1 and Islet2 proteins (1:200; 39.4D5 Developmental Studies Hybridoma Bank), polyclonal rabbit anti-Nkx6.1 (1:1200; gift of O. Madsen), anti-Neurokinin (1:4000) (Trevarrow et al., 1990) (also known as zn5 and DMGRASP: www.zfin.org), polyclonal anti-GABA (1:1000, Sigma), zn1 monoclonal (1:200) (Trevarrow et al., 1990) and zn1 monoclonal (1:1000) (Trevarrow et al., 1990). Embryos were processed as described by Appel et al. (Appel et al., 2001).

RNAi on fly embryos
Two non-overlapping ~500 base fragments of the Nkx6 coding region, excluding the homeodomain, were amplified by PCR for use as templates. RNA was injected as described by Sullivan et al. (Sullivan et al., 1999).

Results
Zebrafish and flies have Nkx6 genes
We used degenerate polymerase chain reaction (PCR) based on sequence homologies between human, mouse, rat and chicken Nkx6.1 proteins to identify a zebrafish nkx6.1 gene fragment. Screening a gastrula stage cDNA library (Faucourt et al., 2001) isolated a longer clone with a complete open reading frame predicting a 312 amino acid protein containing an NK decapetide, characteristic of the Nkx family and a homeodomain (Fig. 2A). The predicted zebrafish protein is closely related to other vertebrate Nkx6.1 proteins (Fig. 2B). Accordingly, we have named this zebrafish gene nkx6.1.

A BLAST search of the fly genome identified a conceptual gene, CG13475, for which there were four identical EST clones that match an Nkx6 cDNA recently cloned from an embryonic fly cDNA library (Uhler et al., 2002). We confirmed flies possess a single Nkx6 gene orthologous to vertebrate Nkx6.1 and Nkx6.2 genes (Fig. 2B). Comparing zebrafish and fly proteins, there is 93% amino acid sequence identity within the homeodomain and 80% identity within the NK decapetide. Outside these two conserved motifs there are several other regions of high amino acid identity (Fig. 2A).

Zebrafish nkx6.1 is expressed in ventral spinal cord
To test our prediction that zebrafish nkx6.1 would be expressed in ventral CNS, we performed RNA in situ hybridization. Transcripts were first detected at the onset of gastrulation in the embryonic shield epiblast (Fig. 3A). Near the end of gastrulation, nkx6.1 was expressed in medial neuroectoderm in two wide, diffuse stripes (Fig. 3B). By the 3-4 somite stage, nkx6.1 was confined to a tight stripe in medial neural keel, extending from the midbrain through the posterior neural plate. This pattern was maintained throughout somitogenesis (Fig. 3D); Nkx6.1 expression persisted in ventral spinal cord until at least 48 hpf (data not shown). Nkx6.1 was detected in ventral hindbrain caudal to the midbrain-hindbrain boundary and in pancreas at later stages (Fig. 3C). To test for control at the level of translation, we labeled zebrafish embryos with a polyclonal anti-Nkx6.1 antibody designed against the highly conserved C-terminus of rat Nkx6.1 (Jensen et al., 1996). Although we cannot rule out the possibility that Nkx6.1 antibody crossreacts with additional Nkx6 proteins, at all stages examined protein
and RNA patterns appeared indistinguishable (data not shown). Cross-sections of 24 hpf embryos revealed Nkx6.1 expression in about five longitudinal cell rows in ventral spinal cord, including both medial and lateral floorplate (Fig. 4C); thus Nkx6.1-positive cells constitute approximately the ventral third of the spinal cord. This domain is similar to the olig2 expression domain; olig2 RNA is expressed in both progenitor and postmitotic cells (Park et al., 2002), thus, Nkx6.1 must also be expressed in both of these cell types. The neuroectodermal stripe of nkx6.1 includes the domain in which motoneuron progenitors undergo their final division (Kimmel et al., 1994; Myers et al., 1986). To determine whether postmitotic motoneurons express Nkx6.1, we performed antibody double-label experiments. Islet (Appel et al., 1995; Korzh et al., 1993) and Nkx6.1 proteins are colocalized in PMNs during early somitogenesis (14 hpf, Fig. 4A); later Nkx6.1 protein is downregulated. By 18 hpf, Nkx6.1 and Islet proteins are largely mutually exclusive and Nkx6.1 is expressed only in a few PMNs (Fig. 4B). Cross-sections at 48 hpf revealed Nkx6.1-positive SMN nuclei surrounded by Neurolin-positive plasma membranes (Fashena and Westerfield, 1999), indicating co-expression in these cells (Fig. 4D and data not shown). Thus both PMNs and SMNs express Nkx6.1 at least transiently.

Recent fate-mapping revealed that in addition to motoneurons, several types of interneurons are derived from the olig2-positive ventral spinal cord domain (H. C. Park and B. Appel, personal communication). We tested whether one of these types of interneurons expressed Nkx6.1, by labeling individual VeLD interneurons with fluorescent dextran, immediately fixing the embryos and examining whether the labeled cells co-expressed Nkx6.1. At 20 hpf most VeLDs were Nkx6.1-positive (Fig. 4E), however by ~24 hpf VeLDs had downregulated Nkx6.1 expression (Fig. 4F). Thus, we infer that VeLDs express Nkx6.1 early in development but downregulate it following axon extension.

**Fly Nkx6 is expressed in ventral neuroblasts and motoneurons**

Nkx6 expression was first detected during early neurogenesis (stage 9) in the nerve cord midline, and it was weakly expressed in ventral column neuroectoderm of rostral segments (Fig. 5A). An hour later (early stage 10), Nkx6 midline and neuroectoderm expression was downregulated. Nkx6 expression was restricted to six ventral column neuroblasts, rostrally located in each hemisegment (Fig. 5B). Consistent with Uhler and colleagues (Uhler et al., 2002) we detected Nkx6 expression in neuroblasts 2-2, 3-1, 3-2 and 4-2 (Fig. 5D). We also found Nkx6 expression in neuroblasts 1-1 and 1-2 (Fig. 5E,F). By early stage 11, Nkx6 was downregulated in neuroblasts and expressed in ganglion mother cells (GMCs) and postmitotic neurons. From stage 14 to the end of gastrulation, Nkx6 was expressed in a segmentally reiterated pattern of CNS neurons (Fig. 5G). At stage 14, many of these Nkx6-positive cells also expressed the postmitotic motoneuron marker, pMAD (Marques et al., 2002) (Fig. 5H) suggesting that many, perhaps all, motoneurons are initially Nkx6-positive. However, at later stages Eve-positive motoneurons no longer expressed Nkx6 (Fig. 5G), consistent with the observation

**Fig. 2.** Homology between Nkx6 proteins. (A) Alignment of fly and zebrafish Nkx6 translated amino acid sequence reveals several regions of high identity: the almost invariant NK domain (dashed line) and homeodomain (solid line), and two other regions indicated by asterisks. Fly Nkx6 was trimmed of the N-terminus.

(B) Maximum likelihood tree. Fly Nkx6 is orthologous to vertebrate Nkx6 proteins, distinct from Vnd/Nkx2.2 proteins. Numbers at the nodes represent bootstrap values. Dm, Drosophila melanogaster; Dr, Danio rerio.

**Fig. 3.** nkx6.1 is expressed in zebrafish ventral spinal cord. (A) Expression is initiated in the embryonic shield at 50% epiboly, approximately 5 hpf (animal pole view, optical section of embryo without yolk). Asterisk denotes epiblast (outer) layer. (B) By bud stage, ~10 hpf, nkx6.1 is broadly expressed in medial neuroectoderm (dorsal view, rostral to left). (C) At 26 hpf, nkx6.1 is strongly expressed in ventral CNS from the midbrain through the tail (lateral view; rostral to left). Arrowhead denotes pancreas expression. (D) Higher magnification view of spinal cord shown in (C). Scale bar: 50 μm for A,B,D; 25 μm for C. sc, spinal cord; n, notochord; y, yolk.
that the CNS contained Nkx6-negative, pMAD-positive motoneurons (Fig. 5I). These results reveal that some Nkx6-positive motoneurons are derived from Nkx6-positive neuroblasts, and raise the possibility that other Nkx6-positive motoneurons are derived from Nkx6-negative neuroblasts. Therefore, it is likely that Nkx6 expression is differentially regulated in neuroblasts and motoneurons. These results also suggest that Eve-positive fly motoneurons are similar to fish PMNs in that they both downregulate Nkx6 expression during development.

Hh induces nkd6.1 expression in zebrafish but not in flies

Studies in chick and mouse suggest Hh induces expression of Nkx6.1 in ventral neural tube (Briscoe et al., 2000), thus, we investigated whether Hh establishes or maintains nkd6.1 expression in zebrafish. Injection of synthetic shh mRNA caused a dramatic dorsal expansion of nkd6.1 expression. At 3-5 somites and 18 hpf, injected animals had many ectopic

nkd6.1-positive cells within the neural tube (Fig. 6B and data not shown) compared to wild types (Fig. 6A). Thus, Hh is sufficient to induce nkd6.1 expression in zebrafish CNS. However, nkd6.1 expression never expanded into the dorsalmost region of the neural tube.

Fig. 4. Nkx6.1 is expressed in zebrafish motoneurons. Nkx6.1 (green) Islet1/2 (red) antibody double labels. (A) 14 hpf lateral view reveals Rohon-Beard neurons (RBs) in dorsal spinal cord express only Islet proteins and PMNs in ventral spinal cord are double labeled (yellow). (B) By 18 hpf Nkx6.1 is largely absent from PMNs; most RBs are out of focal plane. (C) Cross-section of 24 hpf embryo showing Nkx6.1-positive nuclei, which comprise about five cell rows in the ventral spinal cord including medial (†) and lateral (‡) floorplate. (D) Cross-section of 48 hpf embryo double labeled with Nkx6.1 (green) and Neurolin (red) antibodies. Nkx6.1-positive nuclei are surrounded by Neurolin-labeled cell surfaces. Laterally-located slow muscle cells are also Neurolin-positive. (E) 20 hpf lateral view of individually labeled VeLD interneuron (yellow) expressing Nkx6.1 (green). Most individually labeled VeLDs in 20-22 hpf embryos expressed Nkx6.1 (n=11, 82%). (F) By 24 hpf VeLDs have downregulated Nkx6.1 (n=13, 85%). Scale bar: 50 μm for A,B,D,E,F; 75 μm for C.

Fig. 5. Nkx6 is expressed in fly ventral CNS and motoneurons. (A) Ventral view of stage 9 embryo showing Nkx6 RNA in cephalic neuromere and CNS midline. (B) At stage 10, Nkx6 is ventrally restricted to rostral neuroblasts in each hemisegment. (C) By the end of gastrulation Nkx6 is expressed in neurons throughout the CNS. (D-F) Nkx6 is expressed in neuroblasts 1-1, 1-2, 2-2, 3-1, 3-2 and 4-2. Neuroblasts expressing Nkx6 mRNA (blue) were identified by their position relative to Eagle-positive neuroblasts (brown; NB2-4, arrowhead; NB3-3, arrow; NB6-4, asterisk; NB7-3, white arrowhead) and other neuroblasts. The same two segments of a stage 11 embryo are shown at different focal planes (D, superficial; E, middle; F, deep). White line, ventral midline. (G) At stage 14, Nkx6 (RNA in situ, purple) is confined to a population of neurons distinct from those expressing the dorsal motoneuron determinant Eve (antibody, brown). The prominent brown cells near the midline are RP2 motoneurons (†). (H) pMAD (antibody, brown) and Nkx6 (RNA in situ, purple) expression are coincident in many cells at stage 14. (I) By stage 16, cells positioned laterally are positive for pMAD and Nkx6 (bracket), but more medial cells are clearly only pMAD-positive. Rostral is up in all images. Scale bar: 50 μm for A-C; 16 μm for D-I.
Fig. 6. Hh signaling induces zebrafish nkx6.1 expression. (A) 18 hpf wild-type expression of nkx6.1. (B) Dramatic dorsal expansion of nkx6.1 in an 18 hpf embryo ectopically expressing shh (shh OE, 87% of injected animals, n=283). (C) 12 hpf wild-type expression of nkx6.1. (D) 12 hpf syu mutant with reduced nkx6.1 expression. (E) 12 hpf syu mutant injected with ehh and twhh MOs. nkx6.1 expression is largely absent (28% of injected clutch from syu heterozygous parents, n=120). (F) Wild-type expression of nkx6.1 in spinal cord at 24 hpf. (G) 24 hpf syu mutant has wild-type levels of nkx6.1 expression in spinal cord. (H) Few nkx6.1-positive cells remain in a 24 hpf smu mutant spinal cord. (I) 24 hpf syu mutant injected with ehh and twhh MOs has no nkx6.1 expression in spinal cord (21% of injected clutch from syu heterozygous parents, n=128). C-D dorsal views; all others are lateral. Rostral to left in all images. Scale bar: 50 μm for A,B; 100 μm for C-E; 25 μm for F-I.

We next tested whether Hh is necessary for nkx6.1 expression. At 24 hpf, Nkx6.1 expression appeared fairly normal in syu (shh) mutants (Fig. 6G), but was greatly reduced in smu (slow muscle omitted) which encodes zebrafish Smoothened mutants (Fig. 6H) as compared to wild types (Fig. 6F). smu mutants are more severe than syu mutants, however they still retain some early Hh signaling (Chen et al., 2001; Varga et al., 2001). To further suppress Hh signaling we injected echidna hedgehog (ehh) (Ekker et al., 1995) and riggy winkle hedgehog (twhh) (Currie and Ingham, 1996) morpholino antisense oligonucleotides (MOs) into syu mutants. At 24 hpf nearly 25% of injected embryos displayed severely reduced nkx6.1 neural tube expression (Fig. 6I). This probably represents the syu mutant class with the greatest loss of Hh signals. About 75% of injected embryos had weaker spinal cord nkx6.1 expression than wild types, and thus probably constituted knockdown of ehh and twhh in a wild-

Nkx6.1 is sufficient to generate supernumerary motoneurons and suppress interneurons in zebrafish

Because in zebrafish nkx6.1 is expressed in motoneurons and their progenitors, we tested whether nkx6.1 was sufficient to generate these cells. All zebrafish PMNs initially express islet1 (is1l); later two specific PMNs, CaP and VaP downregulate is1l and initiate expression of a related gene, islet2 (is2l) whereas two other PMNs, MiP and RoP continue to express is1l (Appel et al., 1998; Tokumoto et al., 1995). We injected synthetic nkx6.1 mRNA and assayed for the presence of is1l-positive or is2l-positive PMNs by RNA in situ hybridization at 18 hpf. The is1l probe revealed supernumerary MiPs and RoPs (data not shown) and the is2l probe revealed supernumerary CaPs and VaPs (Fig. 7A,B), which we confirmed by labeling individual CaPs and VaPs in nkx6.1-injected embryos with fluorescent dextrans (data not shown). We also observed large clusters of zn1-positive motoneurons projecting axons to the periphery (Fig. 7D) as compared to wild types (Fig. 7C). Many of these supernumerary PMNs were located more dorsally than native PMNs (Fig. 7A-D), suggesting that Nkx6.1 converted some dorsal cells to a ventral fate. Injection of a GATA-2:GFP transgenic line that expresses GFP predominantly in SMNs (Meng et al., 1997) (Fig. 7E) with synthetic nkx6.1 mRNA revealed supernumerary SMNs at 24 hpf (Fig. 7F). Because Nkx6.1 is expressed in V eLD interneurons (Fig. 4E,F), we also tested whether overexpression of Nkx6.1 affected this cell type.
Nkx6 promotes fly and fish motoneurons

VeLDs are recognized by cell body position and GABA expression (Bernhardt et al., 1992). Embryos ectopically expressing nkx6.1 RNA have fewer GABA-positive VeLDs than wild types at 24 hpf (Fig. 7G,H), suggesting cells that would normally become VeLDs become motoneurons instead.

Hh can induce nkx6.1, and nkx6.1 is sufficient for formation of supernumerary PMNs and SMNs, suggesting that nkx6.1 acts downstream of Hh. We tested this by injecting synthetic nkx6.1 mRNA into clutches of embryos derived from smu heterozygotes; smu mutants have fewer PMNs and no SMNs because of reduced Hh signaling (Chen et al., 2001; Lewis and Eisen, 2001). At 18 hpf, approximately 25% of injected embryos lacked isl2 expression in caudal spinal cord, just like 25% of embryos from a smu heterozygote cross (data not shown), indicating that nkx6.1 was insufficient to restore PMNs in the absence of Hh. Similarly at 30 hpf, nkx6.1 was insufficient to restore SMNs in smu mutants (data not shown). We conclude that nkx6.1 alone is only sufficient to induce motoneurons in the presence of Hh, suggesting that Nkx6.1 collaborates with additional factors downstream of Hh during motoneuron induction.

Nkx6.1 is required for formation of zebrafish secondary motoneurons

To test whether Nkx6.1 is required for motoneuron formation, we injected embryos with an nkx6.1-specific MO (Fig. 8A,B and data not shown). Surprisingly, nkx6.1 MO-injected animals had normal numbers of PMNs, revealed by isl1 expression at 12 hpf and isl2 expression at 18 hpf (Fig. 8C,D and data not shown). MO-injected embryos initiated the spontaneous tail reflex around 18 hpf, thus PMNs were functional (Saint-Amant and Drapeau, 1998). However, in contrast to embryos injected with a mispaired control nkx6.1 MO which appeared wild type at 36 and 48 hpf, nkx6.1 MO-injected embryos did not swim when touched, suggesting an absence of SMNs. Consistent with this, at 48 hpf, nkx6.1 MO-injected animals consistently had fewer SMNs (Fig. 8F). At this stage there are more than...
30 SMNs per spinal hemisegment; these cells are difficult to count because their somata are closely packed (Fig. 8E). Thus, we divided MO-injected embryos into two categories: those with nearly wild-type numbers of SMNs, and those with less than half of the wild-type number. Most MO-injected embryos had less than half of the wild-type number of SMNs (Fig. 8F); in a few cases SMNs were entirely absent. To test whether SMNs were dying in MO-injected embryos, we performed TUNEL assays at several stages between 18 and 48 hpf. There was no discernible difference in the number of TUNEL-positive nuclei in the ventral spinal cords of MO-injected and wild-type embryos at any stage (data not shown). We also tested whether decreased proliferation accounted for the decrease in SMNs in MO-injected embryos. BrdU incorporation showed no difference between MO-injected and wild-type embryos at 24, 30 and 36 hpf (data not shown).

We conclude that lack of SMNs is not due to a change in birth or death of these cells, suggesting that in the absence of Nkx6.1, they undergo a fate change. There are many more wild-type embryos at 24, 30 and 36 hpf (data not shown).

Fig. 9. Nkx6 function is conserved between fish and flies. (A) isl2-positive CaPs and VaPs in an18 hpf zebrafish embryo. isl2-positive RBs are out of focus. Wild-type embryos have 1.3±0.7 isl2-positive motoneurons per spinal hemisegment (n=5). (B) 18 hpf embryo ectopically expressing Nkx6 (fly gene, Nkx6 OE) RNA with supernumerary isl2-positive cells (2.3±0.3 isl2-positive cells per hemisegment), similar to the phenotype caused by ectopic expression of zebrafish nks6.1 RNA (compare with Fig. 7B). The number of isl2-positive motoneurons is significantly different (P<0.0003). (C) PMNs in 24 hpf wild-type embryo labeled with zn1 and znpl1; RBs and several axon tracts are also visible. (D) 24 hpf embryo ectopically expressing Nkx6 (fly gene) RNA generates ectopic PMNs (compare with Fig. 7D). (E) Stage 17 wild-type fly embryo stained with Fas II. Arrowheads indicate SNb nerves. (F) sga>Nkx6.1 (fly gene) fly embryos with visibly thicker SNb nerves (88%, n=42 hemisegments). (A-D) Lateral views of zebrafish spinal cord. (E,F) Dissected fly embryo musculature. Scale bar: 50 μm for A,B; 33 μm for C-F.

Zebrafish and fly Nkx6 gene function is conserved in CNS patterning

We addressed whether Nkx6 genes have conserved functions by overexpressing the fly gene in zebrafish and the zebrafish gene in flies. We first asked whether ectopic expression of fly or zebrafish Nkx6 produces the same phenotype in zebrafish embryos. 18 hpf zebrafish embryos overexpressing fly Nkx6 mRNA had supernumerary PMNs (Fig. 9B,D) as compared to wild types (Fig. 9A,C), similar to the phenotype of embryos overexpressing zebrafish nks6.1 (Fig. 7); both fish and fly Nkx6 appear equally potent at generating ectopic PMNs in zebrafish.

Next we tested whether zebrafish or fly Nkx6 is sufficient to generate ectopic motoneurons in fly embryos. We created fly lines carrying UAS-nks6.1 (zebrafish) or UAS-Nkx6 (fly) transgenes and used sga-Gal4 to drive Nkx6 expression in neurectoderm and all neuroblasts. Endogenous Nkx6 is extinguished from neuroblasts by stage 12 (Fig. 5B); in contrast, in embryos expressing sga-Gal4 and either the fly or the zebrafish transgene, Nkx6 expression is maintained at least through stage 13 (data not shown). We assayed for supernumerary motoneurons by molecular markers and motor projections. The segmental nerve B (SNb) motor nerve to ventral muscles was substantially thicker than in wild-type embryos (Fig. 9E,F), consistent with production of supernumerary motoneurons.

We next assayed embryos misexpressing fly or zebrafish Nkx6 genes for changes in several motoneuron markers: Eve, which labels all dorsally projecting motoneurons, Islet and HB9, which label ventrally projecting motoneurons, and pMAD, a pan-motoneuron marker (Broihier et al., 2002; Landgraf et al., 1999; Marques et al., 2002; Odden et al., 2002). Misexpression of either the fly or zebrafish gene resulted in supernumerary motoneurons and loss of interneurons in the fly CNS. Most supernumerary motoneurons were in the lateral cluster of HB9-positive, Islet-positive motoneurons (Fig. 10H,J). There was also occasional duplication of the Eve-positive RP2 motoneuron (Fig. 10A,B). We conclude that Nkx6 is sufficient for formation of both ventrally projecting and dorsally projecting motoneurons. However, the phenotype of these embryos is complex. Some motoneurons appeared unaffected, for example the HB9-positive, Islet-positive RP1,3,4,5 motoneurons (Fig. 10E-G) and one type was slightly decreased, the Eve-positive U motoneurons (Fig. 10C,D). We also saw consistent loss of identified interneurons, including the Eve-positive ELs and Islet-positive EWs (Fig. 10C-F). Interestingly, in transgenic animals, cells in the EW position often expressed pMAD, a definitive motoneuron marker, consistent with a transformation of these interneurons into motoneurons.

Supernumerary motoneurons might arise from neuroblast duplication or change within a neuroblast lineage. To test whether there were duplicated neuroblasts, we examined sga>Nkx6 or sga>nks6.1 fly embryos using various markers including Engrailed, Odd-skipped, Vnd, and Ind (McDonald et al., 1998; Patel et al., 1989; Spana and Doe, 1995; Weiss et al., 1998). We saw normal numbers of neuroblasts in both backgrounds (data not shown), ruling out neuroblast duplication, and suggesting that ectopic motoneurons result from an alteration in neuroblast lineage, for example, an
Interneuron to motoneuron transformation or a switch in GMC identity.

To examine potential lineage effects, we expressed fly Nkx6 under the control of Eagle (Eg), which is expressed in neuroblast 7-3 and its progeny, the HB9-positive EW interneurons and GW motoneurons. We found the same number of Eg-positive, HB9-positive cells in controls and embryos overexpressing Nkx6 than in embryos expressing pMAD in embryos overexpressing Nkx6 (Us, 2.5±1.4, n=34; ELS, 5.2±2.3, n=52). This result suggests that Nkx6 may be involved in the specification of interneurons.

We also tested whether Nkx6 was necessary for fly motoneuron formation by RNAi. We saw no change in the numbers of HB9 or pMAD-positive cells in embryos lacking Nkx6, suggesting that it is not required for motoneuron formation (data not shown), consistent with the phenotype of Nkx6 mutants (Broihier et al., 2004).

Discussion

Our key finding is that Nkx6 genes have conserved expression patterns and functions in flies and zebrafish. One function of Nkx6 genes is to promote motoneuron and inhibit interneuron formation, however, as we discuss below, the role of this gene in neurogenesis is clearly more complex.

Zebrafish Nkx6.1 promotes motoneuron and suppresses interneuron formation

Nkx6.1 is expressed in a zebrafish spinal cord domain that generates diverse cell types, including PMNs and SMNs, interneurons and oligodendrocytes (Park et al., 2002) (H. C. Park and B. Appel, personal communication). We focused on the role of nkx6.1 in motoneurons and VeLD interneurons. However, a complete understanding of how this gene functions requires lineage analysis to ascertain when it is expressed in each cell type generated in this region, and how these cell types are related to one another. In zebrafish, Nkx6.1 is required for formation of SMNs, but not PMNs. This is surprising considering that in mice lacking Nkx6.1 all subtypes of spinal motoneurons are similarly depleted (Sander et al., 2000). Thus, we expected to see fewer PMNs and SMNs in zebrafish. It would be interesting to learn whether mice lacking Nkx6.1 are missing specific motoneuron subsets, such as later-generated motoneurons. Nkx6.1 is one of the few known proteins that differentially affects SMN and PMN formation in zebrafish, raising the possibility that other, related genes may participate in PMN formation. A good candidate is Nkx6.2, which is able to substitute for Nkx6.1 in mice lacking Nkx6.1 function (Vallstedt et al., 2001). Interestingly, mouse Nkx6.2 is not normally expressed in the motoneuron progenitor domain, but its expression expands into this domain in the absence of Nkx6.1. It will be important to learn whether zebrafish has an Nkx6.2 homolog, where it is expressed and if it is required for PMN formation.

The decreased number of SMNs in nkx6.1 MO embryos was accompanied by an increase in VeLD interneurons. Conversely,
Fly Nkx6 generally promotes motoneuron and suppresses interneuron formation

Overexpression of fly Nkx6 in fly CNS produced a complex phenotype that might result from fate changes within neuroblast lineages. For example, cells in the EW interneuron position often expressed pMAD, a definitive motoneuron marker, suggesting an interneuron-to-motoneuron fate change. There are many more motoneurons in the lateral cluster than can be simply explained by EWs becoming motoneurons; thus other sources must also contribute to formation of supernumerary, HB9-positive, lateral cluster motoneurons. HB9-positive motoneurons project to ventral muscles via SNb (Broihier et al., 2002; Odden et al., 2002), thus, they probably contribute to the thicker SNb motor nerves. Both HB9 and Islet are required for proper ventral motoneuron projections (Broihier and Skeath, 2002; Odden et al., 2002; Thor and Thomas, 1997), suggesting Nkx6 interacts with them during this process.

Nkx6 and Eve are expressed in mutually exclusive neuronal subpopulations at the end of fly gastrulation. All dorsally projecting motoneurons are Eve-positive (Landgraf et al., 1999) and thus Nkx6 must be restricted to interneurons or the ventrally projecting, Islet-positive, HB9-positive motoneurons at this developmental stage. However, at earlier stages Nkx6 is expressed in some neuroblasts that generate Eve-positive motoneurons and probably in those motoneurons themselves. Thus, in flies as in fish, Nkx6 expression is apparently downregulated in at least some motoneurons. However, Nkx6 must play a role in the generation of these cells as overexpression causes duplicated Eve-positive RP2 motoneurons and fewer Eve-positive U motoneurons. Understanding how expression of Eve and Nkx6 is regulated in these cells should elucidate when Nkx6 acts during motoneuron formation.

Are Nkx6 genes ancient regulators of motoneuron development?

Several dorsoventral patterning genes are expressed in strikingly similar patterns in the developing CNS of vertebrates and flies, motivating us to test whether these genes have conserved functions. Mouse Nkx2.2 and Gsh-1, orthologs of fly Vnd and Ind, produced no phenotype when overexpressed in fly embryos, revealing that the vertebrate proteins do not function in the context of the other species (T.V.O., unpublished) and suggesting functional domains have become distinct over time. That zebrafish Nkx6.1 and fly Nkx6 have similar overexpression phenotypes suggests their functions in CNS patterning have been preserved over 800 million years of evolution. We propose the bilaterian ancestor utilized Nkx6 proteins both to pattern ventral CNS and to promote motoneuron and suppress interneuron development. In vertebrates, Nkx6.1 is ventrally expressed, consistent with the ventral origin of CNS motoneurons. In flies, Nkx6 is also initially ventrally restricted, although its expression is not strictly correlated with motoneuron-producing neuroblasts, which are distributed throughout the CNS dorsoventral axis. Later, fly Nkx6 is expressed at least transiently in many, perhaps all, developing motoneurons, thus it must be expressed in some motoneurons whose neuroblast antecedent was Nkx6-negative. This suggests that expression of Nkx6 is differentially regulated in neuroblasts and their progeny.

How flies generate motoneurons from all CNS dorsoventral levels and vertebrates from only ventral CNS remains a mystery. Thor and Thomas (Thor and Thomas, 2002) proposed that the common ancestor of vertebrates and arthropods had both dorsally and ventrally projecting motoneurons and that vertebrates lost the dorsally projecting subset because of constraints imposed by evolution of the notochord. This is consistent with the observation that the ventrally projecting motoneurons in both flies and vertebrates express the same transcription factors, Nkx6, Islet, HB9 and Lim3. The origin of motoneurons can be addressed by studying nervous system patterning in other protostome and deuterostome phyla to learn whether ventral restriction of motoneurons is a basal or derived characteristic.

Transcription factors that control motoneuron formation are regulated by different mechanisms in vertebrates and arthropods

The inputs establishing Nkx6 expression have apparently diverged between vertebrates and arthropods. In flies there are at least two spatially and temporally distinct phases of Nkx6 expression, early in ventral neuroblasts and later in neurons, only some of which are derived from Nkx6-positive neuroblasts. This has allowed us to ask whether the same signaling mechanism affects Nkx6 function at different times and in different cell types. Because Hh is required for Nkx6 expression in vertebrates, we asked whether Hh also affected Nkx6 in flies. We found that Hh does not affect Nkx6 expression in fly neuroblasts, showing that it is not involved in establishing the early pattern. We also found that motoneuronal progeny of at least one Nkx6-positive neuroblast develop in the absence of Hh signaling, thus Hh is also probably not involved in establishing the later pattern of Nkx6 expression. What regulates formation of fly motoneurons is still an enigma.

In contrast to flies, Hh is required to induce nkh6.1 in all vertebrates tested thus far, including zebrafish. Because motoneurons arise from progenitors in the ventral domain it is unclear whether Nkx6 is regulated differently in progenitors and their progeny. This could be tested by downregulating Hh at later developmental stages.

The ability of ectopic nkh6.1 to induce supernumerary PMNs in zebrafish raises a conundrum. Hh is both necessary and sufficient for nkh6.1 expression, however we and others have found that ectopic Hh is insufficient to induce
supernumerary PMNs except in the most rostral spinal cord (Hammerschmidt et al., 1996) (S.E.C. and J.S.E., unpublished). How can a downstream gene be sufficient to generate a particular cell type when the upstream gene that induces it is insufficient? One possibility is that Hh promotes expression of both positive and negative regulators of motoneuron formation. Normal levels of Hh lead to a balance between these negatively acting and positively acting downstream genes, and PMNs are formed. In contrast, excess Hh tips the balance in favor of negative regulators, thus preventing formation of supernumerary PMNs. Hh is known to induce other factors that regulate motoneuron formation such as olig2, which can only generate PMNs in concert with Hh (Park et al., 2002), showing that additional Hh-dependent factors are required; nkh6.1 is a good candidate for fulfilling this role.

It is clear that although the same transcription factors regulate formation of ventrally projecting motoneurons in vertebrates and arthropods, these transcription factors are regulated by different mechanisms in these distinct taxa. It will be exciting to learn what regulates the Nkx6 pathway leading to motoneuron formation in flies and whether formation of dorsally projecting and of ventrally projecting motoneurons are regulated by the same mechanisms.

We thank José Campos-Ortega, Andre Quinkertz, Jim Skeath, Heather Broshier, Bruce Appel and Hae-Chul Park for generously sharing data before publication, John Postlethwait, Bruce Appel, Susan Bassham, William Jackman and Stephen Schneider for critical comments on earlier drafts of the manuscript, Joanne Odden, Bruce Draper, Kristin Wildermuth and Deanna Grant for technical assistance, Ole Madsen for the generous gift of Nkh6.1 antibody, David Kimelman and Thierry Lepage for the gastrula stage cDNA library, the University of Oregon Zebrafish Facility staff for fish husbandry and members of the Eisen and Doe labs for support. Supported by NSF DGE9972830 (SEC), NIH HD27056 (TVO, MJL, CQD), and NIH NS23915 (JSE), with special thanks to Gabrielle LeBlanc.

We dedicate this paper to our dear friend and colleague José Campos-Ortega.

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