Development of branchiomotor neurons in zebrafish

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SUMMARY

The mechanisms underlying neuronal specification and axonogenesis in the vertebrate hindbrain are poorly understood. To address these questions, we have employed anatomical methods and mutational analysis to characterize the branchiomotor neurons in the zebrafish embryo. The zebrafish branchiomotor system is similar to those in the chick and mouse, except for the location of the nVII and nIX branchiomotor neurons. Developmental analyses of genes expressed by branchiomotor neurons suggest that the different location of the nVII neurons in the zebrafish may result from cell migration.

To gain insight into the mechanisms underlying the organization and axonogenesis of these neurons, we examined the development of the branchiomotor pathways in neuronal mutants. The valentino b337 mutation blocks the formation of rhombomeres 5 and 6, and severely affects the development of the nVII and nIX motor nuclei. The cyclops b16 mutation deletes ventral midline cells in the neural tube, and leads to a severe disruption of most branchiomotor nuclei and axon pathways. These results demonstrate that rhombomere-specific cues and ventral midline cells play important roles in the development of the branchiomotor pathways.

Key words: zebrafish, hindbrain, branchiomotor neuron, axonogenesis, valentino, cyclops

INTRODUCTION

Intricate mechanisms have evolved in multicellular organisms for generating specific neuronal cell types and for interconnecting them to create functional circuits (Goodman and Shatz, 1993; McConnell, 1995). In vertebrates, the mechanisms underlying the specification and pathfinding of neurons that innervate craniofacial structures are relatively obscure, and are addressed in this report. The segmentally iterated pharyngeal arches, which give rise to the jaws and other branchial tissue, along with their supporting structures and musculature (Schilling and Kimmel, 1994), are innervated by branchiomotor neurons that differentiate in specific segments, or rhombomeres, within the hindbrain (Noden, 1983; Gilland and Baker, 1993). A 2:1 correspondence between the hindbrain rhombomeres and the pharyngeal arches is evident both at the level of neural crest migration, whereby neural crest arising in individual even-numbered rhombomeres contributes to a single arch (Noden, 1983; Lumsden et al., 1991; Akimenko et al., 1994), and at the level of motor innervation, whereby motor neurons differentiating in pairs of rhombomeres innervate a single arch. Thus, in the chick and mouse, the first pharyngeal (mandibular) arch is innervated by neurons in rhombomere 2 (r2) and r3, the second pharyngeal (hyoid) arch is innervated by neurons in r4 and r5, the third pharyngeal arch is innervated by neurons in r6 and r7, and the remaining pharyngeal arches are innervated by neurons in the caudalmost hindbrain (reviewed in Gilland and Baker, 1993).

The molecular basis of hindbrain segmentation and its influence on pharyngeal arch morphogenesis and innervation are being rapidly elucidated (Lumsden and Krumlauf, 1996). Krox20, kreisler and Hoxa-1 are required for segmentation (Lufkin et al., 1991; Chisaka et al., 1992; Frohman et al., 1993; Schneider-Maunoury et al., 1993; Swiatek and Gridley, 1993; McKay et al., 1994), while expression of hox genes in rhombomere-specific patterns has been shown to be required for aspects of segment identity within the hindbrain (Lufkin et al., 1991; Chisaka et al., 1992; Goddard et al., 1996; Studer et al., 1996). Mutations in several of these genes affect the organization of the cranial nerves (Lufkin et al., 1991; Chisaka et al., 1992; Schneider-Maunoury et al., 1993; Swiatek and Gridley, 1993; McKay et al., 1994), and in some cases have been shown to affect the specification of particular branchiomotor nuclei (Lufkin et al., 1991; Schneider-Maunoury et al., 1993; Swiatek and Gridley, 1993; Goddard et al., 1996; Studer et al., 1996).

We wished to address the issue of branchiomotor neuron specification and pathfinding in the zebrafish embryo, a vertebrate that is particularly amenable to genetic analyses (Nusslein-Volhard, 1994; Driever et al., 1994; Kimmel, 1993; Kuwada, 1995). As a first step in this endeavor, we have characterized the positions and axon pathways of the zebrafish branchiomotor neurons. Our results demonstrate extensive similarities with the branchiomotor organization of other species, but also some unexpected differences, specifically with respect to the location of the nVII (facial) motor nucleus. We have also assessed the effect of mutations in cyclops (Hatta et al., 1991) and valentino (Moens et al., 1996) on branchiomotor neuron specification and pathfinding. valentino, the
zebrafish homolog of the mouse kreisler gene (Cordes and Barsh, 1994), is required for the development of rhombomeres 5 and 6 from their common precursor ‘protosegment’ (Moens et al., 1996; and unpublished observations). The branchiomotor defects observed in valentino and cyclops mutant embryos suggest that rhombomere-specific cues, rhombomere boundaries and hindbrain floor plate cells play important roles in the specification, organization and pathfinding of these motor neurons.

We have also addressed the issue of branchiomotor neuronal migration. While chick branchiomotor neurons do not appear to migrate longitudinally within the hindbrain, examination of branchiomotor nuclei in wild-type and Hoxb-1 mice suggests that facial motor neurons may migrate caudally during development (Fritzsch, 1996; Goddard et al., 1996; Studer et al., 1996). We studied the spatial regulation of two genes expressed by zebrafish branchiomotor neurons. Our observation that the distribution of presumptive branchiomotor neurons shifts caudally during development, taken together with our data on the branchiomotor phenotype of valentino mutant embryos, suggests that there may be extensive caudal migration of branchiomotor neurons in the zebrafish hindbrain after specification.

MATERIALS AND METHODS

Animals

Adult zebrafish were reared and maintained as described in Westerfield (1995). Embryos were collected from breeding colonies, staged and allowed to develop at 28.5°C to the required age. Throughout the text, the developmental age of the embryos will correspond to the number of hours elapsed since fertilization (hours post-fertilization, hpf) for embryos older than 24 hpf, and to the hpf based on somite number (Kimmel et al., 1995), for embryos younger than 24 hpf. To inhibit pigmentation, embryos were transferred to fish water containing 0.2 mM phenylthiourea (Sigma) between 18 and 22 hpf (Burrill et al., 1996; and unpublished observations). The branchiomotor phenotype of valentino mutant embryos, caudally during development, taken together with our data on the branchiomotor nuclei of wild-type and Hoxb-1 mice suggests that facial motor neurons migrate caudally during development (Fritzsch, 1996; Goddard et al., 1996; Studer et al., 1996). We studied the spatial regulation of two genes expressed by zebrafish branchiomotor neurons. Our observation that the distribution of presumptive branchiomotor neurons shifts caudally during development, taken together with our data on the branchiomotor phenotype of valentino mutant embryos, suggests that there may be extensive caudal migration of branchiomotor neurons in the zebrafish hindbrain after specification.

Photoconversion of DiI fluorescence

The fluorescent DiI signal of labeled neurons and axons was converted by photooxidation (Lubke, 1993) into a visible brown precipitate that was stable in subsequent procedures such as antibody staining, in situ hybridization and cryostat sectioning. Briefly, labeled embryos were released from the agar, deyolked and decapitated at the level of the third somite with microsurgical scissors. The head fragments were incubated in PB containing 0.5 mg/ml dianisobenzidine (DAB) for 15 minutes, and mounted dorsally in a drop of DAB/PB between coverslips using vaseline supports. The fluorescence in the labeled cells was used to photooxidize DAB into a brown reaction product. After photoconversion, the embryos were released from between the coverslips, washed once in PB, fixed overnight in 4% paraformaldehyde/PB; they then served as the starting material for other procedures.

The data presented in this paper on the developmental appearance and rhombomeric location of the branchiomotor neurons were obtained from retrograde-labeling experiments performed on embryos at 26-30 hpf (n=28), 30-36 hpf (n=142), 40 hpf (n=15) and 48-52 hpf (n=109).

Immunohistochemistry

Embryos were fixed in 4% paraformaldehyde/PB containing 1% dimethylsulfoxide (DMSO). Processing of embryos for immunohistochemistry with the acetylated α-tubulin antibody (Piperno and Fuller, 1985), the zn5 antibody (Trevorrow et al., 1990), the distal-less antibody (Panganiban et al., 1995) and the islet antibody (39.4D5, Korzh et al., 1993) was performed as described previously (Chitnis and Kuwada, 1990) with the following changes: the Triton X-100 concentration was increased to 0.2% and all the buffers contained 1% DMSO. All antibodies except anti-distal-less are monoclonal.

In situ hybridization

Digoxigenin-labeled RNA probes were synthesized with components from a kit using the manufacturer’s instructions (Boehringer Mannheim). Hybridization of zebrafish embryos was performed as described in Westerfield (1995). Hybridization to sense RNA probes generated no detectable signal in embryos.

RESULTS

Neurons innervating the mandibular arch are located in rhombomeres 2 and 3

Since the zebrafish offers several advantages for the study of neuronal development, we initiated a study of neurons innervating the pharyngeal arches of the zebrafish embryo. In order to determine the location of the arch-innervating neurons, their cell bodies were retrogradely labeled by injection of a fluorescent lipophilic dye, DiI, into the pharyngeal arch. The result of such an experiment, in which DiI was injected into the hyoid arch, is shown in Fig. 1E.

Efferent neurons were retrogradely labeled by DiI injection into the mandibular arch. After photoconversion of the DiI fluorescence in the labeled cells, the embryos were labeled with the zn5 antibody to identify hindbrain rhombomeres (Fig. 1A). The zn5 antibody labels many cell types including the axons of hindbrain commissural neurons that lie at rhombomere boundaries (Trevorrow et al., 1990). Rhombomeres were numbered on the basis of two criteria: (1) their locations relative to the otocyst, in particular r5, which is just medial to the otocyst at all the ages examined here (Kimmel et al., 1995; data not shown), and (2) the location of the zn5-labeled abducens motor nucleus in r5 (Kimmel et al., 1985; Trevorrow et al., 1990), which is conserved in vertebrates (Gilland and Baker, 1993). Furthermore, since the zn5-labeled commissural
axons exhibit distinctive trajectories in r5 (Fig. 1A), this pattern was used to identify r5 in younger embryos where the abducens nucleus was not labeled (e.g. Fig. 1B).

Two clusters of retrogradely labeled neurons, one each in r2 and r3, can be identified in 48 hpf embryos (Fig. 1A). The r2 cluster can be retrogradely labeled at 28 hpf, whereas the earliest time when the r3 cluster can be retrogradely labeled is between 36 and 40 hpf (data not shown). Consistent with this result, the axons extending into the mandibular arch are first seen as a few fibers at 27 hpf, medial to the trigeminal ganglion (data not shown), and extend into the rostral half of the arch between 30 and 36 hpf (Fig. 2A,B). At 48 hpf, the numbers of Dil-labeled cells in the r2 and r3 clusters are 14.8±5.6 and 10.9±5.4, respectively (n=17). The neurons are equidistant from the pial and ventricular surfaces of the hindbrain. The axons from each cluster fasciculate and extend laterally away from the midline until they encounter the afferent fibers of the trigeminal sensory neurons (Hatta et al., 1990). In addition, the relatively lateral position of these neurons (compare Fig. 1C and D), and the close association of their axons with the trigeminal afferent axons, are in accord with the anatomy of trigeminal motor neurons (nV) in other vertebrates (Moody and Heaton, 1983). Furthermore, the hindbrain exit points of the zebrafish axons extending into the mandibular and other arches (Fig. 2, and summarized in Fig. 4) are the same as those described for branchiomotor neurons in the chick (Lumsden and Keynes, 1989) and the mouse.
(Marshall et al., 1992; Carpenter et al., 1993). Taken together, these observations indicate that the efferent neurons being studied are most likely to represent the zebrafish branchiomotor neurons, and will be referred to as such throughout the rest of the paper. However, these neuronal clusters may contain some non-branchiomotor efferent neurons.

**Branchiomotor neurons innervating the hyoid arch (nVII) are located in rhombomeres 6 and 7**

The nVII neurons were retrogradely labeled by DiI injection into the hyoid arch (Fig. 1E). Two clusters of nVII neurons, one each in r6 and r7, can be labeled in 36 hpf embryos (Fig. 1B). Although both motor neuron clusters can be retrogradely labeled by 30 hpf (data not shown, see Fig. 5A), the r6 cluster labels more reliably than the r7 cluster between 30 and 48 hpf. At 36 hpf, the numbers of DiI-labeled cells in the r6 and r7 clusters are 9.3±4.7 cells (n=24) and 3.1±1.6 (n=11), respectively. A transverse section through r6 in a 36 hpf embryo (Fig. 1D) reveals that the motor neurons are very ventral and medial, almost adjacent to the floor plate cells. The axons from the two clusters fasciculate and extend rostrally along a medial pathway that is parallel to the midline (Fig. 1B). Tubulin labeling of the medial longitudinal fascicle (MLF) in embryos with photoconverted nVII axons shows that they are closely apposed to the MLF (data not shown).

Within r4, the motor axons make a sharp turn away from the midline (the genu) and follow the rostromedial margin of the otocyst into the arch (Fig. 1B,E; see also Fig. 5A). Examination of tubulin- and distal-less-labeled embryos shows that the axons innervating the hyoid arch exit the hindbrain at 28-29 hpf (data not shown) at the dorsorostral margin of the otocyst, and have extended into the arch mesenchyme by 36 hpf (Fig. 2A,B).

Since the nVII neurons are located primarily in r4 and r5 in other vertebrates (Gilland and Baker, 1993), we verified the unusual location of these motor neurons in the zebrafish by anterogradely labeling their axons by DiI application to their cell bodies in r6 in 36 hpf embryos and found that the axon terminals were located within the hyoid arch (n=6; data not shown).

**Branchiomotor neurons innervating the gill arches (nIX, nX) are located in rhombomere 7 and the caudalmost hindbrain**

The nIX neurons were retrogradely labeled by DiI injection into the first gill arch in 48 hpf embryos. These motor neurons are located very medially in a single cluster in r7 (Fig. 3A). The motor axons extend into r6 anteriorly along a medial pathway that is parallel to the midline, then make a sharp turn away from the midline (the genu) until they encounter the dorsocaudal margin of the

![Fig. 2. Axons that innervate the pharyngeal arches exit the hindbrain from specific rhombomeres in a manner characteristic of branchiomotor axons. Both panels show lateral views; dorsal up, rostral to the left. (A) 30 hpf and (B) 36 hpf embryos were processed for immunohistochemistry with antibodies against acetylated α-tubulin, which labels various neurons (tg, al, pl) and axons (arrowheads), and the distal-less protein, which labels the pharyngeal arch mesenchyme (m, h, g1) in addition to other tissues. The axons innervating the pharyngeal arches exit from rhombomeres 2, 4, 6 and the caudalmost hindbrain, and probably correspond to the cranial nerves V, VII, IX and X, respectively (see text for details). al, anterior lateral line ganglion; e, eye; g1, first gill arch; g, all gill arches; h, hyoid arch; m, mandibular arch; oto, otocyst; pl, posterior lateral line ganglion; tg, trigeminal ganglion. Bar, 20 μm (A), 40 μm (B).](Image 225x250 to 559x435)

![Fig. 3. The motor neurons innervating the first gill arch (nIX) and gill arches 2-5 (nX) are located in r7 and the caudalmost hindbrain, respectively. (A,B,D) Dorsal views. (C), lateral view. Rostral is to the left in all panels. Double-headed arrows mark the midline. (A,B) nIX neurons (black arrowheads) and their axons (black arrow) were retrogradely labeled and photoconverted after DiI injection into the first gill arch on one side in 48 hpf embryos. The embryos were subsequently processed for zn5 immunohistochemistry to label hindbrain commissural axons and the abducens nuclei. (A) The nIX axons exit the hindbrain in r6. The cell bodies, which are out of focus, lie in r7. Long lateral dendrites (white arrowheads) of nIX neurons contact inadvertently labeled nX neurons (white arrows). The asterisk indicates the sharp lateral turn, the genu, of the motor axons. (B) The nIX neurons express the antigen recognized by the zn5 antibody. The photoconverted nIX axons are out of focus, and could be seen only to the right of the midline, as in A. Two different embryos are depicted in A and B. (C,D) nIX neurons (black arrowheads) and their axons (black arrow) were retrogradely labeled and photoconverted after DiI injection into the posterior gill arches on one side in 48 hpf embryos. (D) Axons from the nX neurons form three bundles that join a large axon fascicle (black arrow) at the sites indicated by the asterisks. The white arrows in C and D indicate stained blood cells, an artifact of photoconversion. ab, abducens motor nucleus; chb, caudalmost hindbrain; oto, otocyst; r5-7, rhombomeres 5-7; sm, somitic musculature. Bars, 20 μm (A,B); 20 μm (C,D).](Image 309x620 to 559x719)
branchiomotor neurons in the zebrafish

The earliest axons exit the hindbrain at 30-32 hpf (data not shown), and extend along the ventromedial surface of the otocyst between 30 and 36 hpf (Fig. 2B). Interestingly, the nIX neurons are the only branchiomotor neurons that express the zn5-recognized antigen (Fig. 3B), which is encoded by the DM-Grasp gene (Kanki et al., 1994; Fashena, 1996).

The nX neurons were retrogradely labeled by DiI injection into gill arches 2-5 in 48 hpf embryos. The motor neurons are located in the caudalmost hindbrain (Fig. 3C,D). Although clustering of neurons is not evident, a dorsal view (Fig. 3D) suggests that these neurons extend axons ventrolaterally in several bundles, then turn anteriorly to form a large fascicle that exits from the caudalmost hindbrain (Figs 2B, 3C). At present, the correspondence between the axon bundles (Fig. 3D) and the gill arches that they innervate is not known.

The nX neurons possess long lateral dendrites (Fig. 3A). In embryos where nIX and nX neurons were both inadvertently labeled (nr=4), the nIX-associated dendrites contact the rostralmost nX neurons (Fig. 3A), suggesting that the motor neurons innervating the gill arches may interact.

Our observations on the zebrafish branchiomotor nuclei (summarised in Fig. 4) show that these motor nuclei share many characteristics of branchiomotor nuclei described in other vertebrates (Gilland and Baker, 1993). However, there is one major difference. The zebrafish nVII neurons are found in r6 and r7, and not in r4 and r5 as in the chick (all nVII neurons, Lumsden and Keynes, 1989) and the mouse (most nVII neurons, Marshall et al., 1992; Carpenter et al., 1993). Consequently, no zebrafish branchiomotor neurons are located in r4 and r5. Furthermore, the nIX and one cluster of nVII neurons are both located in r7, but their relative positions suggest that the two clusters are not mixed together (see Fig. 5B).

The zebrafish branchiomotor nuclei express the isl1 and tag1 genes

To study the appearance and organization of the branchiomotor neurons before their axons exit the hindbrain, we sought molecular markers that were expressed early by these neurons. We found that two neuronal genes, isl1 (Inoue et al., 1994; Appel et al., 1995) and tag1 (Warren et al., 1995), were expressed by branchiomotor neurons continuously between 30 and 48 hpf (Fig. 5; Warren et al., 1995).

The isl1 gene, which encodes a LIM-homeodomain protein, is essential for motor neuron differentiation in the mouse (Pfaff et al., 1996). The islet 39.D5 monoclonal antibody (Korzch et al., 1993) labels cells in the hindbrain that express isl1 (Fig. 5; Inoue et al., 1994). Retrograde labeling of the various branchiomotor nuclei followed by islet immunolabeling shows that neurons in all of these nuclei (nV, nVII, nIX and nX) express isl1 (Fig. 5A, data not shown). In addition to the branchiomotor nuclei, other islet-labeled cells in r5 and r6 may constitute the abducens motor nuclei (Fig. 5B).

The tag1/axonin1 gene encodes an axonal cell surface glycoprotein that is transiently expressed on a number of sensory, motor and interneurons in the rat and chick (Furley et al., 1990; Stoeckli and Landmesser, 1995). The zebrafish homolog of tag1 is similarly expressed by a subset of neurons, including clusters of hindbrain cells. Retrograde labeling of the branchiomotor neurons followed by in situ hybridization with a tag1 riboprobe demonstrated that tag1 is expressed by neurons in all of the branchiomotor nuclei, except nIX (Warren et al., 1995).

These results demonstrate that although neurons in all of the branchiomotor nuclei express isl1, the nIX nucleus differs from the other nuclei by expressing DM-Grasp (Fig. 3B), and not tag1. This heterogeneity in gene expression between nIX and nVII neurons reflects cellular differences that may enable their axons to innervate different arches in spite of their cell bodies being in the same environment (i.e. in r7).

The distribution of presumptive nVII neurons shifts caudally during development

Since no branchiomotor neurons are found in r4 and r5 in the zebrafish, we wondered whether the nVII motor neurons were born in r4 and r5, as in other vertebrates, and subsequently migrated into r6 and r7. To address whether nVII neurons may migrate across rhombomeres during development, we examined isl1 and tag1 gene expression in presumptive nVII neurons between 16 and 36 hpf. Assuming that cells express the isl1 and tag1 genes stably between 16 and 36 hpf, we predicted that if cells migrated from r4/5 into r6/7, then we would find isl1- and tag1-expressing cells in r4/5 early but not later. This was indeed what we found (Fig. 6).

At 16 hpf, a few isl1-expressing cells are located bilaterally in r4 (Fig. 6A), whereas there are no tag1-expressing cells. Rhombomeric boundaries were estimated by designating the hindbrain spanning the central half of the otocyst as r5, and those spanning the rostral and caudal quarters of the otocyst as parts of r4 and r6, respectively. By 20 hpf, there are bilateral rostromedial columns of isl1- and tag1-expressing cells (Fig. 6.C,D). The isl1-expressing cells span r4 through r7, while the tag1-expressing cells span r5 through r7. By 24 hpf, isl1-expressing cells are still found in r4 (Fig. 6E), while cells expressing high levels of tag1 are found in r6 and r7 (Fig. 6F). By 36 hpf, most isl1- and tag1-expressing cells are confined to r6 and r7, where the nVII neurons are located (Fig. 6G,H).
contrast to the nVII neurons, presumptive nV neurons expressing *isl1* and *tag1* are located in r2 and r3 at 30 hpf (data not shown) and 36 hpf (Figs 6G,H and 7C), suggesting that they do not migrate after birth. These results are consistent with the hypothesis that at least some nVII motor neurons are born in r4 and r5, and subsequently migrate into r6 and r7. However, we cannot rule out that the observed changes in the positions of *isl1* - and *tag1* -expressing cells in fact represent downregulation of these genes in cells in r4 and r5, and concomitant activation of these genes in different cells in r6 and r7.

**Development of the nVII and nIX neurons is defective in valentino mutant embryos**

Since the branchiomotor neurons occupy well-defined locations within specific rhombomeres, we wanted to know if rhombomere-specific cues played any role in the organization of these motor neurons and their axons. The *valentino* b337 mutation is especially interesting because it blocks the formation of r5 and r6 from their precursor (rX), shortening the mutant hindbrain by one rhombomere (Fig. 4; Moens et al., 1996). Furthermore, the abducens motor nuclei normally located in r5 and r6 are missing in mutant embryos (Moens et al., 1996). Since some nVII neurons are located in r6, we predicted that the nVII nuclei would be affected in val embryos. Indeed, we found that the nVII neurons, and surprisingly the nIX neurons, were severely affected in val - embryos.

Organization of the nV and nVII neurons were examined in 48 hpf embryos by DiI injection into the mandibular and hyoid arches, respectively. The nV neurons are found in two clusters in val - embryos, one each in r2 and r3, and appear indistinguishable from those in wild-type embryos (data not shown). The location and number of *tag1* -expressing cells in r2 and r3, the nV neurons, are also unaffected in val - embryos (Fig. 6).
7C,D). In contrast, the nVII neurons and their axons were disrupted in val− embryos. Two motor neuron clusters, in r6 and r7, are found in wild-type siblings (Fig. 7A). However, in all val− embryos (n=30), the retrogradely labeled neurons are not clustered and are scattered over an approximately two rhombomere span, probably r2 and r7 (Fig. 7B). The distribution of tag1-expressing cells also shows that the presumptive nVII neurons are disorganized in val− embryos. In 36 hpf wild-type siblings, bilateral groups of tag1-expressing cells, one each in r6 and r7, are evident (Fig. 7C). However, in val− embryos, the tag1-expressing cells are found in disorganized clumps spanning two rhomboheres (Fig. 7D).

The distribution of isl1-expressing cells in 48 hpf wild-type and val− embryos also demonstrates that the nVII neurons are disorganized in mutant embryos (Fig. 8D). Interestingly, the numbers of tag1-expressing presumptive nVII neurons (spanning r4 through r7) in 24 hpf wild-type and val− embryos are similar at 18.7±3.6 (n=20) and 15.7±2.8 (n=14), respectively. These results demonstrate that the valentino b337 mutation disrupts the organization of the nVII neurons, and suggest that the mutation does not affect their specification.

Although nVII axons do extend into the hyoid arch, some aspects of axonal pathfinding are affected in val− embryos. In wild-type embryos, nVII axons are tightly fasciculated throughout their length in the hindbrain (Fig. 7A). In contrast, in val− embryos, the nVII axons are significantly defasciculated, and join the main fascicle(s) at random points along its length (Fig. 7B). Interestingly, although the axons are frequently defasciculated, they always turn sharply away from the midline in r4 or in the rostral margin of rX, in a manner similar to wild-type axons. Since the retrograde labeling experiments provide information only on neurons that have correctly extended into the hyoid arch in mutant embryos, the number of neurons in rX/r7 that either do not extend axons or extend axons into inappropriate regions is not known.

The nIX neurons are also severely affected in val− embryos. Immunolabeling of sagittal sections of 48 hpf wild-type and val− hindbrains with the zn5 antibody shows that the zn5-labeled cell bodies in r7 corresponding to the nIX neurons (Figs 3B, 7E) are mostly missing in val− embryos (Fig. 7F). Islet immunolabeling also shows that the isl1-expressing cells corresponding to the nIX nucleus are missing in 48 hpf val− embryos (Fig. 8D). Consistent with these observations, the nIX axons that normally extend into the first gill arch (Figs 8A, 2B) are missing in val− embryos (Fig. 8C). Interestingly, a novel branch of the cranial X nerve extends into the first gill arch in val− embryos (Fig. 8C), which is reminiscent of an apparent fusion of the cranial IX and X nerves seen in kreasler mutant mouse embryos (McKay et al., 1994). The organization of the nX neurons in the caudal-most hindbrain, and the innervation of the posterior gill arches by nX axons are unaffected in val− embryos (Fig. 8C, D). These results demonstrate that although the val b337 mutation autonomously blocks the formation of only r3 and r6 (Moens et al., 1996), the mutation also disrupts the formation of the nIX neurons in r7.

**Specification of branchiomotor neurons and pathfinding by their axons are defective in cyclops mutant embryos**

Since floor plate-derived cues have been shown to be important

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**Fig. 7.** The val b337 mutation perturbs the development of the nVII and nIX neurons. (A-D), dorsal views. (E,F) Lateral views, dorsal up. Rostral is to the left in all panels. Double-headed arrows mark the midline. (A,B) nVII neuronal organization was determined by retrogradely labeling the motor neurons by DiI injection into the hyoid arch in 36 hpf wild-type sibling (A) and val− (B) embryos. (A) The motor neurons are organized in two clusters (arrowheads) in r6 and r7. Their axons (arrow) exhibit the characteristics described earlier. (B) In the mutant embryo, there is a disorganized clump of motor neurons spanning two rhomboheres (branch).

Although the axons (arrow) possess wild-type-like trajectories, they are significantly defasciculated. White arrowheads indicate stained blood cells, an artifact of photoconversion. oto, otocyst. (C,D) Branchiomotor neurons were labeled by in situ hybridization to a tag1 riboprobe in 36 hpf embryos. (C) In the wild-type embryo, tag1-expressing cells are found in bilateral groups (arrowheads), which correspond to the two nVII neuron clusters seen in A. (D) In the mutant embryo, the tag1-expressing cells are found in disorganized clumps spanning two rhomboheres (branch). The white arrows indicate tag1-expressing nV neurons in r2 and r3, and nX neurons in the caudalmost hindbrain. Since the otocyst and other peripheral tissue were dissected away, the tag1-expressing cells of the acoustic ganglion are missing in C and D (compare to Fig. 6H). p, posterior lateral line ganglion. (E,F) nIX neurons were examined after zn5-immunolabeling of sagittal sections of 48 hpf embryos. (E) In the wild-type embryo, the nIX neurons and the abducens motor nuclei (ab) are readily identified (see also Fig. 3B). (F) In contrast, in the val− embryo, both neuronal populations are mostly missing. The embryos depicted here were employed by Moens et al. (1996) to document the absence of the abducens neurons in val− embryos. Bars, 20 µm (A-D) and (E,F).
Fig. 8. Pharyngeal arch innervation (A,C,E) and isl1 expression in the hindbrain (B,D,F) of 48 hpf val- and cyc- embryos. Arch innervation was visualized by tubulin immunolabeling, and isl1 gene expression by islet immunolabeling.

(A,C,E), lateral views. (B,D,F), dorsal views. Rostral is to the left in all of the panels.

(A,C,E) White arrowhead indicates hyoid-arch innervating axons (nVII), black arrowhead indicates first gill arch-innervating axons (nIX, except C), and the arrow indicates second gill arch-innervating axons (nX). (A) The normal pattern of innervation in wild-type embryos was described earlier (Fig. 2B). (C) In the val- embryo, nIX axons are missing. Instead, a novel branch of the posterior gill arch-innervating nX axons invades the first gill arch.

(E) In the cyc- embryo, all arches, except the mandibular, receive normal-looking axons. (B) Isl1-expressing cells in the wild-type hindbrain. The white arrowheads indicate out-of-focus cells that are putative abducens neurons (see Fig. 5B). The black arrowheads indicate out-of-focus nIX neurons. The two groups of nVII neurons are enclosed by the bracket. (D) In the val- hindbrain, the nVII neurons are found in a disorganized clump. In addition, the nIX and the putative abducens neurons are missing (Fig. 7F; Moens et al., 1996). (F) In the cyc- hindbrain, there are a few isl1-expressing cells (white arrows) whose neuronal identities cannot be ascertained. In B, D and F, oto indicates the location of the out-of-focus otocyst, and the black arrows indicate out-of-focus nX neurons. pl, posterior lateral line ganglion; tg, trigeminal ganglion. Bars, 40 μm (A,C,E); 20 μm (B,D,F).

Consistent with the greatly reduced number of nVII and nIX neurons in cyc- embryos, tubulin immunolabeling revealed that the axons extending into the hyoid and first gill arches are absent in 36 hpf mutant embryos (data not shown). However, the pattern of axons extending into these arches in 48 hpf mutant embryos is similar to that in wild-type embryos (Fig. 8E). It is possible that a significant number of the arch-innervating axons at 48 hpf in fact represent afferent fibers of sensory neurons, whose cell bodies are not labeled by the tubulin antibody, and which are unaffected in 48 hpf cyc- embryos. We confirmed this hypothesis for the cranial IX nerve by applying the lipophilic dye, DiI, at the nerve exit point in rhombomere 6 in 48 hpf embryos. We observed that comparable numbers of sensory neurons, lying between the otocyst and the first gill arch, were labeled in wild-type and cyc- embryos, and that the trajectories of the afferent fibers of these neurons were identical to those of nIX motor axons in wild-type embryos (data not shown).

All of the branchiomotor axons project to ipsilateral targets in wild-type embryos. The nVII axons are especially interesting because they remain ipsilateral and extend rostrally in wild-type embryos, where they are in close proximity to the floor plate cells (Figs 1B, 5A). This observation suggests that floor plate-derived cues may play a role in nVII axon pathfinding, as demonstrated previously for other zebrafish neurons (Bernhardt et al., 1992a,b; Hatta, 1992). Consistent with this hypothesis, in about 50% (11/20) of cyc- embryos with labeled
nVII neurons, the cell bodies are located on the midline or on the contralateral side (Table 1, Fig. 9B,D), indicating that the axons readily cross the midline. Furthermore, in 75% (15/20) of the mutant embryos with labeled neurons, their axons are extremely defasciculated and neuronal processes frequently cross the midline regardless of the location of the cell bodies (Fig. 9B,C). These results suggest that floor plate-derived repulsive cues may play a role in the guidance of nVII motor axons.

**DISCUSSION**

**Unusual location of the nVII neurons**

The arrangement of the zebrafish branchiomotor nuclei and axon exit points is remarkably similar to those in the chick and the mouse (this report; Kimmel et al., 1985; Gilland and Baker, 1993). However, we found that the zebrafish nVII neurons are located in r6 and r7, whereas the nVII neurons in other vertebrates are found in r6 and r7 (reviewed in Gilland and Baker, 1993). Colocalization of the nVII and nIX nuclei in r7 is not unique to the zebrafish, since it occurs to some degree in the mouse (see above) and extensively in many salamander species (Wake, 1993).

What causes the zebrafish nVII neurons to be located in r6 and r7, rather than in r4 and r5? We propose two hypotheses: (1) nVII neurons are specified in r4, and subsequently migrate caudally into r5, r6 and r7, and (2) the nVII neurons may be specified and remain in r6 and r7 throughout development. Our results and other studies lead us to favor the former hypothesis.

First, analyses of developmental expression of the tag1 and isl1 genes indicate that presumptive nVII neurons are located in r4, r5 and r6 early in development (Fig. 6). Since most isl1- and tag1-expressing cells are located in r6 and r7 a few hours later, these observations are consistent with a caudally directed migration of nVII neurons during development. This interpretation assumes that the isl1 and tag1 genes are expressed continuously, and therefore that their expression is a reliable marker for presumptive nVII neurons during the stages at which the cells are monitored. An alternative explanation is that our observations reflect dynamic changes in isl1 and tag1 gene expression in different cells located in different rhombomeres.

Second, branchiomotor axon tracing experiments in shark embryos have shown that nVII cell bodies are initially located in r4 and r5, and later appear in r6 (Gilland and Baker, 1992). Furthermore, the characteristic shape of nVII axons, the genu (Fig. 5A), is consistent with neuronal specification in r4 and subsequent caudal migration into their final locations (Gilland and Baker, 1992). Recent experiments suggest that some nVII neurons may also migrate caudally from r4 into r5 and r6 in the mouse (Fritzsch, 1996; Goddard et al., 1996; Studer et al., 1996). Analysis of branchiomotor nuclei in chick/quail chimeras containing rhombomere transplants suggests that nVII neurons can migrate across rhombomere boundaries in the chick as well (Marin and Puelles, 1995). Although a caudally directed migration of nVII neurons is believed to establish the adult pattern of branchiomotor nuclei in many vertebrates (Gilland and Baker, 1993), the zebrafish is unique in that this putative migration of nVII neurons occurs very early during hindbrain development.

Our proposal of inter-rhombomeric neuronal migration may appear to contradict observations from cell-lineage experi-

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**Table 1. nVII motor neuron specification and axonogenesis in cyclops" embryos**

<table>
<thead>
<tr>
<th>Phenotype</th>
<th>Embryos injected</th>
<th>Embryos with no labeled cells</th>
<th>Embryos with labeled cells located</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Ipsilateral</td>
<td>Midline</td>
<td>Contralateral</td>
</tr>
<tr>
<td>Wild type</td>
<td>29 (3)</td>
<td>2</td>
<td>27</td>
<td>0</td>
</tr>
<tr>
<td>cyc&quot;</td>
<td>53 (4)</td>
<td>33</td>
<td>9</td>
<td>3</td>
</tr>
</tbody>
</table>

All values are total number of embryos. Numbers in parentheses refer to the number of experiments performed.
ments in the chick that the vast majority of cells in adjacent rhombomeres do not mix during early development (Fraser et al., 1990; Birgbauer and Fraser, 1994). It is possible that the few cells that were observed to cross rhombomere boundaries in these studies (Birgbauer and Fraser, 1994) were motor neurons (Marin and Puelles, 1995). Moreover, it is also becoming clear that once the developmental identity of a cell is specified according to its rhombomeric location early in embryogenesis, the cell may move freely across rhombomeres (Lumsden and Krumlauf, 1996). Neuronal migration across rhombomeres may occur by soma translocation within leading processes, which has been implicated in neuronal migration in many vertebrates (Book and Morest, 1990; Gilland and Baker, 1992; Fritsch et al., 1993). The questions of whether nVII neurons migrate, and their mode of migration, can be addressed by observing vitally labeled, presumptive nVII neurons in vivo with time-lapse microscopy.

**Defective motor neuron organization in valentino mutant embryos**

In mutants of the zebrafish segmentation gene, *valentino*, r5 and r6 fail to be subdivided from a common precursor ‘protosegment’. Consequently, this precursor persists as rX, a region with mixed identity, which fails to form boundaries with either r4 rostrally or r7 caudally. *valentino* is the zebrafish homolog of the mouse *kreisler* gene (Cordes and Barsh, 1994), and encodes a bZIP transcription factor (Moens et al., unpublished). *valentino* is expressed throughout r5 and r6, which is consistent with a cell-autonomous requirement for *val* function in these rhombomeres, as inferred from transplantation experiments (Moens et al., 1996). Also consistent with a cell-autonomous requirement for *val* function in r5 and r6 is the absence in *val*− embryos of the abducens motor nuclei, which normally differentiate in r5 and r6 (Moens et al., 1996).

We show here that the nVII neurons form disorganized, irregular clumps in *val*− embryos, and that their axons are poorly fasciculated as they extend toward their exit point in r4. Furthermore, the single cluster of nIX neurons in r7 is absent. Since the numbers of *tag1*-expressing presumptive nVII neurons are comparable in wild-type and *val*− embryos, the disorganization of the nVII nuclei in mutant embryos may reflect normal specification of nVII neurons in r4 and defective caudal migration due to aberrant r5/6 development. In contrast, the absence of the r7-specific nIX neurons is unexpected in a mutant whose primary and cell-autonomous defect is in r5 and r6, and could result from defects either in signaling or cell migration between rhombomeres. The nIX neurons may normally be induced in r7 by r5/6-derived signals that are absent in *val*− embryos. Alternatively, the nIX neurons may normally be specified in r5/6 and subsequently migrate caudally into r7. If nIX neurons normally migrate into r7, their absence in r7 of *val*− embryos may result from their failure to be specified due to aberrant r5/6 development. The characteristic shape of nIX axons in wild-type embryos, the genu (Fig. 3A), is also consistent with neuronal specification in r6 and subsequent caudal migration into r7. In vivo, time-lapse microscopic observations on vitally labeled nIX neurons can address whether these cells migrate caudally during development.

The nVII axons are abnormal in *val*− embryos (Fig. 7B). Although they are frequently defasciculated, a majority of the axons exhibit normal trajectories, that is, they turn sharply away from the midline in r4 or in the rostral margin of rX. This result suggests that although the motor neurons are disorganized in *val*− embryos, their axons are able to respond normally to putative guidance cues in r4 or in the rostral margin of rX. Furthermore, since nVII axons are defasciculated in rX in spite of *tag1* gene expression in these neurons (Fig. 7D), it is possible that fasciculation of these axons may involve other cell adhesion molecules whose expression is affected in *val*− embryos.

The defective branchiomotor phenotype of *val*− embryos is consistent with the results of gene-disruption experiments in the mouse. In the mouse, the nV neurons are located primarily in r2 and r3, and the nVII neurons are located primarily in r4 and r5. *Krox20*− mutant embryos, in which r3 and r5 are eliminated, have few nV neurons (Schneider-Maunoury et al., 1993). *Hoxa-1*− mutant embryos, in which r5 through r8 are affected and r5 is missing, have severely disorganized nVII neurons (Luftkin et al., 1991; Carpenter et al., 1993). *Hoxb-1*− mutant embryos, in which *Hoxb-1* expression in r4 is eliminated, fail to form the nVII nucleus (Goddard et al., 1996). In mutant embryos, nVII neurons are specified normally in r4, but apparently do not migrate into r5 (Studer et al., 1996), resulting in the absence of the nVII nucleus. Taken together with these results, our analyses demonstrate that rhombomere-specific cues play vital roles in the specification, organization and axonogenesis of the branchiomotor neurons.

**Role of ventral midline cells in branchiomotor neuron specification and axon guidance**

Our analysis of the branchiomotor phenotype in cyc− embryos suggests that ventral midline cells of the neural tube, probably the floor plate cells, play a major role in the specification of branchiomotor neurons and in preventing their axons from crossing the ventral midline (Fig. 9). Previous studies on axonogenesis by well identified spinal neurons and hindbrain reticulospinal neurons have established the importance of ventral midline structures, including the floor plate cells, in axon guidance in the zebrafish (Bernhardt et al., 1992a,b; Hatta, 1992; Greenspoon et al., 1995). Our observation that the nVII axons frequently cross the ventral midline in cyc− embryos is consistent with a role for floor plate cells in their guidance (Colamarino and Tessier-Lavigne, 1995). Indeed, Guthrie and Pini (1995) have shown that chick branchiomotor axons are repelled by ectopic floor plate cells, suggesting a role for floor plate-derived repulsive cues in normal axonogenesis of these neurons. Alternatively, since the nVII axons may fasciculate with the MLF, as demonstrated for other zebrafish axons (Kuwada et al., 1990; Hatta, 1992), the frequent fusion of the MLF in cyc− embryos (Hatta, 1992) may lead to the midline-crossing phenotype of nVII axons in mutant embryos. Misexpression studies with genes encoding growth-cone repelling molecules, which are specifically expressed in the floorplate cells (Halloran et al., 1996), will allow for an assessment of the role of growth cone repulsion in branchiomotor axon guidance.

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