Mutational Analysis of Endothelin Receptor b1 (rose) during Neural Crest and Pigment Pattern Development in the Zebrafish Danio rerio

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Pigment patterns of fishes are a tractable system for studying the genetic and cellular bases for postembryonic phenotypes. In the zebrafish Danio rerio, neural crest-derived pigment cells generate different pigment patterns during different phases of the life cycle. Whereas early larvae exhibit simple stripes of melanocytes and silver iridophores in a background of yellow xanthophores, this pigment pattern is transformed at metamorphosis into that of the adult, comprising a series of dark melanocyte and iridophore stripes, alternating with light stripes of iridophores and xanthophores. Although several genes have been identified in D. rerio that contribute to the development of both early larval and adult pigment patterns, comparatively little is known about genes that are essential for pattern formation during just one or the other life cycle phase. In this study, we identify the gene responsible for the rose mutant phenotype in D. rerio. rose mutants have wild-type early larval pigment patterns, but fail to develop normal numbers of melanocytes and iridophores during pigment pattern metamorphosis and exhibit a disrupted pattern of these cells. We show that rose corresponds to endothelin receptor b1 (ednrb1), an orthologue of amniote Ednrb genes that have long been studied for their roles in neural crest and pigment cell development. Furthermore, we demonstrate that D. rerio ednrb1 is expressed both during pigment pattern metamorphosis and during embryogenesis, and cells of melanocyte, iridophore, and xanthophore lineages all express this gene. These analyses suggest a phylogenetic conservation of roles for Ednrb signaling in the development of amniote and teleost pigment cell precursors. As murine Ednrb is essential for the development of all neural crest derived melanocytes, and D. rerio ednrb1 is required only by a subset of adult melanocytes and iridophores, these analyses also reveal variation among vertebrates in the cellular requirements for Ednrb signaling, and suggest alternative models for the cellular and genetic bases of pigment pattern metamorphosis in D. rerio. © 2000 Academic Press

INTRODUCTION

The mechanisms responsible for patterning phenotypes of adult vertebrates remain largely unknown. Yet, identifying the genes and cell behaviors underlying adult form will be essential for a deeper understanding of normal development, syndromes in which development has gone awry, and the identification of clinical strategies for correcting these problems. A useful system in which to assess later patterning mechanisms is the complex life cycle, in which individuals undergo a metamorphosis some time during their development (Moran, 1994). In a biomedical context, metamorphosis is an outstanding model for postembryonic and fetal development in mammals (Tata, 1993). In a comparative context, a metamorphosis is present in the majority of animals and is most often thought to “decouple” traits expressed at different stages, thereby permitting independent adaptations to different environments and selective regimes (Haldane, 1932; Ebenman, 1992; Moran, 1994). Among vertebrates, both amphibians and fishes undergo a metamorphosis affecting numerous traits, including the
skin, body shape, appendages, and behavior (Webb, 1999; Shi, 2000). Nevertheless, the extent of trait interdependence across stages and how uncoupling might be achieved remain largely unknown (Parichy, 1998).

One trait that undergoes extensive changes at metamorphosis is the pattern formed by neural crest-derived pigment cells in vertebrates. Pigment patterns of fishes and amphibians result from the spatial arrangements of three principal classes of pigment cells: black melanocytes (melanophores); silver iridophores; and yellow xanthophores (Bagnara, 1998; Reedy et al., 1998). In the zebrafish Danio rerio, these cells form very different patterns during different life cycle phases (Kirschbaum, 1975; Milos and Dingle, 1978a; Milos et al., 1983; Johnson et al., 1995b; Kelsh et al., 1996; Parichy et al., 2000). In embryos, neural crest cells differentiate as all three classes of pigment cells to generate an early larval pigment pattern, comprising a series of melanocyte and iridophore stripes, with xanthophores widely distributed over the flank. This pattern remains largely unchanged during early larval development. At \( \sim 14 \) days, however, metamorphic changes in the pigment pattern begin to be manifested. First, beginning between 14 and 21 days, early metamorphic (EM) melanocytes arise dispersed over the flank in regions not previously occupied by these cells (previously referred to as early stripe melanocytes; Johnson et al., 1995b). These cells gradually coalesce at prospective sites of the first adult stripes, dorsal and ventral to the horizontal myoseptum, and simultaneously, early larval melanocytes in this region begin to die. Subsequently, beginning between 21 and 28 days, additional, late metamorphic (LM) melanocytes differentiate already in the position of adult stripes (referred to as late stripe melanocytes; Johnson et al., 1995b). By 30 days, the adult pigment pattern has been established, initially comprising two stripes of melanocytes with overlying iridophores, as well as lighter interstripe regions of xanthophores and iridophores, with additional stripes arising as the fish grow (Fig. 1A).

Recent studies of D. rerio mutants have started to identify genes required for pigment cell development and pigment pattern formation (Kelsh et al., 1996). For example, specification of early larval and adult melanocytes depends on nacre (Lister et al., 1999), an orthologue of the transcription factor-encoding locus mitf, which also is essential for melanocyte specification in mammals (Opdecamp et al., 1997). Early larval and adult pigment patterns also depend on the activities of the ancestrally paralogous genes kit and fms, each encoding receptor tyrosine kinases expressed by pigment cell precursors (Parichy et al., 1999, 2000). Whereas kit is essential for development of early larval melanocytes and EM melanocytes, fms is essential for development of early larval xanthophores and LM melanocytes. Three loci thus have been characterized molecularly that are essential for both early larval and adult pigment pattern development.

In addition to mutations affecting pigment patterns at both life cycle phases in D. rerio, other mutations identify genes that are essential for the pigment pattern in early larvae or adults, but not both. For example, shady mutants lack early larval iridophores, but subsequently develop wild-type adult pigment patterns (Kelsh et al., 1996; Haffter et al., 1996; S.S.L. and R.N.K., unpublished data). Conversely, leopard mutants have wild-type early larval pigment patterns, but develop spots rather than stripes as adults (Kirschbaum, 1975; Johnson et al., 1995b). It is not known how activities of such genes are partitioned across life cycle stages. For example, these loci could represent novel genes, not previously implicated in amniote pigment pattern development, with life cycle stage-specific expression and requirements. Indeed, one such mutant, hagoromo, which perturbs adult but not early larval stripe development, has been identified as a D. rerio orthologue of Dactylin, a gene not previously suspected to have a role in pigment pattern formation (Kawakami et al., 2000). Alternatively, genes with life cycle stage-specific effects could represent orthologues of previously identified genes acting in known genetic pathways. In this event, stage-specific effects presumably would reflect differential regulation of such loci across life cycle phases, specific features of the genetic background (e.g., genetic redundancy and pleiotropic relationships, which may differ from amniotes), or the presence of cryptic cellular populations with differing genetic requirements. Distinguishing between these possibilities will be an essential step in understanding morphological reorganization at metamorphosis in D. rerio, and the genetic and cellular bases for postembryonic development in vertebrates more generally.

One mutant in which visible pigment pattern defects are limited to just a single stage of the life cycle is rose. At early larval stages, rose mutants exhibit pigment patterns indistinguishable from those of wild-type (Johnson et al., 1995b). During pigment pattern metamorphosis, rose mutants also experience an increase in melanocyte number initially similar to that observed in wild-type larvae between days 14 and 21. During later metamorphosis, however, rose mutants develop fewer melanocytes than wild-type between days 21 and 28. Adult rose mutants exhibit only half as many stripe melanocytes as wild-type adults; although these cells are arranged in stripes dorsally, only spots are formed ventrally (Figs. 1B–1D). Consistent with the stages at which phenotypic effects are manifested, genetic analyses suggest that rose is essential for the development of LM melanocytes, but not EM melanocytes (Johnson et al., 1995b; Parichy et al., 2000). Fish doubly mutant for rose and either fms or leopard (which ablate LM melanocytes) do not have more severe melanocyte deficits than single mutants. In contrast, fish doubly mutant for rose and kit (which ablates EM melanocytes), lack virtually all adult melanocytes, indicating additive effects of the two mutations. Rose mutant adults—but not early larvae—also exhibit a severe deficit of iridophores.

Previous analyses mapped the rose mutation to the cen-
tromere of linkage group 1, in the vicinity of endothelin receptor b1 (ednrb1; Johnson et al., 1995a, 1996; Postlethwait et al., 1998). In amniotes, endothelins were initially identified for physiological roles in vasoconstriction (Yanagisawa et al., 1988). These 21-amino acid peptides are the ligands for seven pass G-protein-coupled endothelin receptors, and several endorphins and endothelin receptors now have been identified in amniotes (Arai et al., 1990; Sakurai et al., 1990; Hall et al., 1999; Gether, 2000). An unexpected role for ednrb signaling in neural crest development was discovered when mouse knock-outs of Endothelin receptor B (Ednrb) and endothelin-3 (edn3) were found to lack virtually all melanocytes, and to exhibit aganglionic megacolon due to a failure in the development of neural crest-derived enteric neurons (Baynash et al., 1994; Hosoda et al., 1994). Genetic analysis further indicated that Ednrb and edn3 correspond to piebald lethal (sl) and lethal spotting (ls), respectively, two mouse mutants long studied for their defects in neural crest development (Little, 1915; Mayer and Maltby, 1964; Mayer, 1965, 1967; Pavan and Tilghman, 1994; also see Garvey et al., 1996; Shin et al., 1997). Subsequent analyses have identified roles for endothelin receptor signaling in the proliferation and differentiation of neural crest-derived cells including melanocytes and their precursors, and in promoting the dendricity of fully differentiated melanocytes (Hara et al., 1995; Swope et al., 1995; Lahav et al., 1996, 1998; Reid et al., 1996; Imokawa et al., 1996; Yoshioka et al., 1996; Stone et al., 1997; Opdecamp et al., 1998; Sviderskaya et al., 1998). Moreover, a critical period for Ednrb activity in mouse has been identified during early development, corresponding to the period of neural crest cell dispersal: ablation of Ednrb signaling during or prior to this time results in partial or complete absence of melanocytes, whereas ablation of Ednrb signaling after this time does not result in pigment pattern defects (Shin et al., 1999). Together, these analyses of Ednrb function in amniotes suggest D. rerio ednrb1 as a good candidate for correspondence to rose.

Here, we test the correspondence of rose and ednrb1, and identify cell populations that express ednrb1 in D. rerio. We identify three ednrb1 lesions in three independent rose alleles, strongly supporting the correspondence of rose and ednrb1. Furthermore, we demonstrate that ednrb1 is expressed both during pigment pattern metamorphosis, when pigment pattern defects are first manifested, and, unexpectedly, during embryogenesis as well. Finally, we show that ednrb1 is expressed by melanocytes and their precursors, as well as xanthophore precursors, iridophores, and iridophore precursors. These findings reveal an essential role for ednrb signaling during pigment pattern development in D. rerio, as in amniotes, although in contrast to amniotes, ednrb1 is essential for the development of only a subset of adult pigment cells.

MATERIALS AND METHODS

Fish Rearing and Mutant Alleles

Rearing of D. rerio followed Westerfield (1993). All mutant rose alleles analyzed were recessive. roseb140 was isolated as a spontaneous allele in the AB background, and was provided initially by C. Walker. roseb140, roseb161, and roseb170 are ethylnitrosourea-induced alleles in the SJD genetic background and were identified by noncomplementation of roseb170. ednrb1 expression was also assessed in embryos segregating a mutation in endothelin-1 (kindly provided by C. Miller and C. Kimmel; Miller et al., 2000), and embryos homozygous for fms2bio (Parichy et al., 2000) and shadyv30 (Kelsh et al., 1996).

Cloning, Sequencing, and Phylogenetic Analysis

To clone a D. rerio ednrb1 cDNA, we used degenerate reverse transcriptase PCR to isolate an internal fragment, and then isolated 5' and 3' ends of this transcript by rapid amplification of cDNA ends (RACE) using a commercially available kit and a RACE cDNA library derived from 24-h wild-type embryos (Clontech, Palo Alto, CA). We then used these end sequences to clone and sequence a full-length D. rerio ednrb1 cDNA (Genbank Accession No. AF275636). To test the correspondence of ednrb1 and rose, we compared sequences of PCR-amplified exons from genomic DNA isolated from wild-type and rose mutant backgrounds. To amplify exon sequences, we first designed primers to amplify across the location of introns predicted by comparison with amniote ednrb sequences. We sequenced introns 1-5 in their entirety, but were unable to amplify intron 6. We then used sequence from introns 1-5, as well as 5' and 3' untranslated regions to amplify entire coding sequences from ednrb1 exons 1-6. For exon 7, we designed a 15-nucleotide forward primer immediately 3' to intron 6; our analyses of mutant ednrb1 sequences exclude these 15 nucleotides from consideration. All primer sequences are available upon request. Sequencing was performed using AmpliTaq FS or BigDye (Perkin Elmer, Norwalk, CT) dye terminator chemistry on an ABI-377 automated sequencer, and four to eight individuals were sequenced for each genetic background. Nucleotide and protein sequences were compared against existing databases by BLAST and phylogenetic analyses were performed using PAUP 4.0.0d55 (Swoford, 1999), after inspecting sequences aligned with the Pileup program of the GCG (Genetics Computer Group, Madison, WI) software package.

In Situ Hybridization

Methods for riboprobe preparation and in situ hybridization of embryos have been described (Law et al., 1996), and employed digoxigenin- and fluorescein-labeled riboprobes, alkaline phosphatase-conjugated anti-digoxigenin or anti-fluorescein Fab fragments, and NBT/BCIP (Roche, Indianapolis, IN) or FastRed (Sigma, St. Louis, MO) substrates. Hybridizations were carried out for 12-24 h at 68-72°C, followed by stringency washes at the same temperatures. Larvae older than 5 days were fixed in 4% paraformaldehyde, 5% DMSO in phosphate-buffered saline, and were cut transversely after 30 min to facilitate penetration of reagents. All sectioning was performed after embryos or larvae were stained as described above, then transversely after 30 min to facilitate penetration of reagents. All sectioning was performed after embryos or larvae were stained as described above, then transversely after 30 min to facilitate penetration of reagents. All sectioning was performed after embryos or larvae were stained as described above, then transversely after 30 min to facilitate penetration of reagents. All sectioning was performed after embryos or larvae were stained as described above, then transversely after 30 min to facilitate penetration of reagents. All sectioning was performed after embryos or larvae were stained as described above, then transversely after 30 min to facilitate penetration of reagents. All sectioning was performed after embryos or larvae were stained as described above, then transversely after 30 min to facilitate penetration of reagents. All sectioning was performed after embryos or larvae were stained as described above, then transversely after 30 min to facilitate penetration of reagents. All sectioning was performed after embryos or larvae were stained as described above, then transversely after 30 min to facilitate penetration of reagents. All sectioning was performed after embryos or larvae were stained as described above, then transversely after 30 min to facilitate penetration of reagents. All sectioning was performed after embryos or larvae were stained as described above, then transversely after 30 min to facilitate penetration of reagents. All sectioning was performed after embryos or larvae were stained as described above, then transversely after 30 min to facilitate penetration of reagents.
with either T3 or T7 polymerases (Promega). We also used a 540-bp fragment of D. rerio xanthine dehydrogenase (xdh) for riboprobe synthesis [this gene is also identified as D. rerio expressed sequence tag (EST) fc18g02; Accession Nos. AI657925, AI641077], and D. rerio ESTs to generate a 1200-nucleotide riboprobe for an endothelin-1-like transcript (fa95f03; AI331947, AI330487), and a ~4-kb riboprobe for the receptor tyrosine kinase c-ret (fc36a03; AI793987). A cDNA encoding the microphthalmia-associated transcription factor, mitf/nacre, was provided by D. Raible and J. Lister (Lister et al., 1999).

RESULTS

rose Corresponds to a D. rerio Orthologue of Endothelin Receptor b

Previous studies mapped rose near ednrb1 (Postlethwait et al., 1998); we further mapped rose meiotically within ~0.1 cM of ednrb1 (Fig. 2A). As Ednrb mutants in amniotes exhibit melanocyte deficiencies (see Introduction), we asked whether D. rerio ednrb1 might correspond to an ednrb orthologue, and whether mutations within D. rerio melanocyte stripe and a fragmented ventral melanocyte stripe, as in rose140. (D) rose361 mutant adults have a marginally less severe melanocyte defect, typically having one additional melanocyte stripe compared to rose140 and rose361. Scale bar: 1 cm.

FIG. 2. rose corresponds to a D. rerio orthologue of endothelin receptor B. (A) Meiotic mapping places rose within 0.1 cM of ednrb1 (B) Phylogenetic analyses reveal three clades of endothelin receptor-encoding genes (A, B2, B) and demonstrate that ednrb1 is more closely related to amniote ednrb genes than either ednra or EDRNB2/ETCR genes. Shown is a phylogenetic reconstruction (50% majority rule consensus tree) based on analyses of amino acid sequences (413 informative characters); a similar topology was obtained from analyses of nucleotide sequences (665 informative characters; data not shown). Bootstrap support for all clades is 100% (1000 replicates) except where indicated by numbers above branches. Corresponding sequence gi numbers are (top to bottom): 7521407; 4885323; 416726; 6226779; 1705504; 128383; 232185; 1246127; 119605; 345834; 7549758; 2961105; 507894; 3036823; 539483; 544259; 108668; 6226861; 2144084; 6681269; 7331300; 119622; 1429269; 9858055 ERBP, endothelin receptor type-B-like protein; R37, G-protein-coupled receptor 37; BRS, bombesin receptor subtype; NMB-R, neuromedin-B receptor; GRP-R, gastrin-releasing peptide receptor. (C) Sequence analysis of ednrb1 exons reveals a G → A transversion (arrow) in rose361 predicted to generate a premature stop codon in the sixth transmembrane of Ednrb1. (D) ednrb1 lesions are present in multiple rose mutant backgrounds. Shown are ednrb1 open reading frames in wild-type and each of three rose mutant backgrounds. Premature stop codons were identified in rose361 and rose362, each predicted to result in a null allele. A missense substitution was detected in the phenotypically weaker allele, rose361. Green, predicted signal or transmembrane domains; dark gray, untranslated regions in wild-type cDNA. No lesions were detected in exons amplified from roseb140, rose361, or rose3623277 mutant backgrounds; the nature of these mutations remains unresolved.

FIG. 1. Wild-type and rose mutant adult D. rerio. (A) Wild-type adults exhibit several dark stripes comprising melanocytes and xanthophores, with intervening light stripes comprising xanthophores and iridophores. (B–D) rose mutant adults have fewer melanocytes than wild-type, and these cells form stripes dorsally but spots ventrally. rose mutants also exhibit an iridophore defect, which is especially noticeable lateral to the gills (arrow) and over the abdomen. (B) rose140 adults exhibit a pigment pattern defect but are both viable and fertile as homozygotes. (C) rose361 adults exhibit a similar pigment pattern defect to rose140, but are severely runted. Shown is an individual comparable in age to that shown in (B). rose361 adults that attain larger sizes exhibit only a single dorsal melanocyte stripe and a fragmented ventral melanocyte stripe, as in rose140. (D) rose361 mutant adults have a marginally less severe melanocyte defect, typically having one additional melanocyte stripe compared to rose140 and rose361. Scale bar: 1 cm.
ednrb1 might be responsible for the rose phenotype. We cloned a full-length ednrb1 cDNA, including a 1278-nucleotide open reading frame predicted to encode 426 amino acids. Comparisons of deduced amino acid sequences reveals greater similarity of D. rerio ednrb1 to amniote Ednrb proteins than amniote Ednra proteins (e.g., 71 and 65% amino acid similarity to human ET-B and ET-A, respectively). Additionally, D. rerio ednrb1 is more similar to quail EDNRB than the recently identified, melanocyte lineage-specific quail EDN RB2 (87 and 68% amino acid similarity, respectively). Figure 2B presents a maximum parsimony phylogenetic reconstruction of endothelin
receptor-like genes in vertebrates and reveals a clade of ednrb orthologues, ednrb orthologues, and a clade consisting of quail EDNRB2 and Xenopus ET_3.R. These three distinct clades were evident in maximum parsimony and distance-based UPGMA reconstructions from nucleotide and amino acid sequences, as well as reconstructions based on maximum likelihood analyses of nucleotide sequences (data not shown). Together, these data indicate that D. rerio ednrb1 is more closely related to amniote ednrb genes than either ednra, EDNRB2 (quail), or ET_3.R (Xenopus), and thus can be considered a D. rerio orthologue of ednrb.

To test the correspondence of rose and ednrb1, we amplified ednrb1 coding sequences from genomic DNA isolated from wild-type and rose mutant backgrounds. This analysis revealed ednrb lesions in three rose alleles (Figs. 2C, 2D). In both rose363 and rose364, premature stop codons are likely to result in null alleles (Gether, 2000). In rose365, a nonconservative Ala → Gln substitution is present at a site that is otherwise invariant in all endothelin receptors (Fig. 2B), suggesting that this substitution is likely to be functionally significant. Consistent with these inferences, rose363 homozygotes are severely runted (suggesting additional, nonpigmentary roles for ednrb1) whereas rose363 homozygotes are vigorous and often exhibit less severe pigment pattern defects compared to either rose363 or rose364 (Fig. 1). We did not identify a lesion within coding sequences of the spontaneous allele rose364 although homozygous rose364 exhibit greatly reduced levels of ednrb1 mRNA compared to wild-type (data not shown). Although the nature of this mutation remains unresolved, the pigment pattern defect in these fish is similar to that of rose363. Together, these data strongly suggest that rose corresponds to a zebrafish orthologue of ednrb.

ednrb1 is Expressed by the Neural Crest—Melanocyte Lineage

Although ednrb1 mutant D. rerio do not exhibit defects in the early larval pigment pattern, ednrb genes of murine and avian embryos are expressed by premigratory and early migrating neural crest cells (Nataf et al., 1996; Brand et al., 1998; Southard-Smith et al., 1998; Lecoin et al., 1998). To test whether D. rerio neural crest cells similarly express ednrb1, we examined the distribution of ednrb1+ cells by in situ hybridization during embryogenesis. By 18 h, ednrb1+ cells are present in the position of premigratory neural crest cells along the trunk dorsal neural tube. Subsequently, ednrb1+ cells are present in neural crest migratory pathways during the stages of neural crest cell migration, consistent with a neural crest origin: ednrb1+ cells are visible in a ventromedial neural crest migratory pathway (between somites and neural tube or notochord) several hours before they are visible in a dorsolateral neural crest migratory pathway (between somites and epidermis), concordant with the relative time of neural crest cell dispersal into these two pathways (Raible and Eisen, 1994). More anteriorly, ednrb1+ cells are abundant during these stages at sites of neural crest origin both at the midbrain–hindbrain boundary and immediately posterior to the otic vesicles (Schilling and Kimmel, 1994). Relatively few ednrb1+ cells are observed over the hindbrain.

Since Ednrb promotes the development of melanocytes during embryonic stages in amniotes (Pavan and Tilghman, 1994; Shin et al., 1999), we asked whether cells in the melanocyte lineage express ednrb1 in D. rerio. To test this possibility, we used two-color in situ hybridization to stain simultaneously for ednrb1 and three different markers of the melanocyte lineage: kit, which encodes a type III receptor tyrosine kinase required for normal melanocyte migration and survival (MacKenzie et al., 1997; Parichy et al., 1999); mitf, which encodes a basic helix–loop–helix–zipper transcription factor essential for melanocyte specification (Opdecamp et al., 1997; Lister et al., 1999); and dct, which encodes an enzyme in the melanin synthesis pathway (Steel et al., 1992; Kelsh et al., 2000). These analyses reveal cells that coexpress ednrb1 and kit (Fig. 3C), ednrb1 and mitf (data not shown), and ednrb1 and dct (Fig. 3D) as early as 24 h. During later development through ~48 h, ednrb1 expression is also detectable in lightly melanized melanocytes that coexpress dct (Fig. 3F). Thus, ednrb1 is expressed by cells in the neural crest–melanocyte lineage in the zebrafish embryo.

Coordinate Expression of ednrb1 and endothelin-1

Ednrb-type receptors exhibit affinity for endothelin-1, endothelin-2, and endothelin-3 ligands (Sakurai et al., 1990; Takasuka et al., 1994). In vivo, avian endothelin-3 and amniote endothelin-1 and endothelin-3 are expressed at sites consistent with roles in promoting melanocyte development via Ednrb-mediated signal transduction, and in vitro, endothelin-3 and endothelin-1 are equally effective at promoting melanocyte development (Swope et al., 1995; Reid et al., 1996; but see Brand et al., 1998). In D. rerio, we identified an EST similar to that of endothelin-1 genes of amniotes. Phylogenetic analyses using this nucleotide sequence and the exclusively mammalian endothelin sequences available in GenBank tend to place the D. rerio sequence as the basal-most member in a clade of endothelin-1 orthologues (60% of 1000 bootstrap replicates using parsimony based reconstruction from 220 informative characters). A UPGMA phenogram similarly clusters the D. rerio EST with mammalian endothelin-1 genes (data not shown). This EST is thus likely to represent a D. rerio endothelin-1 orthologue.

To test a potential role for D. rerio endothelin-1 in signaling to ednrb1+ neural crest cells, we examined the expression of endothelin-1 during embryonic stages. As early as 12 h, we observe endothelin-1 expression within the mid-trunk neural keel (data not shown), in addition to other sites of expression reported previously (Miller et al., 2000). During subsequent development through at least 32 h, endothelin-1 expression gradually diminishes anteriorly and increases posteriorly, and at a given axial level is
detectable slightly before ednrb1 expression in overlying neural crest cells (Figs. 3F–3H). The expression of D. rerio endothelin-1 thus differs from that in amniotes, in which endothelins presumed to have roles in neural crest development are expressed by epidermis or mesoderm lining neural crest migratory pathways (Brand et al., 1998; Nataf et al., 1998a,b). The spatial and temporal patterns of ednrb1 and endothelin-1 expression are consistent with a role for endothelin-1-mediated signaling during neural crest development in D. rerio (particularly since endothelin precursors must first be processed proteolytically to generate active endothelin peptides; Baynash et al., 1994). Nevertheless, molecular genotyping of embryos and early larvae segregating an endothelin-1 mutation did not reveal gross alterations in ednrb1 expression or numbers of differentiated pigment cells in homozygous endothelin-1 mutants compared to heterozygous or wild-type individuals (data not shown; also see Miller et al., 2000). Thus, endothelin-1 may promote—but is not essential for—the development of ednrb1+ neural crest cells.

### ednrb1 Is Expressed by Xanthophore Precursors and Iridophores

Ednrb signaling in amniotes promotes the development of multiple neural crest-derived cell types (Hosoda et al., 1994; Stone et al., 1997), raising the possibility that ednrb1 might contribute to the development of other neural crest-derived cell types in D. rerio as well. Ectothermic vertebrates have two additional major classes of neural crest-derived pigment cells, yellow xanthophores, and silver iridophores, which derive their coloration from pteridine pigments and purine-containing reflecting platelets, respectively (Bagnara, 1998; Reedy et al., 1998). Thus, we asked whether ednrb1 is expressed by these nonmelanocyte lineages. To test whether ednrb1 is expressed by xanthophores or their precursors, we used two-color in situ hybridization with probes for ednrb1 and fms, which is expressed by cells in the xanthophore lineage (Parichy et al., 2000). We find numerous cells that coexpress ednrb1 and fms (Fig. 4A). To further test whether these are xanthophore precursors, we examined the distribution of ednrb1+ cells in fms mutant embryos, in which xanthophore precursors fail to disperse from the neural crest (Parichy et al., 2000). In contrast to wild-type, fms mutant embryos exhibit abnormal accumulations of ednrb1+ cells at the midbrain–hindbrain boundary, where many xanthophore precursors originate (Fig. 4C). Further posteriorly, between 28 and 48 h of development, fms mutant embryos also lack unmelanized ednrb1+ cells that are present between melanocyte stripes in wild-type embryos, and fms mutants exhibit greater numbers of ednrb1+ cells in a nondispersed position along the dorsal myotomes (Fig. 4D). Finally, since fms may be expressed by precursors to other pigment cell classes as well, we also tested for coexpression of ednrb1 and xdh, which encodes an enzyme involved in the synthesis of pteridine pigments contained by xanthophores (Reaume et al., 1991; Ziegler et al., 2000). Two-color in situ hybridization reveals numerous cells expressing both ednrb1 and xdh (Fig. 4B). Together, these data indicate that ednrb1 is expressed by xanthophore precursors in the zebrafish embryo.

The iridophore defect in adult ednrb1 mutant D. rerio raised the possibility that ednrb1 might be expressed by iridophores or their precursors as well. Iridophores lose their reflecting platelets during processing for in situ hybridization and molecular markers specific to iridophores have not been described. To test whether iridophores express ednrb1, we thus compared the positions of iridophores prior to fixation with the positions of ednrb1+ cells in embryos processed individually for in situ hybridization (N = 15). Figure 4E shows the correspondence of iridophores and ednrb1+ cells in a 3-day wild-type larva (a stage when ednrb1 expression is diminished in melanocytes and xanthophore precursors). Thus, differentiated iridophores express ednrb1. As an independent test of this inference, we also compared ednrb1 expression between wild-type and shady mutant embryos and larvae, which lack iridophores but not other pigment cell classes prior to 3 weeks (Kelsh et al., 1996; S.S.L. and R.N.K., unpublished data). In contrast to wild-type, shady mutants lack unmelanized cells expressing high levels of ednrb1 along the dorsal midline and within other larval stripes where iridophores are found at 72 h (Fig. 4F). An absence of unmelanized ednrb1+ cells in shady embryos is also observed at 48 h, a stage at which most differentiated iridophores have not yet become visible (data not shown). Together, these data indicate that ednrb1 is expressed by iridophores and their precursors during normal pigment pattern development in D. rerio.

Although amniote Ednrbas also promote the development of neural crest-derived enteric neurons (Hosoda et al., 1994), we do not observe coexpression of ednrb1 and the neuronal marker c-ret (Bisgrove et al., 1997; Kelsh and Eisen, 1999) at any of 7 time points examined between 19 and 72 h; however, we do not exclude the possibility of coexpression at levels below the threshold of detection (D.M.P. and J.F.R., unpublished data).

### ednrb1 Is Expressed during Pigment Pattern Metamorphosis

Despite the absence of any gross pigment pattern defects in ednrb1 mutant embryos, ednrb1 mutant adults exhibit a severe deficit of iridophores and a severe reduction in melanocyte number compared to wild-type (Fig. 1; Johnson et al., 1995b; Parichy et al., 2000). This could reflect a failure in the development of precursors that normally would arise due to Ednrb signaling at embryonic stages. Or, the pigment pattern defects arising during the development of the adult pigment pattern could reflect a later requirement for ednrb1. To investigate this possibility, we tested whether ednrb1 is expressed by cells in melanocyte or iridophore lineages during pigment pattern metamorphosis. In situ hybridization during early stages of pigment pattern metamorphosis...
metamorphosis (14–21 days) reveals a horizontal stripe of ednrb1+ cells coincident with the position of the first adult iridophore stripe, suggesting that these cells are iridophores or their precursors (Figs. SA, 5C–5E). Additionally, scattered ednrb1+ cells are present elsewhere over the flank and some of these are lightly melanized, indicating that ednrb1 also is expressed by the melanocyte lineage during metamorphosis (Fig. 5B). During later stages (22–30 days), ednrb1 continues to be expressed by densely packed unmelanized cells between melanocyte stripes, as well as less densely packed cells that are widely dispersed in the skin (Fig. 5F).

Analysis of ednrb1 expression in cryosections during these stages indicates that dense staining for ednrb1 occurs adjacent to melanocyte stripes, and these cells occupy a similar plane to stripe melanocytes, immediately superficial to the myotomes (Fig. 5G). In contrast, dispersed ednrb1+ cells occur more superficially in the dermis, and are frequently associated with the inner surface of dermal
scales (Fig. 5H). Many of these unmelanized ednrb1-1 cells are likely to be iridophores that contribute to the zebrafish adult pigment pattern or melanocyte precursors. Together, these data indicate that ednrb1 is expressed both during embryogenesis and during pigment pattern metamorphosis by cells of the melanocyte and iridophore lineages.

**DISCUSSION**

The results of this study identify roles for an endothelin receptor B orthologue during pigment pattern development in *D. rerio*. These findings have implications for our understanding of roles for endothelin receptors during pigment pattern development in amniotes and teleosts, and suggest two alternative models for the molecular and cellular bases of pigment pattern metamorphosis in *D. rerio*.

**ednrb1 Is Essential for Pigment Pattern Development in *D. rerio***

Studies of amniotes have implicated ednrb-like genes in promoting the development of cells in the neural crest–melanocyte lineage (e.g., Shin et al., 1999). Our finding of three independent ednrb1 lesions in three different rose alleles strongly suggests a correspondence of rose and ednrb1 in *D. rerio*, and, in turn, reveals a phylogenetic conservation of endothelin receptor-mediated signaling across amniote and teleost lineages. These findings thus extend previous studies demonstrating conserved genetic pathways during the development of neural crest and pigment cells across even widely divergent groups of vertebrates (e.g., Lahav et al., 1994; Liem et al., 1995; Wehrle-Haller and Weston, 1995; Opdecamp et al., 1997; Lister et al., 1999; Parichy et al., 1999; Nguyen et al., 2000). These observations lend further credence to the notion that studies of the genetically tractable organism *D. rerio* may provide insights relevant not only to normal amniote development but also human disease syndromes (Kelsh and Eisen, 1999; Dooley and Zon, 2000). Moreover, as an additional genome duplication in teleosts appears to have furnished paralogous genes with, in some instances, the partitioning of gene activities (Force et al., 1999; de Martino et al., 2000), *D. rerio* mutants also may exhibit fewer pleiotropic effects than mutants of orthologous amniote loci, facilitating studies of defects associated with particular cell types or organ systems. For example, *D. rerio* kit mutants

![FIG. 5. ednrb1 is reexpressed during pigment pattern metamorphosis.](image-url)

(A) A wild-type metamorphosing larva exhibits a bright stripe of iridophores (arrow) immediately ventral to the horizontal myoseptum and between the first developing dorsal and ventral melanocyte stripes. Shown is the posterior trunk of an 18-day larva. (B) Lightly melanized melanocytes express ednrb1 during pigment pattern metamorphosis. Shown are ednrb1+ (blue) melanocytes in flat-mounted skin from a 20 day larva. An additional dark melanocyte can be seen deeper within the larva and out of the plane of focus. (C) ednrb1 is strongly expressed by cells coincident with the developing first iridophore stripe (arrow) immediately ventral to the horizontal myoseptum. Shown is a 21-day larva. (D) A 12-μm cryosection through the trunk of a larva at the stage in (A). Blue ednrb1+ cells can be seen superficial to the myotome (m) and beneath the epidermis near the horizontal myoseptum (h). (E) Higher magnification view of the bracketed region in (D), showing ednrb1+ cells between the myotome (m) and epidermis (e). Spatial resolution among these cells does not allow distinguishing whether faint melanin deposition is associated with ednrb1+ cells or intermingled cells that may not express ednrb1. (F) During later stages of pigment pattern metamorphosis (here, 28 days), ednrb1 expression is maintained between melanocyte stripes and also is evident at lower levels within melanocyte stripes. (G) Cryosection of a similarly staged larva reveals ednrb1+ cells (arrowheads) in the same plane as melanocytes that contribute to dark horizontal stripes. Arrow, dermal scale. (H) Unmelanized ednrb1+ cells (arrowhead) also are evident superficial to stripe melanocytes, associated with the inner surface of scales. Scale bars: (A) 400 μm; (B) 10 μm; (C,F) 100 μm; (D) 100 μm; (E) 10 μm; (G,H) 20 μm.
have defects in melanocyte morphogenesis, but lack the pleiotropic effects on hematopoiesis and gametogenesis that complicate studies of Kit signaling during development of the amniote neural crest–melanocyte lineage (Parichy et al., 1999). Similarly, Ednrb mutations in mouse and human are associated with aganglionic mega-Sor as well as pie-baldism, and null alleles are lethal (Puffenberger et al., 1994; Jackson, 1997; Spritz, 1998). Studies of roles in pigment cell morphogenesis and differentiation during later stages of development are thus complicated by neonatal lethality due to defects in the enteric nervous system. Our results show that in D. rerio, however, even ednrb1 presumptive null mutants (such as ednrb<sup>316c</sup>) are viable and survive through adult stages (perhaps reflecting the existence of additional ednrb homologues; see below), and this will permit a fuller assessment of roles for Ednrb-mediated signaling in the development of pigment cell lineages.

Our identification of roles for ednrb1 in pigment pattern development in D. rerio suggests a conservation of molecular mechanisms for pigment cell development across vertebrates. Yet, our analyses also reveal interspecific variation in the timing of endothelin receptor expression. Several endothelin receptor-encoding loci have been identified in other taxa, including ednra and ednrb orthologues of mammals and birds, and more recently, a second ednrb-like gene, EDNRB2, of quail, and ET<sub>c</sub>R, of Xenopus laevis, encoding an endothelin-3-specific receptor. Phylogenetic analyses of endothelin receptor genes revealed a clade consisting of ednrb orthologues, including D. rerio ednrb1, and a separate clade comprising quail EDNBR2 and Xenopus ET<sub>c</sub>R. In D. rerio, we observe ednrb1 expression by early migrating neural crest cells as well as melanoblasts and early differentiated melanocytes in both dorsolateral and ventromedial migratory pathways. In contrast, amniote ednrb orthologues are expressed by early migrating neural crest cells and do not appear to be expressed by melanocyte precursors that have entered the dorsolateral neural crest migratory pathway (although dct<sup>+</sup> melanoblasts express Ednrb1 in vitro; Nataf et al., 1996; Southard-Smith et al., 1998; Opdecamp et al., 1998; Shin et al., 1999), whereas avian EDNRB2 is expressed by melanoblasts migrating in the dorsolateral neural crest migratory pathway as well as differentiated melanocytes, and ET<sub>c</sub>R is expressed by differentiated X. laevis melanophores (Karne et al., 1993; Lecoin et al., 1998). Thus, ednrb1 expression during early development in D. rerio has characteristics of both ednrb- and EDNRB2-class genes in amniotes.

ednrb1 Mutant Phenotype Suggests Alternative Models for Pigment Pattern Development

Our finding that rose corresponds to ednrb1 and our analyses of ednrb1 expression relative to other loci suggest potential roles for this gene in the development of neural crest-derived cell lineages, and also provide insights into the mechanisms of pigment pattern metamorphosis. The appearance of a mutant phenotype only during the development of the adult pigment pattern raised the possibility that the rose locus might be expressed only during metamorphosis. The embryonic and early larval expression of ednrb1 by cells of melanocyte, iridophore, and xanthophore lineages is thus somewhat unexpected. Since ednrb1 mutant early larvae do not exhibit gross pigment pattern defects, these observations point to a possible nonessential role in the development of early larval pigment cells. For example, genetic redundancy could allow a defect in ednrb1 signaling to be compensated for by the activity of a paralogous locus (see below). Or, morphogenetic redundancy could allow compensation via other genetic pathways; e.g., a loss of ednrb1 signaling that normally stimulates proliferation might be overcome by enhanced kit signaling that also stimulates proliferation (Reid et al., 1996; Kelsh et al., 2000; Rhim et al., 2000). Alternatively, ednrb1 mRNA expression in these cells during embryogenesis may be gratuitous (Cavener, 1989) and may not reflect the potential for ednrb1-mediated signaling (e.g., if post-transcriptional processing does not occur, or if ednrb1 is required by neural crest cells only prior to the expression of lineage-specific molecular markers). In either event, these findings contrast with studies of murine embryos, in which Ednrb is required by virtually all melanocyte precursors such that a failure of Ednrb signaling results in a near complete absence of melanocytes and melanoblasts (Hosoda et al., 1994). Moreover, the requirement for murine Ednrb strictly during neural crest migration (Shin et al., 1999) and the immediate manifestation of defects in Ednrb mutants (Pavan and Tilghman, 1994) differ from D. rerio, in which the ednrb1 mutant phenotype arises only late in development (although our study cannot address the temporal requirement for ednrb1 activity in D. rerio).

In contrast, the melanocyte and iridophore defects in adult ednrb1 mutants reveals an essential role for this gene in adult pigment pattern development. This finding prompts two related questions: (i) how does ednrb1 promote the development of these pigment cells? and (ii) how are these effects partitioned across life cycle stages to influence the adult phenotype, but not the early larval phenotype? Below, we suggest two models for the genetic and cellular bases of ednrb1 activity during pigment pattern development in D. rerio. Although we focus on melanocytes for simplicity, neither model specifies the differential potential of individual ednrb1<sup>+</sup> cells. These cells could be competent to differentiate as both melanocytes and iridophores, or cells could be committed to only one or the other cell lineage.

In the first model, ednrb1 is essential for promoting the development of only one of two or three distinct populations of pigment cell precursors. In this model, ednrb1 is not required by precursors that generate the early larval pigment pattern, or by precursors to EM melanocytes (14–21 days), but is required by precursors to LM melanocytes (21–28 days). One way in which such genetically distinct populations of precursors might arise is through partially redundant gene activity. Specifically, if an ednrb1
paralogue is present in D. rerio and expressed by early larval and EM melanocyte precursors, such a locus could allow the development of these cells even when ednrb1 activity is abolished. In turn, a failure of LM melanocyte precursors to express such a paralogue could explain the abolished. In turn, a failure of LM melanocyte precursors to activate the second phase of pigment pattern metamorphosis. Thus, a single ednrb1-dependent population contributes to early larval pigment pattern formation and during the entire period of pigment pattern metamorphosis. Therefore, a single ednrb1-dependent population contributes to early larval melanocytes, cytohesin, and LM melanocytes. This model postulates that in ednrb1 mutants, which develop early larval and EM melanocytes but not LM melanocytes, only enough precursors are generated to supply melanocytes during embryonic development and the first phase of pigment pattern metamorphosis; the supply is exhausted by the second phase of pigment pattern metamorphosis. Should an ednrb1 paralogue exist, its activity presumably would be insufficient to fully expand this single population of precursors when ednrb1-mediated signaling is lost. Isolation of new molecular markers for pigment cell precursors as well as screening for additional ednrb orthologues and analyses of temporal requirements for their activities will help to distinguish between these models.

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