The C. elegans POU-domain transcription factor UNC-86 regulates the tph-1 tryptophan hydroxylase gene and neurite outgrowth in specific serotonergic neurons

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SUMMARY

A fundamental question in developmental neurobiology is how a common neurotransmitter is specified in different neuronal types?. We describe cell-specific regulation of the serotonergic phenotype by the C. elegans POU-domain transcription factor UNC-86. We show that unc-86 regulates particular aspects of the terminal neuronal identity in four classes of serotonergic neurons, but that the development of the ADF serotonergic neurons is regulated by an UNC-86-independent program. In the NSM neurons, the role of unc-86 is confined in late differentiation; the neurons are generated but do not express genes necessary for serotonergic neurotransmission. unc-86-null mutations affect the expression in NSM of tph-1, which encodes the serotonin synthetic enzyme tryptophan hydroxylase, and cat-1, which encodes a vesicular transporter that loads serotonin into synaptic vesicles, suggesting that unc-86 coordinately regulates serotonin synthesis and packaging. However, unc-86-null mutations do not impair the ability of NSM to reuptake serotonin released from the ADF serotonergic chemosensory neurons and this serotonin reuptake is sensitive to the serotonin reuptake block drugs imipramine and fluoxetine, demonstrating that serotonin synthesis and reuptake is regulated by distinct factors. The NSM neurons in unc-86-null mutants also display abnormal neurite outgrowth, suggesting a role of unc-86 in regulating this process as well.

Key words: C. elegans, POU domain, Transcription, Neuron identity, Neurotransmitter, Serotonin, Serotonin reuptake inhibitors, Axon guidance

INTRODUCTION

Serotonin (5-hydroxytryptamine; 5-HT) is a monoamine neurotransmitter that regulates mood, aggression, satiety and body temperature (for a review, see Lucki, 1998). Drugs that modulate serotonin signaling are potent antidepressants and affect rates of metabolism (Gray et al., 1992; Kaye et al., 1998; Leibowitz and Alexander, 1998). In both vertebrates and invertebrates, serotonergic neurons represent a small population of neurons with diverse morphology and function. The specification of serotonergic phenotypes appears to be a terminal differentiation event – in general, serotonin production starts about 24 hours or later after the neurons exit from the cell cycle (Lidov and Molliver, 1982; Marois and Carew, 1997; Lundell and Hirsh, 1994). Some components of neuronal identity must be shared by all classes of serotonergic neurons, such as enzymes that synthesize serotonin, transporters that load serotonin into synaptic vesicles and that reuptake extracellular serotonin. Others may be restricted to a particular class of serotonergic neuron, such as receptors to specific synaptic inputs and factors mediating axon pathfinding. Factors required for early stages of the development of serotonergic neurons are beginning to be elucidated (Matise et al., 1998; Ye et al., 1998; Van Doorninck et al., 1999; Briscoe et al., 1999; Hynes and Rosenthal, 1999). An intriguing issue is whether there are ‘master’ genes that switch on serotonergic phenotypes in all neuronal classes or whether different regulatory genes for each neuronal type coordinately regulate transmitter and other aspects of the final neuronal identity.

The nematode C. elegans has a relatively simple serotonergic system. Of 302 neurons in an adult hermaphrodite, nine neurons of five distinct classes are detected with antibodies raised against serotonin (Horvitz et al., 1982; Desai et al., 1998; Sze et al., 2000). Biosynthesis of serotonin in C. elegans requires the tph-1 gene, which encodes a tryptophan hydroxylase that catalyzes the first and rate-limiting step of serotonin biosynthesis (Sze et al., 2000). tph-1 is expressed in the serotonergic neurons, and...
animals bearing a tph-1 deletion mutation show no detectable serotonin immunoreactivity (Sze et al., 2000). The cat-1 gene encodes a vesicular monoamine transporter that loads serotonin into synaptic vesicles and is important for serotonin signaling (Duerr et al., 1999; Nurrish et al., 1999).

The POU-domain transcription factor UNC-86 is expressed in 57 neurons throughout the life of the animal, including the NSM, AIM, RIH and HSN serotonergic neurons (Finney et al., 1988; Finney and Ruvkun, 1990). A transcriptional cascade downstream of UNC-86 in the touch receptor neurons has been characterized: UNC-86 continuously regulates the expression of the LIM-homeobox gene mec-3 (Way and Chalfie, 1989; Xue et al., 1992), and UNC-86-MEC-3 complex regulates touch receptor specific components, such as the MEC-7 β-tubulin and MEC-4 ion-channel (Duggan et al., 1998), to specify and maintain mechanosensory function. These studies indicate that UNC-86 may interact with cell-specific co-factors to regulate specific neuronal components. The mammalian unc-86 orthologs, Brn3a/Pou4f1 and Brn3b/Pou4f2, also mediate development, maintenance and function of the endocrine and nervous systems (for a review, see McEvilly and Rosenfeld, 1999) and regulate the expression of axon guidance genes (Lakin et al., 1995; Smith et al., 1997a; Erkman et al., 2000). Although it has been shown that unc-86 is required for the maturation of the HSN neurons (Desai et al., 1988), the role of unc-86 in determining the serotonergic neural fate has not been analyzed.

There are several examples that homeodomain transcription factors act in postmitotic cells to specify neurotransmitter phenotypes in particular neurons. In C. elegans, UNC-30 directly regulates the expression of genes encoding GABA synthetic enzyme glutamate decarboxylase and vesicular GABA transporter in just one class of the neurons (Eastman et al., 1999), whereas GABAergic phenotype in the other neurons requires the LIM-factor LIM-6 (Hobert et al., 1999). Similarly, in Drosophila, islet acts in subsets of ventral cord neurons to specify the serotonergic and dopaminergic neural fates (Thor and Thomas, 1997), and the POU-domain factor Cjlu regulates the dopamine decarboxylase gene in specific dopaminergic neurons (Johnson and Hirsh, 1990).

We describe the effect of unc-86-null mutations on serotonin synthesis, packaging and reuptake in a subset of the serotonergic neurons. The results from this study support the notion that serotonergic phenotypes in different neurons may be regulated by different transcription factors, and within the same neuron serotonin biosynthesis, packaging, reuptake, and other properties are regulated by distinct regulatory programs.

**MATERIALS AND METHODS**

Worm strains

The strains used in this study were wild-type C. elegans Bristol strain (N2), unc-86(n846), unc-86(e1416), tph-1(mg280) and nss-1(yz12). Constructs
tph-1-ABCDE::gfp is a translation fusion of the tph-1 genomic sequence encompassing 3.1 kb 5'-upstream sequence from the translation start to the beginning of exon 4 and GFP in pPD95.75 (Sze et al., 2000). tph-1-BCDE::gfp, tph-1-CDE::gfp, tph-1-DE::gfp and tph-1-E::gfp are PCR fragments amplified using tph-1-ABCDE::gfp as a template. The forward PCR primers correspond to the particular region of the tph-1 5'-upstream sequence as indicated in Fig. 4, and the reverse primers correspond to the sequence downstream of the unc-54 3'-uncoding sequence in pPD95.75 (A. Fire). Deletion of the region D in tph-1-BCDE::gfp was generated by fusing the fragments corresponding to the region BC and tph-1-E::gfp, using PCR with primers containing the joint site sequence. tph-1-::gfp is a translation fusion of a predicted GTP-cyclohydrolase 1 (gtpch-1) and GFP. The sequence of gtpch-1 is the cosmids F32G8.6, and the structure of GTP-cyclohydrolase was predicted by Genefinder (C. elegans Sequencing Consortium, 1998). The gtpch-1 sequence including 2 kb upstream from the predicted translation start to amino acid 63 of predicted gtpch-1 in exon 2 was amplified from N2 genomic DNA, using PCR. The amplified gtpch-1 fragment was fused to GFP and unc-54 3'-uncoding sequence in pPD95.75, by PCR with primers containing the joint site sequence. The PCR amplified fusion products were directly used to generate transgenic animals.

**GFP expression**

The expression of GFP was observed in transgenic animals carrying individual GFP fusion gene constructs. The transgenic animals were generated by microinjection of the GFP fusion genes into wild-type animals, with the plasmid pRF4 that contains the dominant Rol-6 gene co-injected as a genetic marker for the transgene (Mello et al., 1991). The plasmid containing tph-1-ABCDE::gfp construct was injected at 50 ng μl−1, the PCR products of GFP fusion were injected without dilution, and pRF4 was injected at 100 ng μl−1. The tph-1-ABCDE::gfp transgene was integrated to wild-type chromosome (Sze et al., 2000); four independent integrated lines were obtained. All other GFP reporters were transmitted as extrachromosomal arrays. For each construct, two to four transgenic lines were examined. To determine the effect of unc-86 and tph-1 on the GFP expression, two lines of each GFP construct were crossed into unc-86(n846), unc-86(e1416) and tph-1(mg280).

**Imunoanalysis**

The serotonin antibody staining was performed using a whole-mount procedure as described (McIntire et al., 1999; Sze et al., 2000). For imipramine and fluoxetine experiments, the drugs were dissolved in distilled water and the solution was poured onto NG agar plates with a lawn of E. coli OP50. After the drug plates were dried for 2 hours, worms were washed off from their culture plates and transferred onto the drug plates, incubated at 20°C for 12-16 hours, then fixed for the antibody staining. Initially, we incubated worms on the plates containing imipramine at the final concentration of 0.75 mg ml−1, and fluoxetine at 1 mg ml−1 (Weinshenker et al., 1995). We found that worms did not move much and tended to group together, thus they may not be able to access the drugs fully. Therefore, we reduced imipramine to 0.4 mg ml−1 and fluoxetine to 0.5 mg ml−1. The control animals were raised in parallel but without drug treatments. The staining was carried out many times; every time animals treated with or without drugs were stained in parallel. The summary of two most recent trials is reported here (Table 1; Fig. 3).

**Isolation of nss-1(yz12) and construction of nss-1(yz12); unc-86**

nss-1(yz12) was isolated from a genetic screen for genes that regulate tph-1 expression in specific serotonergic neurons. We mutagenized wild-type hermaphrodites carrying integrated tph-1-ABCDE::gfp with ethyl methanesulfonate, and F2 progeny that failed to express GFP were isolated. nss-1(yz12) and 23 other mutants were identified based on the reduction/absence of GFP in the ADF chemosensory neurons from screening of about 6500 haploid genomes. None of the mutants showed 100% absence of GFP expression in ADF, but nss-1(yz12) and five other mutants showed relatively high penetrance. nss-1(yz12) mutants have been backcrossed four times. About 65-90% of the backcrossed yz12 animals showed no GFP or weak GFP in ADF; whereas the GFP expression in NSM and HSN was equivalent to that
in wild-type (n>200). The nss-1(ycz12) mutation is recessive and mapped to the X chromosome. Double mutants of unc-86(n846) or unc-86(e1416) and nss-1(ycz12) were constructed by following the Mec phenotype of unc-86 (Chalfie and Au, 1989) and the lack of tph-1::gfp expression in ADF of nss-1(ycz12). In each case, the strain was confirmed by outcrossing the double mutants and reisolating the single mutations.

RESULTS

unc-86 regulates tph-1 expression in a subset of the serotonergic neurons

Of five classes of the neurons that accumulate serotonin, four classes express the transcription factor UNC-86: the NSM neurons, a pair of pharyngeal secretory neurons that modulate feeding behavior; the HSN neurons, a pair of motoneurons that mediate egg-laying behavior; and a single RIH and a pair of the AIM interneurons in the head region (Avery and Horvitz, 1989; Desai et al., 1988; White et al., 1986). UNC-86 expression begins in the precursor of the NSM neurons, but in AIM, RIH and HSN, UNC-86 expression is initiated in the postmitotic differentiating neurons. In all these neurons, UNC-86 expression is maintained throughout the life of the animal (Finney and Ruvkun, 1990).

UNC-86 is not required for the generation of these serotonergic neurons. For example, the NSM, AIM and RIH neurons are generated and have no obvious morphological defects in unc-86-null mutants (Finney and Ruvkun, 1990). In an unc-86-null mutant, the HSN neurons are generated but do not acquire adult HSN features (Desai et al., 1988).

The tph-1 gene encodes a tryptophan hydroxylase, which is required for serotonin biosynthesis (Sze et al., 2000). This gene is expressed in the serotonergic neurons as they begin to accumulate serotonin (Sze et al., 2000). To assess whether unc-86 specifies the serotonergic phenotype in these neurons, we used a GFP fusion to tph-1 to examine the effect of unc-86-null mutations on tph-1 expression. A tph-1::gfp fusion gene is expressed in ADF, NSM, HSN and very weakly in RIH and AIM (Sze et al., 2000) (Fig. 1). We crossed the tph-1::gfp fusion gene into two unc-86-null alleles, n846 and e1416. In both unc-86-null alleles, GFP expression was only observed in the pair of the ADF neurons (Fig. 1), which do not express unc-86. To ensure that the lack of GFP expression was not due to a defect in the fusion gene, we examined GFP expression from two independent tph-1::gfp integrant lines and from extrachromosomal arrays. No GFP was observed in unc-86-expressing cells at any developmental stage of unc-86-null mutants. These observations suggest that UNC-86 is specifically required for tph-1 expression in unc-86-expressing neurons.

unc-86-null mutations also affect the expression of the CAT-1 serotonin vesicular transporter

The C. elegans homeobox gene unc-30 coordinately regulates the expression of the GABA synthetic enzyme glutamate decarboxylase and GABA vesicular transporter (Eastman et al., 1999). In both vertebrates and invertebrates, the genes encoding choline acetyltransferase and acetylcholine vesicular transporter are co-regulated by a common promoter (Rand, 1989; Eiden, 1998; Kitamoto et al., 1998). To determine whether genes for serotonin synthesis and packaging also are coordinately regulated, we examined the effect of unc-86-null mutations on the expression of the cat-1 vesicular monoamine transporter gene, which transports serotonin, dopamine and perhaps other monoamine neurotransmitters (Duerr et al., 1999; Nurrish et al., 1999).

cat-1::gfp is a functional fusion of GFP to the entire protein coding segment of the cat-1 gene and is integrated onto a wild-type sequence has punctate expression pattern, as it appears as two puncta in the ADF neuron.
other neurons were not changed (Fig. 2C,D; not shown). Thus, significantly reduced in NSM, whereas the expression levels in GFP fluorescence was absent in AIM, RIH and HSN, into Rand and Nonet, 1997). We crossed the serotonergic and dopaminergic neurons (Sulston et al., 1975; Ruvkun, 1990) expressing cat-1::gfp (A-F) Effects of unc-86 on the expression of the cat-1 monoamine vesicular transporter. Expression of an integrated cat-1::gfp fusion gene was examined in wild type, unc-86-null and tph-1 mutants. (A,B) In wild-type, this functional cat-1 fusion to GFP was specifically expressed in all predicted serotonergic and dopaminergic neurons; representative expression in the serotonergic NSM, HSN, dopaminergic PDE neurons and the nerve ring is shown. (C,D) In unc-86 mutants, GFP expression in HSN was completely absent, and in NSM was significantly reduced. However, unlike tph-1::gfp (Fig. 1), cat-1::gfp expression in NSM was not completely absent (C). Note the unc-86 mutants had extra PDE neurons (D) (Finney and Ruvkun, 1990) expressing cat-1::gfp. (E,F) In the serotonin synthesis mutant tph-1(mg280), cat-1::gfp levels in NSM and other neurons were indistinguishable from wild-type. (G,H) Expression of a GFP fusion to the F32G8.6 GTP-cyclohydrolase 1, gtpch-1::gfp, in wild-type (G) and unc-86 mutant (H) animals. In wild-type animals, GFP was observed in all predicted serotonergic and dopaminergic neurons, as well as in the head and body wall muscles (arrowhead). Except for the absence of GFP in HSN (arrowhead in H), the expression levels in unc-86 mutants were very similar to wild type. All animals shown are adults, and the anterior is to the left.

chromosome (S. Nurrish, personal communication). Fig. 2A,B show that cat-1::gfp is specifically expressed in the serotonergic and dopaminergic neurons (Sulston et al., 1975; Rand and Nonet, 1997). We crossed the cat-1::gfp fusion gene into unc-86(n846) and unc-86(e1416) animals, and found that GFP fluorescence was absent in AIM, RIH and HSN, significantly reduced in NSM, whereas the expression levels in other neurons were not changed (Fig. 2C,D; not shown). Thus, UNC-86 activates both tph-1 and cat-1 expression in the NSM, AIM, RIH and HSN neurons. Unlike tph-1::gfp, cat-1::gfp expression in NSM is not completely absent in the unc-86-null mutants, suggesting that factors in addition to UNC-86 contribute to cat-1 expression in NSM.

Since unc-86-null mutations affect tph-1 expression, the reduced cat-1 expression observed in NSM, AIM, RIH and HSN might result from the lack of serotonin production rather than the lack of unc-86. However, no change in cat-1::gfp expression was observed in tph-1(mg280) mutants that contain no detectable serotonin (Fig. 2E,F). Thus, UNC-86 activates cat-1::gfp expression in the NSM, AIM, RIH and HSN neurons, but has no effect on cat-1 expression in the dopaminergic neurons or the ADF serotonergic neurons that do not express UNC-86.

**UNC-86 is not required for the survival or gross fate-specification of the NSM, AIM and RIH serotonergic neurons**

The neurons do not express tph-1, and cat-1 in the unc-86-null mutant may require unc-86 to acquire their specific serotonergic neuronal fate and/or for survival. In unc-86-null mutants, tph-1::gfp was not observed at any developmental stage, and there was no obvious difference in the expression level of cat-1::gfp between the mutant larvae and adults. Thus, the loss of tph-1 and cat-1 expression is not due to progressive neuronal degeneration. To assess whether these neurons express other markers of serotonergic neural fates, and thus rule out homeotic transformation of the neural fate, we have examined the effect of unc-86-null mutations on the expression of another gene specific for catecholaminergic neurons. The gene F32G8.6 encodes a probable GTP-cyclohydrolase I (GTPCH-1), a co-factor of tryptophan hydroxylase (Sanders-Bush and Mayer, 1996). We constructed a gtpch-1::gfp fusion gene, and examined the expression pattern in transgenic animals. In wild-type animals, GFP was observed in all identified serotonergic and dopaminergic neurons and many muscle cells (Fig. 2G). We crossed two independent gtpch-1::gfp transgenic arrays into unc-86-null mutants. Although GFP expression was not observed in HSN, the expression levels in NSM and the other serotonergic neurons were not changed in the unc-86-null mutants (Fig. 2H). All of the serotonergic neurons except HSN exhibited normal position, size and shape, indicating these neurons were generated and survived in the unc-86 mutant. These observations indicate that unc-86-null mutations do not alter the overall fate of NSM, AIM and RIH, only their expression of specific genes.

**Serotonin-reuptake and serotonin-synthesis are independent events in NSM development**

The NSM and ADF neurons continue to accumulate serotonin in unc-86(n846) and unc-86(e1416) null-mutant animals, as
revealed by immunofluorescent detection of serotonin with anti-serotonin antibodies (Fig. 3C; Table 1). Because tph-1 is essential for serotonin synthesis (Sze et al., 2000) and unc-86-null mutants have no detectable tph-1::gfp expression in NSM (Fig. 1), we thought of two possible sources of serotonin in NSM of unc-86 mutants: (1) the NSM neurons take up extracellular serotonin; (2) another transcription factor also activates tph-1 expression but its target is not included in our GFP reporter construct.

To assess the role of extracellular serotonin transport, we examined NSM serotonin in unc-86 mutants treated with the serotonin reuptake inhibitors imipramine or fluoxetine (Baldessarini, 1996). Imipramine stimulates C. elegans egg laying and pharyngeal pumping in wild-type but not in serotonin-deficient mutants (Weinshenker et al., 1995; Avery and Horvitz, 1990). Thus, imipramine functions in C. elegans presumably by enhancing serotonin signaling by preventing reuptake of serotonin from the synapse. We found that imipramine treatment significantly reduced serotonin in the NSM but not in the ADF neurons of unc-86 mutants (Fig. 3E; Table 1): 74-86% of the NSM neurons had no detectable serotonin and 14-20% showed weak serotonin in the imipramine treated unc-86 mutant animals, whereas 100% of NSM accumulated serotonin in untreated unc-86 mutant animals. No change in ADF serotonin level was observed (Fig. 3E,F), indicating that the imipramine treatment did not reduce serotonin accumulation in general. No reduction of NSM serotonin immunofluorescence was observed in wild-type animals treated with imipramine (Fig. 3F). Similarly, we observed reduced serotonin in NSM of unc-86 mutants treated with fluoxetine (Table 1): 36% had no detectable serotonin and 54% showed weak serotonin level in NSM. These results indicate that UNC-86 activates serotonin synthesis in all serotonergic neurons except ADF, but that the NSM neurons continue to take up serotonin, presumably released from ADF, in an unc-86 mutant. We do not exclude the possibility that additional transcriptional regulators can activate low levels of serotonin synthesis in the absence of unc-86.

NSM and ADF are the only neurons that accumulate serotonin in unc-86 hermaphrodites (Fig. 3C,D). To determine if ADF is the source of NSM serotonin in unc-86 mutants, we constructed double mutants of unc-86 and a mutation affecting serotonin biosynthesis in ADF. We have isolated several nss (neuron-specific serotonin defective) mutations that affect serotonergic phenotypes in specific serotonergic neurons (see Materials and Methods). The nss-1(yz12) mutation specifically affects serotonin accumulation in ADF: 72% of nss-1(yz12) mutants showed no ADF serotonin immunofluorescence, whereas the NSM immunofluorescence was equivalent to that in wild-type (Fig. 3H; Table 1). We constructed unc-86 and nss-1(yz12) double mutant animals, and found that nss-1(yz12) affects NSM serotonin accumulation in the unc-86 mutant background (Fig. 3G; Table 1): 56% of the double mutants had no detectable serotonin immunofluorescence, whereas the remaining animals had low serotonin immunofluorescence in ADF, but NSM serotonin immunofluorescence was either completely absent or very faint, only 15 of out 188 animals examined showed relatively strong NSM serotonin immunofluorescence. As nss-1(yz12) does not completely eliminate ADF serotonin, this may account for the residual NSM serotonin in the double mutants. Thus, NSM can take up serotonin from ADF and unc-86-null mutations do not disrupt

![Fig. 3. Analysis of NSM serotonin immunoreactivity in adult hermaphrodites.](https://example.com/fig3.png)

(A,B) In wild-type animals, nine neurons of five classes were stained by the anti-serotonin antibody. In general, the frequency of the AIM and RIH neurons stained is lower than of NSM, ADF and HSN, and the intensity of the staining in AIM and RIH is often lower. (C,D) In unc-86-null mutants, serotonin immunoreactivity in NSM and ADF remained, unlike in AIM, RIH and HSN. The ADF neurons are the only class of the serotonergic neurons that does not express unc-86, and unc-86 mutations had no effect on ADF serotonin immunoreactivity. (E,F) Treatment of animals with the serotonin reuptake block drug imipramine significantly reduced NSM but not ADF serotonin immunoreactivity in unc-86 mutants (E), and this effect was not observed in wild-type animals treated with imipramine at the same concentration (F). (G) No serotonin could be detected in the unc-86(e1416);nss-1(yz12) double mutant. unc-86(n846);nss-1(yz12) showed similar staining pattern (not shown). (H) The nss-1(yz12) mutation specifically affects serotonin immunoreactivity in ADF. Adult animals are shown, and the anterior is towards the left. For each strain, the immunostaining was performed many times, and quantification of the observation from two recent trials is presented in Table 1.
the serotonin reuptake machinery in NSM. These results suggest that the components for serotonin production and reuptake are regulated by distinct regulatory programs in NSM development.

We did not observe serotonin immunofluorescence in AIM, RIH and HSN in unc-86 mutants, even without serotonin reuptake inhibitor treatment. The absence of serotonin in HSN supports previous studies that unc-86 is required for several features of HSN maturation (Desai et al., 1988). Serotonin levels in AIM and RIH are lower than in HSN, NSM and ADF; thus, we may not be able to detect it if the level is further reduced because of reduced serotonin synthesis in the unc-86 background. Alternatively, unc-86 may have a broader role in RIH and AIM differentiation.

**tph-1 regulatory elements**

To distinguish whether tph-1 expression in ADF and unc-86-expressing cells is mediated by different regulators, or there is a common tph-1 regulator that may act downstream of nss-1 and unc-86, we constructed GFP fusion genes that bear various tph-1 regulatory elements and surveyed the expression pattern in transgenic animals. The tph-1-ABCDE::gfp fusion gene has GFP fused at exon 4 of tph-1 and contains 3.1 kb 5'-upstream uncoding sequence, and was strongly expressed in NSM, ADF at all stages and in HSN only at the adult stage (Fig. 4). We have shown that a tph-1 gene containing this upstream region and the entire coding region with introns can direct wild-type levels of serotonin synthesis in all the serotonergic neurons in a tph-1 deletion mutant (Sze et al., 2000). We constructed a series of deletions of the 5'-region from tph-1-ABCDE::gfp (Fig. 4), introduced individual constructs into wild-type animals, and the expression pattern of each construct in two to four transgenic lines has been examined. The construct tph-1-BCDE::gfp, which contains 377 bp upstream from the translation start site, recapitulated the tph-1-ABCDE::gfp expression pattern (Fig. 4B). However, deletion to \(-238\) bp (tph-1-CDE::gfp) resulted in reduced GFP level in ADF, and a further deletion to \(-158\) (tph-1-DE::gfp) greatly diminished GFP expression in ADF, but these deletions had no effect on the expression level in unc-86-expressing cells (Fig. 4B). These observations indicate that different transcription factors regulate tph-1 expression in ADF and unc-86-expressing cells.

The transcription factors, possibly encoded or regulated by nss-1, may activate tph-1 expression in ADF.

Interestingly, GFP expression of other fusion constructs in the HSN neurons was only observed in the adults, but 93% of the transgenic animals carrying the construct tph-1-DE::gfp began to express GFP in HSN at the first larval (L1) stage \((n=66)\). The pair of the HSN motoneurons modulates egg-laying behavior, and serotonin is observed only in adult HSN (Desai et al., 1988). Our results suggest that this temporal regulation of serotonin synthesis is mediated by the sequence located between \(-239\) to \(-159\) of the tph-1 gene.

Deletion to \(-81\) of tph-1 (tph-1-E::gfp) greatly reduced GFP expression in NSM and HSN, as well as in ADF (Fig. 4B). To determine the sequence specifically mediating tph-1 expression in these UNC-86-expressing cells, we constructed internal deletions. The construct tph-1-BCE::gfp is a fusion of the sequence \(-377\) to \(-166\) and tph-1-E::gfp. This internal deletion of the sequence between \(-165\) and \(-82\) of tph-1 significantly reduced GFP levels in NSM and HSN but had no effect on ADF: 37% of the transgenic worms showed no GFP and 62% showed very weak GFP in NSM; 86% showed no GFP and 14% weak GFP in HSN; whereas 100% showed normal GFP levels in ADF \((n=65)\). These results suggest that the sequence between \(-159\) and \(-82\) of tph-1 plays a major role in tph-1 expression in NSM and HSN.

A sequence motif (GGCGATAATAAAACAAT) at \(-98\) to \(-82\) matches the consensus UNC-86 binding site (Gruber et al., 1997). We used two approaches to test if UNC-86 directly activates tph-1 expression. First, we deleted this motif sequence from the construct tph-1-BCDE::gfp. We observed that the deletion caused a partial reduction of GFP expression in NSM and HSN: 9% showed no GFP and 50% showed weak GFP in NSM, and 8% showed no GFP and 30% showed weak GFP in HSN \((n=70)\), from four transgenic lines. For comparison, the non-truncated tph-1-BCDE::gfp construct was expressed 100% in NSM, and 97% in HSN \((n=36)\). Second, we tested interaction of the UNC-86 protein with the tph-1 promoter. In the touch receptor neurons, although UNC-86 interacts with MEC-3 to activate the transcription of mec-3 and mec-7, UNC-86 on its own binds to the targets in the promoter of these genes (Xue et al., 1992; Lichtsteiner and Tjian, 1995; Duggan et al., 1998). We tested the binding of

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**Table 1. Serotonin immunoreactivity in unc-86-null mutants**

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<tr>
<th>Mutant</th>
<th>Drug</th>
<th>% of ADF</th>
<th>% of NSM</th>
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<tr>
<td>N2</td>
<td>None</td>
<td>100</td>
<td>100</td>
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<tr>
<td>unc-86(n846)</td>
<td>Imipramine</td>
<td>100</td>
<td>100</td>
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<tr>
<td>unc-86(e1416)</td>
<td>Imipramine</td>
<td>100</td>
<td>100</td>
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<tr>
<td>nss-1(yz12)</td>
<td>Imipramine</td>
<td>12</td>
<td>100</td>
</tr>
<tr>
<td>nss-1; unc-86(e1416)</td>
<td>None</td>
<td>30</td>
<td>100</td>
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The worms were stained with anti-serotonin antibody using a whole-mount procedure (McIntire et al., 1992). Imipramine concentration was 0.4 mg ml\(^{-1}\) and fluoxetine concentration was 0.5 mg ml\(^{-1}\) (see Materials and Methods). The definition of the strength of the immunoreactivity: Strong, equivalent to that shown in Fig. 3A,B; weak, the entire range from less than strong to very faint; none, not visually detectable. For each strain, percentage of animals in each category is scored only in adults; other neurons were scored in larvae and adults. na, not analyzed.
the UNC-86 protein synthesized from E. coli and in vitro to DNA fragments spanning nucleotides -159 to -4 or -377 to -4 of tph-1 by gel mobility-shift assays. We observed a weak shifted product that was dependent on UNC-86, and can be competed by unlabelled DNA fragments spanning -159 to -4 of tph-1, but not when the consensus UNC-86 binding motif was truncated from this region. However, the binding was much poorer (about 40- to 60-fold less) than the binding of the same protein preparations to the UNC-86 targets CS2 and CS3 on the mec-3 promoter (data not shown). These results suggest that UNC-86 may interact with a co-factor for high-affinity binding to the tph-1 promoter, or UNC-86 indirectly regulates tph-1 expression.

Together, the analyses of the tph-1 promoter indicate that tph-1 expression in the ADF and UNC-86-expressing serotonergic neurons is controlled by different regulators, and that distinct regulators mediate the temporal and spatial expression of tph-1 in the HSN neurons.

**NSM exhibit neurite outgrowth defects in unc-86 mutants**

Does unc-86 specifically regulate tph-1 and cat-1 expression, or does it also regulate other aspects of the final identity of the serotoninergic neurons? The unc-86 mammalian orthologs Brn3a and Brn3b have been shown to regulate axon outgrowth and pathfinding (Lakin et al., 1995; Smith et al., 1997a; Erkman et al., 2000). We examined the effect of unc-86 on NSM morphology as revealed by serotonin immunofluorescence. The pair of the NSM secretory neurons is bipolar. The cell bodies are located symmetrically in the subventral nerve cord. Both processes extend from the posterior of the cell body: one process runs posteriorly, the other one runs across the ventral side to the dorsal nerve cord, then turns towards posterior, both processes terminate before reaching the terminal bulb of the pharynx (Albertson and Thomson, 1976) (Fig. 5A). unc-86-null mutations do not affect the cell position, but defects in neurite outgrowth and pathfinding were observed in some of the mutant animals (Fig. 5B-E): 38% showed extra neurite outgrowth; 18% exhibited one posteriorly directed process; in rare cases, the neurons had one process running anteriorly and the other posteriorly (n=164). Similar defects were observed in both unc-86(n846) and unc-86(e1416) alleles, and were also revealed in the unc-86-mutants carrying gtpch-1::gfp (not shown). As tph-1 mutants that do not produce serotonin show a normal NSM axon outgrowth (Sze et al., 2000), we suggest that these outgrowth defects are not due to decreased serotonin signaling, but that unc-86 regulates genes involved in axon outgrowth and pathfinding in NSM.

**DISCUSSION**

Our results showed that unc-86 regulates serotoninergic phenotypes in four classes of the serotoninergic neurons. In the NSM neurons unc-86 regulates the expression of the serotonin synthetic enzyme gene tph-1, upregulates the cat-1 vesicular transporter gene, and controls neurite outgrowth, but is not required for the serotonin reuptake. Similarly in the AIM, RIH and HSN neurons, UNC-86 activates the expression of tph-1 and cat-1. By contrast, the serotoninergic phenotype of the ADF neurons is specified by an UNC-86-independent program. These results show that serotoninergic phenotype may be specified by different transcription factors in different neurons, and in a given type of neuron, distinct aspects of the serotoninergic phenotype – synthesis, packaging,
and reuptake – are controlled by different regulatory mechanisms.

**unc-86 regulates serotonergic phenotypes in a subset of serotonergic neurons**

UNC-86 is expressed in the NSM, AIM, RIH and HSN serotonergic neurons. The analysis of **unc-86-null** mutants indicates that UNC-86 controls the synthesis of serotonin in these neurons. Desai et al. (Desai et al., 1988) showed that **unc-86** mutations affect serotonin accumulation in HSN, and we found UNC-86 is required for HSN to express a GFP reporter of the tph-1 tryptophan hydroxylase (Fig. 1). Both serotonin and tph-1::gfp expression levels in AIM and RIH are low in wild-type animals, but we could not detect any serotonin immunoreactivity or tph-1::gfp expression in AIM and RIH in two unc-86-null alleles (Table 1).

**tph-1::gfp** also was not detectable in NSM of **unc-86** mutants. However, NSM continue to accumulate serotonin in **unc-86-null** mutants. Our genetic and pharmacological analyses indicate that the serotonin accumulation in NSM in an **unc-86** mutant is due to import from the ADF neurons (Fig. 3; Table 1): first, NSM serotonin immunoreactivity was significantly reduced in **unc-86** mutants treated with serotonin reuptake block drugs; second, accumulation of NSM serotonin in **unc-86** mutants was much reduced in a genetic background that reduces serotonin levels in ADF. Thus, **unc-86** is a major component in the specification of serotonin in HSN, AIM, RIH and NSM development.

By contrast, **unc-86-null** mutations did not affect serotonin accumulation or tph-1::gfp expression in the pair of the ADF neurons that do not express UNC-86. This indicates that different regulatory mechanisms specify serotonergic phenotypes in ADF and UNC-86-expressing neurons. In support of this model we found distinct cis-regulatory regions mediating tph-1 expression in ADF and UNC-86-expressing cells (Fig. 4) and that the nss-1(yz12) mutation affects tph-1::gfp expression and serotonin accumulation in ADF but has no effect on NSM and HSN (Fig. 3; Table 1). The neuron-specific regulatory mechanism of serotonergic phenotypes has also been identified in *Drosophila*. The LIM-homeobox gene islet is expressed in and required for serotonin synthesis in the neurons in the ventral nerve cord but not the serotonergic neurons in the CNS (Thor and Thomas, 1997). It will be interesting to determine whether functionally conserved serotonergic neurons are specified by conserved regulators.

**unc-86-null** mutations also affect the expression of the cat-1 vesicular monoamine transporter in NSM, RIH, AIM and HSN (Fig. 2). Reduced cat-1::gfp expression was not observed in tph-1 mutants that are incapable of synthesizing serotonin. Thus, reduced cat-1 expression is unlikely to be the secondary consequence of reduced serotonin production; rather, **unc-86** coordinately regulates the expression of genes for serotonin synthesis and its packaging into vesicles. In mammals, the ETS domain protein PET-1 is expressed in serotonergic neurons and binds to the promoter of tryptophan hydroxylase and monoamine vesicular transporter genes (Hendricks et al., 1999). The role of PET-1 in vivo is not known. It is possible that one of the *C. elegans* ETS domain proteins (*C. elegans* sequencing Consortium, 1998) also regulates tph-1 and cat-1 for example in ADF, or acts as an **unc-86** co-factor to regulate tph-1 and cat-1.

Coordinated transcriptional regulation of neurotransmitter synthesis and packaging may represent a general principle for specification of neurotransmitter phenotypes. In mammals, *Drosophila* and *C. elegans*, genes for acetylcholine synthesis and its vesicular transporter are co-regulated by a common promoter (Rand, 1989; Eiden, 1998; Kitamoto et al., 1998). Similarly, the *C. elegans* homeodomain transcription factor UNC-30 binds to and is essential for the expression of both the unc-25/GABA synthetic enzyme glutamate decarboxylase and unc-47/GABA vesicular transporter in the type D motoneurons (Eastman et al., 1999). **unc-86-null** mutations appear to have a stronger effect on the expression of tph-1 than on cat-1. Serotonin can be released by both vesicular and non-vesicular release (for reviews, see Attwell et al., 1993; Bunin and Wightman, 1999). It is conceivable that non-vesicular release is modulated by the rate of serotonin production and vesicular...
release is regulated by neuronal stimuli. *unc-86* gene activity may coordinately regulate serotonin synthesis and non-vesicular release, and *unc-86* and other factors act together to regulate vesicular release in response to specific signals. Interestingly, Hobert et al. (Hobert et al., 1999) found that unlike the essential role that *unc-30* plays in the specification of type D GABAergic motoneurons, deletion of LIM-6 strongly affects *unc-25/glutamate decarboxylase* expression but only has a mild effect on *unc-47/GABA* vesicular transporter expression in the head and tail GABAergic neurons. Thus, cell-specific transcriptional regulation may be a mechanism to regulate cell-specific neurotransmission. UNC-86, LIM-6 and UNC-30 are continuously expressed throughout the life of the animal (Finney and Ruvkun, 1990; Hobert et al., 1999; Jin et al., 1994). It remains to be shown that these regulatory mechanisms that specify neurotransmitter phenotypes during the development of the nervous system continuously regulate neurotransmission in mature neurons.

**unc-86 is not essential for serotonin reuptake**

Unlike the role in the control of serotonin synthesis, *unc-86* appears non-essential for the development of serotonin reuptake machinery. Serotonin released into the synapse is inactivated primarily by reuptake of the transmitter through the serotonin transporter (SERT) present in the plasma membrane of the serotonergic neurons (Amara and Kuhar, 1993). The antidepressants imipramine and fluoxetine block the membrane transporter that reuptakes serotonin and are, thus, thought to enhance effective serotonin signals (Baldessarini, 1996). We found that imipramine and fluoxetine dramatically reduced serotonin accumulation in NSM of *unc-86* mutants (Fig. 3E). These data strongly suggest that *unc-86* mutations disrupt the synthesis of serotonin but do not impair the ability to uptake serotonin.

The argument that imipramine and fluoxetine block NSM uptake of serotonin is further supported by our demonstration that NSM do not accumulate serotonin if *unc-86* mutants also carry a mutation that decreases serotonin biosynthesis in ADF. However, NSM are not connected to ADF (White et al., 1986), thus NSM may uptake serotonin released non-synaptically from ADF. Serotonin release and reuptake are major drug targets to treat depression, eating disorders and obesity, but genetic and molecular basis of the regulatory mechanisms, as well as drug action is poorly understood. Because in *unc-86* mutant background NSM do not accumulate serotonin unless they transport extracellular serotonin released from ADF, isolation of mutations disrupting serotonin accumulation in NSM of *unc-86* mutants will provide a powerful system to define the genetic basis of serotonin release and reuptake.

**unc-86 acts late in the serotonergic neural differentiation**

Although *unc-86* specifies cell-fates of a number of neural lineages (Chalfie et al., 1981; Finney et al., 1988), *unc-86-null* mutations do not transform the cell fates of the serotonergic neurons. In *unc-86-null* mutants, these neurons are generated, the locations of the cell bodies of NSM, RIH and AIM are normal throughout the life of the animal, overall morphology is largely unaffected, and the position of HSN is also normal in the young larvae (Desai et al., 1988). Furthermore, in the absence of UNC-86, NSM, RIH and AIM still express gtpch-1 (which encodes a GTP-cyclohydrolase 1, a co-factor of serotonin synthetic enzyme tryptophan hydroxylase), and NSM are able to transport extracellular serotonin. These observations support the notion that early aspects of the neural differentiation of these serotonergic neurons are properly executed in *unc-86-null* mutants, and the function of UNC-86 is confined in late differentiation to regulate specific aspects of their terminal neuronal identity.

We observed a range of abnormal neurite outgrowth from NSM in *unc-86-null* mutants. Extra processes were extended from the cell body, and the main axonal processes were prematurely terminated (Fig. 5B-E). This abnormal neurite outgrowth is unlikely to be the result of decreased serotonin signaling because such defects were not observed in tph-1 or cat-1 mutants (Duerr et al., 1999; Sze et al., 2000). Rather, we favor the hypothesis that UNC-86 regulates the expression of signaling components that detect and respond to guidance cues, and structural proteins that mediate neurite extension.

The vertebrate *unc-86* orthologs, *Brn3a* and *Brn3b* selectively regulate the expression of genes involved in neurite outgrowth and pathfindings. It has been shown that in the ND7 cell line, *Brn3a* stimulates the expression of the synaptic vesicle protein SNAP-25 and induces axon outgrowth, but *Brn3b* inhibits SNAP-25 expression (Lakin et al., 1995; Smith et al., 1997b). However, *Brn3b* stimulates the actin-binding protein AbLIM and mice bearing a *Brn3b* deletion mutation exhibit aberrant neurite outgrowth and pathfinding in the retina (Erkman et al., 2000). We have previously observed that activation of UNC-86 by fusion of UNC-86 and the VP16 activation domain causes defects in neurite navigation of the touch receptors (Sze et al., 1997). The pathfinding defects of NSM in *unc-86-null* appear to be different from that of touch receptor neurons in UNC-86/VP16 animals. The NSM posteriorly directed processes tend to be missing or prematurely terminated in *unc-86-null* mutants, whereas the major processes of the touch receptors are abnormally extended or wander out in UNC-86/VP16 animals. It is possible that *unc-86* exerts different function on the expression of genes that mediate neurite navigation in different neurons. Alternatively, proper levels of guidance molecules and structural proteins may be essential for correct pattern of neurite navigation, thus either increased expression levels in UNC-86/VP16 animals or decreased expression levels in *unc-86-null* mutants would cause incorrect interpretation of guidance cues and result in neurite outgrowth defects.

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