Morphogenesis defects are associated with abnormal nervous system regeneration following roboA RNAi in planarians

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The process by which the proper pattern is restored to newly formed tissues during metazoan regeneration remains an open question. Here, we provide evidence that the nervous system plays a role in regulating morphogenesis during anterior regeneration in the planarian Schmidtea mediterranea. RNA interference (RNAi) knockdown of a planarian ortholog of the axon-guidance receptor roundabout (robo) leads to unexpected phenotypes during anterior regeneration, including the development of a supernumerary pharynx (the feeding organ of the animal) and the production of ectopic, dorsal outgrowths with cephalic identity. We show that Smed-roboA RNAi knockdown disrupts nervous system structure during cephalic regeneration: the newly regenerated brain and ventral nerve cords do not re-establish proper connections. These neural defects precede, and are correlated with, the development of ectopic structures. We propose that, in the absence of proper connectivity between the cephalic ganglia and the ventral nerve cords, neurally derived signals promote the differentiation of pharyngeal and cephalic structures. Together with previous studies on regeneration in annelids and amphibians, these results suggest a conserved role of the nervous system in pattern formation during blastema-based regeneration.

KEY WORDS: Neural regeneration, Planarian, Axon guidance, ROBO, Schmidtea mediterranea

INTRODUCTION

Freshwater planarians possess amazing regenerative abilities: when cut transversely, the anterior-facing wound regenerates a new head, whereas the posterior-facing wound regenerates a new tail (Newmark and Sánchez Alvarado, 2002; Agata, 2003; Reddien and Sánchez Alvarado, 2004). After amputation, stem cells called neoblasts proliferate to produce the regeneration blastema in which the missing structures will regenerate (Newmark and Sánchez Alvarado, 2002; Reddien and Sánchez Alvarado, 2004). Previous studies suggest that differentiated cells convey the positional information required for proper morphogenesis in planarians (Saló and Baguñà, 1985; Kato et al., 2001) and that epithelio-mesenchymal interactions (Chandebois, 1980), as well as gap junctional communication (Nogi and Levin, 2005), may be important for defining anterior versus posterior regeneration. Recent large-scale RNA interference (RNAi) analysis identified hundreds of genes required for proper regeneration (Reddien et al., 2005); however, the exact mechanisms governing morphogenesis of the planarian regenerate are still largely unknown.

In the initial days of anterior regeneration, primordia of the cephalic ganglia form within the blastema; these cephalic ganglia must then re-establish proper connections with the ventral nerve cords and with each other (Cebrià et al., 2002; Cebrià and Newmark, 2005) to produce a functional central nervous system (CNS). To understand the mechanisms underlying the regeneration of the planarian CNS, we have begun to identify planarian orthologs of genes required for proper axon guidance (Cebrià and Newmark, 2005). Here, we report the isolation and functional characterization of a roundabout gene from the planarian Schmidtea mediterranea (Smed-roboA). ROBO proteins are evolutionarily conserved transmembrane receptors of the immunoglobulin superfamily that bind secreted molecules of the SLIT family (Brose et al., 1999; Kidd et al., 1999); together, they play important roles in guiding axons to their proper targets (Araujo and Tear, 2003; Inatani, 2005). RNAi knockdown of Smed-roboA results in the unexpected production of a supernumerary pharynx and ectopic cephalic outgrowth during anterior regeneration. We show that the development of these ectopic structures correlates with improper connectivity between the newly regenerated cephalic ganglia and the ventral nerve cords. These results suggest that the nervous system is a source of signal(s) required for proper morphogenesis during planarian regeneration.

MATERIALS AND METHODS

Organisms

A clonal line of the diploid, asexual strain of Schmidtea mediterranea was used (Sánchez Alvarado et al., 2002). Planarians were maintained as previously described (Cebrià and Newmark, 2005) and starved for at least 1 week before use.

Isolation of Smed-robo homologues

S. mediterranea genomic sequences encoding predicted proteins similar to ROBO were retrieved from the NCBI Trace Archives and assembled using Sequencher 4.2.2 (Gene Codes Corporation). In total, two different genes encoding predicted ROBO proteins were identified; both were amplified from a planarian cDNA library (Zayas et al., 2005) and RACE was used to obtain additional cDNA sequences. GenBank accession numbers for Smed-roboA and Smed-roboB are DQ336174 and DQ336175, respectively.

Whole-mount in situ hybridization and immunostaining

Planarians were processed in an Intavis In situ Pro hybridization robot (Sánchez Alvarado et al., 2002) and imaged as described previously (Cebrià and Newmark, 2005). Immunostaining was performed as described (Cebrià 2005).
and Newmark, 2005) using: anti-tubulin Ab-4 (NeoMarkers, 1:200) to label axon bundles of the ventral nerve cords (VNCs), transverse commissures and lateral processes; anti-phospho-tyrosine P-Tyr-100 (Cell Signaling Technology, 1:500) to visualize the brain, VNC ganglia, gut and pharynx; and VC-1 to label photosensitive cells (Umesono et al., 1999). Highly cross-absorbed Alexa Fluor 488 goat anti-mouse IgG secondary antibodies (Invitrogen) were used at 1:400. Samples were mounted in Vectashield (Vector Laboratories), imaged with a CARV spinning disc confocal microscope and deconvolved using AutoDeblur 9.3 (AutoQuant Imaging, Inc.).

RNAi analyses

Double-stranded RNA (dsRNA) was synthesized and injected as described previously (Sánchez Alvarado and Newmark, 1999; Cebrià and Newmark, 2005). Injected planarians were amputated pre-pharyngeally, allowed to regenerate and processed for in situ hybridization or immunostaining. At 15 days after the first round of injections, some regenerating animals were re-injected on 3 consecutive days and re-amputated. Control animals were injected with water or GFP dsRNA. No defects were observed in intact or regenerating animals after Smed-roboB RNAi knockdown. Smed-roboA; Smed-roboB double knockdowns showed the same phenotypes as Smed-roboA single knockdown; thus, we limit this report to Smed-roboA.

RESULTS AND DISCUSSION

Smed-roboA is required for the proper guidance of regenerating photoreceptor axons

We identified planarian robo homologues in genomic sequences from S. mediterranea (see Materials and methods). Similar to other robo-family members, Smed-roboA encodes five conserved immunoglobulin repeats and three fibronectin type III repeats in the extracellular domain (Fig. 1A). Smed-roboA mRNA is expressed in the CNS and pharyngeal nerve ganglia in intact planarians (Fig. 1B), as well as in the regenerating CNS (Fig. 1C-E) and pharynx (Fig. 1G).

To analyze the function of Smed-roboA, we performed RNAi (Sánchez Alvarado and Newmark, 1999). A reduction of endogenous transcript after Smed-roboA RNAi was confirmed by in situ hybridization (Fig. 1F,G,I,J). Specific inhibition was observed both within the newly regenerated tissues and within the pre-existing nervous system (Fig. 1I,J); the expression of Smed-roboB was unaffected (Fig. 1H,K). Conversely, Smed-roboB RNAi did not affect levels of the Smed-roboA transcript (data not shown). No abnormal phenotypes were observed in Smed-roboA knockdowns in intact animals (5 weeks after RNAi, two sets of three injections; n=10).

We monitored the effects of Smed-roboA RNAi on photoreceptor regeneration. Planarian photoreceptors consist of two cell types: pigment cup cells and photosensitive cells that reside outside of the pigment-cup opening. The photosensitive cells extend axons posteriorly in a stereotypical pattern; some axons project ipsilaterally, whereas others project contralaterally, forming an optic chiasm that extends to the brain (Okamoto et al., 2005) (Fig. 1L). Smed-roboA RNAi regenerates showed a variety of visual system defects (Fig. 1M-O); the most common phenotypes (39/47 vs 1/43 in controls; see Table S1 in the supplementary material) were ectopic projections that resulted in loops (Fig. 1M,N); in some specimens (8/47 vs 0/43 in controls), the visual axons projected to the most-
anterior portion of the brain without crossing the midline (Fig. 1O, arrowheads). Thus, Smed-roboA is required for the proper guidance of visual axons during regeneration.

**Ectopic pharyngeal development and cephalic outgrowth after Smed-roboA RNAi**

Unexpectedly, after Smed-roboA RNAi, approximately 67% (34/51) of anterior regenerates also produced a supernumerary pharynx between the pre-existing pharynx and the newly regenerated head. The ectopic pharynx typically formed lateral to the midline and closer to the position of the ventral nerve cord (VNC). The extent of ectopic pharyngeal development varied from small masses of pharyngeal cells to a morphologically distinguishable, complete ectopic pharynx (Fig. 2A,B; magenta asterisks, ectopic pharynges). Ectopic pharyngeal cells were detected in the pre-pharyngeal region by in situ hybridization using a pharynx-specific *laminin* (Fig. 2D, magenta asterisk); expression of this marker was restricted to the pharynx in controls (Fig. 2C, white asterisk).

Ectopic pharynges (Fig. 2A,B, magenta asterisks) developed with reversed anteroposterior polarity, as revealed by the opening of the pharyngeal lumen (Fig. 2A, magenta arrow) towards the anterior of the animal. This alteration of polarity could also be observed in the gut. In triclad planarians, the digestive system consists of three main gut branches connected to the central pharynx: one branch grows anteriorly along the midline, ending at the level of the photoreceptors; the other two branches grow posteriorly, lateral to the pharynx and dorsal to the ventral nerve cords, extending through the tail. In three Smed-roboA RNAi animals, two gut branches developed lateral to the ectopic pharynx (Fig. 2B), as they would in post-pharyngeal regions. The ectopic gut branches were connected to the main digestive tract of the animal (Fig. 2B, arrows). None of the animals developed an ectopic mouth opening (the planarian pharynx protrudes through the mouth to ingest food), so it is unlikely that the ectopic pharynges were functional.

Furthermore, approximately 13% (9/67) of Smed-roboA RNAi anterior regenerates produced an ectopic, dorsal outgrowth between the newly regenerated cephalic region and the pre-existing pharynx (Fig. 3A-E). All samples that produced an ectopic outgrowth also developed an ectopic pharynx. These outgrowths were first visible as small, unpigmented regions within the uninjured tissues close to the wound; they became more evident after 2 weeks of regeneration (Fig. 3A, arrowhead). In 79% cases, these outgrowths appeared lateral to the midline (Fig. 3B). The cephalic identity of these outgrowths was demonstrated both morphologically and by using molecular markers for various head-specific cell types: photosensitive cells (Fig. 3C), pigment cups of the photoreceptors (Fig. 3D, arrow), sensory cells (Fig. 3D, purple labeling) and brain-specific cells (Fig. 3E) differentiated within these outgrowths. Even in the absence of

Fig. 2. Supernumerary pharynx formation after Smed-roboA RNAi. (A, B) Confocal projections showing ectopic pharynges after 16 days of regeneration and two rounds of RNAi treatment. Anti-phosphotyrosine and anti-VC-1 labeling is shown. In A, arrows indicate pharyngeal opening; in B, arrows indicate connections between ectopic and pre-existing gut. (C, D) *laminin* (DN293829) in situ hybridization in 16-day regenerates. (C) Control; (D) Smed-roboA RNAi. In all panels, white asterisks indicate original pharynges; magenta asterisks show ectopic pharynges. Anterior is to the left. cg, cephalic ganglia; g, ectopic gut branches. Scale bars: 200 μm in A; 100 μm in B; 300 μm in C, D.

Fig. 3. Development of ectopic cephalic outgrowths after Smed-roboA RNAi. Living planarians imaged at 16 days (A) and 33 days (B) after amputation. (C-E) Cephalic neural markers in outgrowths. (C) Visual-cell marker, VC-1; confocal projection at 35 days after amputation. (D) Sensory-cell marker, cintillo (Oviedo et al., 2003); arrow indicates photoreceptor pigment cells. (E) Clone H.10.2f, marker of cephalic ganglia. (D, E) At 16 days after amputation. (D) Sensory-cell marker, cintillo; arrowhead indicates photoreceptor pigment cells. (E) Clone H.10.2f, marker of cephalic ganglia. (D, E) At 16 days after amputation. In A-E, arrowheads indicate ectopic outgrowths. (F) Ectopic *Smed-netrin1* expression (arrowheads) near an ectopic pharynx (red asterisk); 18-day regenerate. (G-L) Expression of the ventral marker anosmin-1 (AY066061) in an 18-day regenerate. (G) Control: anosmin-1-positive cells are not observed in dorsal views. (H) Smed-roboA RNAi: anosmin-1-positive cells are detected dorsally. (I-L) Control (I, J) and Smed-roboA RNAi (K, L) planarians viewed ventrally (I, K) and dorsally (J, L). Anterior to the left. Scale bars: 1.5 mm in A (bar shown in B); 1 mm in B; 100 μm in C-E; 100 μm in F; 500 μm in I-L.
obvious outgrowths, ectopic Smed-netrin1-expressing cells were detected (Fig. 3F; arrowheads); these cells are normally confined to two narrow rows along the medial cephalic ganglia and ventral nerve cords (Cebrià and Newmark, 2005). In addition, a ventral-specific marker was detected dorsally (Fig. 3G,H). A gene similar to anosmin-1, implicated in Kallman’s syndrome in humans (Franco et al., 1991; Legouis et al., 1991), is expressed both in a subset of cells of the CNS and ventrally, in cells beneath the ventral musculature (Fig. 3I; data not shown). No anosmin-1-positive cells were detected in dorsal views of control planarians (Fig. 3G,J). However, in 8 out of 14 Smed-roboA RNAi animals, ectopic anosmin-1-expressing cells were detected dorsally (Fig. 3H), confined to the region between the newly regenerated head and the pharynx (Fig. 3L). Using a clone with weak similarity to septin (DN302617) as a marker for dorsal mesenchymal cells, we did not observe a concomitant displacement of these cells ventrally (data not shown). Thus, it appears that the polarity of the tissues in which ectopic structures form is only partially altered.

Disruption of neuronal connectivity following Smed-roboA RNAi

Because of the conserved role of robo genes in nervous system development, we examined the pattern of the regenerated CNS in Smed-roboA RNAi animals. Detailed examination revealed defects in the regeneration of the cephalic ganglia. The anterior commissure connecting the two ganglia was greatly reduced (Fig. 4B, 37/51; compare with control in 4A); in extreme cases, no commissure was observed between the two lobes (see Fig. 1O, arrow; 10/51). In wild-type animals, the amputated VNCs grew into the blastema beneath the newly regenerated cephalic ganglia. Both structures overlapped after the completion of regeneration, with the cephalic ganglia positioned directly above the underlying VNCs (Fig. 4C,E,G,I) (Okamoto et al., 2005). By contrast, after Smed-roboA RNAi, the regenerated cephalic ganglia were mis-positioned relative to the nerve cords (Fig. 4D,F,H,J). The ganglia were displaced laterally, resulting in a curvature in the VNCs as they reconnected to the regenerated ganglia (Fig. 4F). In the majority of Smed-roboA RNAi knockdown animals (29/51; 57%), a more dramatic dissociation between the regenerated cephalic ganglia and VNCs was observed (Fig. 4H,J). In these cases, the newly regenerated cephalic ganglia regeneratated lateral to the VNCs; the VNCs appeared truncated and failed to extend to the anterior-most portion of the brain. These defects were observed as early as day 5 of regeneration (Fig. 4H), well before the appearance of ectopic structures. Despite these defects in the organization of the regenerated CNS, no obvious behavioral defects were observed.

An ectopic pharynx was observed in approximately 90% (26/29) of the Smed-roboA RNAi animals that showed a clear disconnection between the brain and the VNCs. By contrast, an ectopic pharynx was observed in only 36% (8/22) of the knockdown animals in which these misconnections were not apparent with the markers that we used. Posterior regeneration (head pieces regenerating new pharynx and posterior regions) proceeded normally in Smed-roboA RNAi knockdown animals; the VNCs grew properly into the new posterior regions and no ectopic pharynges or outgrowths developed (data not shown).

The above results suggest that the nervous system may play an important role in patterning the newly formed anterior tissues during planarian regeneration. Following Smed-roboA RNAi, the VNCs and the newly formed cephalic ganglia are not connected properly. Almost all of the planarians with these neural defects produced ectopic pharynges and cephalic outgrowths. The CNS-specific expression of Smed-roboA during regeneration (Fig. 1C-E) and the observation that the improper connection of the VNCs and ganglia preceded ectopic tissue growth (Fig. 4H) suggest that the development of ectopic structures results from primary defects in the regenerated nervous system. A recent high-throughput RNAi screen in planarians reported that the knockdown of clone H.68.4a, which has low similarity to slit genes, resulted in the development of
ventral cephalic outgrowths (Reddien et al., 2005). Further analyses should clarify the extent of similarities between the defects observed after H.68.4a and Smed-roboA RNAs, and whether or not these two genes could encode a ligand-receptor pair.

In planarians, ectopic outgrowths have also been observed following grafts in which dorsal and ventral tissues are juxtaposed (Santos, 1931; Kato et al., 1999). Likewise, the juxtaposition of anterior and posterior tissues leads to the development of ectopic pharynges (Kobayashi et al., 1999). Thus, discontinuities in anteroposterior or dorsoventral positional values can lead to changes in cell proliferation (resulting in tissue outgrowth) and differentiation (producing new tissues and organs). We suggest that the improper connection between the cephalic ganglia and ventral nerve cords in Smed-roboA-knockdown animals mimics the effects of transplantation or amputation, in which the cephalic ganglia and VNCs are separated. In the absence of this connection, we infer that neurally derived signals are sent to the surrounding tissues; these signals could alter positional identities and trigger the production of an ectopic pharynx and a cephalic outgrowth. This idea is consistent with previous observations showing an increase of neurosecretory granules following amputation (Sauzin-Monnot, 1972) and the stimulation of mitogenic activity in planarians by substance P and substance K (Baguñá et al., 1989).

Such a role for the planarian nervous system may reflect an evolutionarily conserved function in pattern formation during regeneration; thus, in annelids, deflected cut ends of anteriorly facing nerve cords can give rise to ectoptic heads, whereas deflected cut ends of posteriorly facing nerve cords induce the differentiation of ectoptic tails (Kiortsis and Moraitou, 1965). In urodèle amphibians, the dependence of limb regeneration on the nervous system has been clearly shown (Singer and Craven, 1948; Singer, 1952); deviation of the caudal spinal cord can induce supernumerary tails (Kiortsis and Droin, 1961) and nerve deviation to a skin wound can induce ectoptic limbs (Egar, 1988; Endo et al., 2004). Further analyses, combining the tools of functional genomics now available for studying planarians (Newmark and Sánchez Alvarado, 2002; Reddien et al., 2005), will help us to identify the signals that serve to re-establish proper pattern during planarian regeneration.

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