Developmentally Regulated Impediments to Skin Reinnervation by Injured Peripheral Sensory Axon Terminals

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Summary

The structural plasticity of neurites in the central nervous system (CNS) diminishes dramatically after initial development, but the peripheral nervous system (PNS) retains substantial plasticity into adulthood. Nevertheless, functional reinnervation by injured peripheral sensory neurons is often incomplete [1–6]. To investigate the developmental control of skin reinnervation, we imaged the regeneration of trigeminal sensory axon terminals in live zebrafish larvae following laser axotomy. When axons were injured during early stages of outgrowth, regenerating and uninjured axons grew into denervated skin and competed with one another for territory. At later stages, after the establishment of peripheral arbor territories, the ability of uninjured neighbors to sprout diminished severely, and although injured axons reinitiated growth, they were repelled by denervated skin. Regenerating axons were repelled specifically by their former territories, suggesting that local inhibitory factors persist in these regions. Antagonizing the function of several members of the Nogo receptor (NgR)/RhoA pathway improved the capacity of injured axons to grow into denervated skin. Thus, as in the CNS, impediments to reinnervation in the PNS arise after initial establishment of axon arbor structure.

Results

Regenerating Sensory Axons Avoid Their Former Territories in the Skin at Later Developmental Stages

The peripheral axons of trigeminal sensory neurons terminate in elaborate arbor within the skin of the head to mediate somatosensation. Although it is well known that the primary axons of peripheral sensory neurons possess substantial regenerative capacity (reviewed in [1]), few studies have examined the regenerative potential of unmyelinated axon terminals in the skin. We used zebrafish trigeminal neurons as a model to investigate the developmental regulation of cutaneous axon terminal plasticity and whether deficits in skin reinnervation may contribute to incomplete recovery following injury.

The skin of larval zebrafish consists of two epithelial layers, between which trigeminal axon terminals reside. These axons repel one another as they arborize to partition epidermal territory, leading to complete, minimally redundant innervation of the head by 36 hr postfertilization (hpf) [7]. To study the developmental control of skin reinnervation after injury, we severed the peripheral axons of zebrafish trigeminal neurons expressing green fluorescent protein (GFP) with a femtosecond laser (see Figure S1 available online) [8], imaged their regeneration in live embryos for 12 hr, and traced their structure to quantify the success of target reinnervation (Figure 1; Movies S1–S13).

To specifically study axon regeneration within the skin, we directed all axotomies to second- or third-order axon branches, which are situated between the two skin layers. Axon regeneration was analyzed at three stages: 30 hpf, when trigeminal peripheral axons are still actively arborizing; 54 hpf, ~18 hr after arborization is complete; and 78 hpf. In all cases, the distal portions of severed axons degenerated and were cleared within 3 hr, leaving a denervated region of skin. Regenerating axons always partially reinnervated their former territories after axotomy at 30 hpf, but their capacity for reinnervation was significantly diminished after axotomy at 54 hpf and virtually nonexistent at 78 hpf. The portion of former territory reinnervated decreased from 47.5% ± 7.9% at 30 hpf to 0.3% ± 0.2% at 78 hpf (p < 0.0001); the percent of new growth that entered the denervated region decreased from 58% ± 6.3% at 30 hpf to 12.4% ± 8% at 78 hpf (p = 0.0002; Figure 2; Table S1). Most axons severed at 78 hpf initiated new growth but actively avoided their former territories (Figures 2G–2I). Avoidance was manifested as several distinct axon behaviors (Figure S2), including stalling, skirting the edge of the territory, or turning sharply, none of which was observed after axotomy at 30 hpf. Strikingly, although one-third (6 of 18) of axons severed at 78 hpf reentered their former territory, reinnervation was always transient: axons that entered the denervated territory either retracted (2 of 6; Figures S2F–S2J) or degenerated locally (2 of 6), or the parent neuron died (2 of 6; Figures S2K–S2O). Neither phagocytic blood cells nor peripheral myelin was responsible for inhibition, because avoidance was still observed in cloche mutant fish, which lack all blood cells [9], and in fish treated with the drug AG1478, which lacks peripheral myelination (Figure S3 and Table S2) [10]. Axon avoidance of former territory was a persistent effect in that axons imaged for 5 days after 78 hpf axotomy never reinnervated their former territory (n = 7; Figure S4).

Developmental Regulation of Axon Plasticity and Tiling

During early larval zebrafish development, trigeminal axons repel one another to partition epidermal territory [7]. When arbors are removed early in development, neighboring axons expand to fill denervated territory. This strategy for partitioning arbor territories, known as “tiling,” is often employed when multiple neurons of the same type innervate a two-dimensional target. Although the arbors of some tiled neurons retain plasticity into adulthood (e.g., [11, 12]), allowing them to compensate for the loss of neighbors and to create new
innervation patterns after injury, many populations of tiled neu-
rites cannot reorganize after developmental critical periods (e.g., [13–15]).

To characterize the territory-partitioning strategy of trigem-
inal sensory terminals after injury at different developmental
stages, we first investigated the ability of uninjured axons to
sprout into newly denervated territory. To accomplish this, we
laser ablated every cell within a trigeminal ganglion (Figures
S1E and S1F) and calculated the axon growth rate from the unin-
jured contralateral ganglion into newly denervated territory.
When a trigeminal ganglion was ablated at 30 hpf, uninjured
axons from the contralateral ganglion reinnervated most of the
denervated skin within 12 hr (Figure 3A). Following ablation at
78 hpf, growth into denervated territory was markedly reduced,
and very little branching occurred (Figures 3B and 3C; Table S3;
\( \mu \text{m/hr/tip: 30 hpf } 5.7 \pm 0.3, 78 \text{ hpf } 0.5 \pm 0.2; p = 0.0071 \)). Thus,
there was a critical period after which the growth of uninjured
axons into denervated territory diminished severely.

To test directly the hypothesis that uninjured and regenerat-
ing axons compete for denervated territory after injury at 30 hpf,
we transplanted wild-type cells into
neurogenin-1
mor-
phants, which lack somatosensory neurons, generating zebra-
fish with a single trigeminal neuron[7]. Strikingly, isolated axons
severed at 30 hpf reinnervated virtually all (98.1% \( \pm 1.9% \))
of their former territories and grew beyond them (Figures
3E and 3H). In contrast, control axons (wild-type cells trans-
planted into wild-type embryos) only partially (27.3% \( \pm 16.1%; p = 0.008 \))
reinnervated their former territories (Figures
3D and 3H). Thus, incomplete reinnervation of former territory
at 30 hpf was not due to a nonpermissive environment in the
denervated region but rather to competition with uninjured
neighboring axons (Figure 3I).

The peripheral axons of isolated neurons grow until they fill
the entire head, long past 78 hpf [7]. However, following axot-
omy of isolated arboras at 78 hpf, regenerating axons avoided
their former territories, with no significant change in the percent
area reinnervated compared to wild-type control transplants
(1.04% \( \pm 0.8% \) versus 5.4% \( \pm 4.3%; p = 0.3387; \) Figures
3F–3H). These results demonstrate that the denervated region
actively repels regenerating axons at older developmental
stages and that neither diminished growth rate nor competition
from uninjured neighboring axons explains the lack of reinner-
vation (Figure 3I). Thus, contrary to expectation, the peripheral
nervous system (PNS) is not always a permissive environment
for regeneration: at later larval stages, local factors persistently
marking former territories repel regenerating axons.

A Nogo Receptor/RhoA Pathway Is Required
for Inhibition of Skin Reinnervation
We hypothesized that axons in the central nervous system
(CNS) and PNS use similar molecular mechanisms to respond
to inhibitors in their respective environments. In the CNS, myelin-associated inhibitors activate a receptor complex that includes Nogo receptor (NgR) and LINGO-1 to block axon regeneration [16–19]. This complex activates an intracellular signaling cascade that involves the small GTPase RhoA, Rho kinase (ROCK), and collapsin response mediator protein-2 (CRMP-2) to cause growth-cone collapse [20, 21]. Zebrafish trigeminal neurons express homologs of NgR (ZF NgR), LINGO-1 (LINGO-1a), and CRMP-2 during larval stages [22–26].

To test whether the NgR pathway functions in peripheral sensory axon regeneration, we misexpressed dominant-negative (DN) versions of ZF NgR, LINGO-1a, and CRMP-2, as well as human RhoA, in trigeminal neurons, along with GFP [27–30]. Expression of all of the DN transgenes increased the fraction of regenerating axons that entered their former territories at 78 hpf compared to control axons coexpressing GFP and RFP or axons expressing full-length genes (Figure 4; Figure S5 and Table S2). As an additional control, we mutated a conserved amino acid in the DN NgR transgene (D163A) required for NgR binding to LINGO-1 and all known NgR ligands [31]. Axons expressing DN NgR D163A avoided their former territory, similar to controls and significantly different from those expressing DN NgR (Figures 4B and 4D; Figures SSD and S5K; Table S2). Blocking ROCK with the specific inhibitor Y-27632 [32] also improved reinnervation (Figure S6 and Table S2). As an additional control, we mutated a conserved amino acid in the DN NgR transgene (D163A) required for NgR binding to LINGO-1 and all known NgR ligands [31]. Axons expressing DN NgR D163A avoided their former territory, similar to controls and significantly different from those expressing DN NgR (Figures 4B and 4D; Figures SSD and S5K; Table S2). Blocking ROCK with the specific inhibitor Y-27632 [32] also improved reinnervation (Figure S6 and Table S2).

To rule out nonspecific effects of DN transgenes, we further investigated the function of ZF NgR, LINGO-1a, and CRMP-2 with morpholino antisense oligonucleotides (MO) targeting those genes. In all three cases, regenerating axons grew into denervated territory better than axons injected with a control MO (Figure 4; Figures SSG–SSJ and Table S2). Expression of the full-length LINGO-1a cDNA in neurons rescued the defect in repulsion observed in LINGO-1a morphants (Figure 4; Table S2). To determine when this pathway is required to inhibit outgrowth of trigeminal axons in the skin, we injected Y-27632 into embryos 2 hr before axotomy, as well as 1, 4, or 12 hr after axotomy (Figure S6 and Table S2). Reinnervation was only improved when ROCK was inhibited ≤4 hr after axotomy. To determine whether the same pathway was responsible for diminishing the ability of intact neighboring axons to sprout at 78 hpf, we injected Y-27632 2 hr before ablation of an entire trigeminal ganglion. ROCK inhibition had no effect on the ability of uninjured axons from the intact ganglion to sprout across the midline (Table S3). Similarly, intact axons in LINGO-1a morphants did not grow into denervated territory after we ablated a ganglion (Table S3). These results indicate that distinct pathways regulate the ability of injured and intact axon arbors to grow into denervated territory.

Discussion

It is generally believed that, in contrast to the CNS, the periphery is permissive for axon regeneration. Although substantial functional recovery from PNS injury can occur in adulthood, it is often incomplete (reviewed in [2]). Two phenomena are known to contribute to suboptimal PNS axon regeneration: the degeneration of supportive conduits that guide axons to the periphery and the inability of regenerating sensory endings to penetrate the epidermis [1–6]. We show here that inhibitory regions of skin can also be an obstacle to peripheral reinnervation. After a developmental critical period, regenerating cutaneous sensory axon endings specifically avoid reinnervating their former territories. There is a crucial distinction between regeneration and reinnervation: severing an axon stimulates its growth, but factors in the original territory prevent reinnervation. Interestingly, severing axons in the CNS also stimulates exploratory activity,
but very little reinnervation occurs [33], perhaps because axons are repelled by inhibitors expressed by myelin. When a regenerating trigeminal peripheral axon does grow into its former territory, it inevitably retracts, or the cell dies, suggesting that repellents in this skin region may also be toxic to neurons. These local impediments to full reinnervation of the skin may contribute to deficits in functional recovery from peripheral injury [2].

Because inhibition is limited to a region around a degenerated axon's original territory, we speculate that axons alter the extracellular matrix (ECM), leaving behind a persistent "ghost" that demarcates their former territories. This local mark of an axon's territory might be laid down at a specific developmental stage to stabilize arbors. One possibility is that inhibitory factors derive from membrane-associated proteins mediating isoneuronal axon repulsion, perhaps after their ectodomains are shed from the membrane. Alternatively, axons may secrete distinct molecules into the ECM or induce the surrounding epidermal cells to secrete inhibitors.

Perturbing NgR signaling improved the ability of injured peripheral axons to reinnervate former territories. Several members of the NgR pathway, including NgR itself, its coreceptor LINGO-1, and the intracellular signaling molecules RhoA, Rho kinase, and CRMP-2, are at least partially required in axons for avoidance of former territories in the skin. In the CNS, this pathway is involved in responses to myelin-associated proteins that inhibit axon regeneration [21]. Thus, the central and peripheral branches of somatosensory neurons use similar mechanisms to respond to inhibitors in distinct environments. It is possible that known ligands of the NgR complex, expressed in a different context, inhibit peripheral regeneration, but because these proteins are structurally diverse, it is also possible that different ligands functions in the periphery.

Our studies reveal a critical period for the plasticity of somatosensory arbors that limits their ability to respond to injury and fully reinnervate the skin. We propose that after initial development, local inhibitors stabilize sensory axons in the skin, consequently limiting their ability to reinnervate it after injury. Several molecular studies link functional recovery and axon regeneration following spinal cord injury to developmental plasticity in the CNS [34–38]. The NgR pathway limits ocular dominance plasticity in the visual cortex [34], in addition to limiting regeneration in response to CNS injury [39, 40] and, as we have now shown, PNS injury. Our results support the idea that impediments to recovery from injury to the mature PNS are a consequence of the stabilization of neuronal structure that occurs when initial morphogenesis ends.

Experimental Procedures

As previously described, a GFP reporter transgene was used to visualize trigeminal neurons (Tg(sensory:GFP)) [7], as well as a variation expressing RFP (Tg(sensory:RFP)) and an Islet3-GFP line provided by A. Pittman and C.-B. Chien (Tg(Islet3:GFP)) [41]. Details of time-lapse confocal imaging and two-photon axotomy [8], data analysis, transplantation, pharmacological treatments, and morpholino and transgene design are described in the Supplemental Experimental Procedures.

Supplemental Data

Supplemental Data include Supplemental Experimental Procedures, three tables, six figures, and thirteen movies and can be found online at http://www.cell.com/current-biology/supplemental/S0960-9822(09)01913-7.

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