Reduce, Reuse, Recycle - Developmental Signals in Spinal Cord Regeneration

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Review article

Reduce, reuse, recycle – Developmental signals in spinal cord regeneration

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ABSTRACT

Anamniotes, fishes and amphibians, have the capacity to regenerate spinal cord tissue after injury, generating new neurons that mature and integrate into the spinal circuitry. Elucidating the molecular signals that promote this regeneration is a fundamental question in regeneration research. Model systems, such as salamanders and larval and adult zebrafish are used to analyse successful regeneration. This shows that many developmental signals, such as Notch, Hedgehog (Hh), Bone Morphogenetic Protein (BMP), Wnt, Fibroblast Growth Factor (FGF), Retinoic Acid (RA) and neurotransmitters are redeployed during regeneration and activate resident spinal progenitor cells. Here we compare the roles of these signals in spinal cord development and regeneration of the much larger and fully patterned adult spinal cord. Understanding how developmental signalling systems are reactivated in successfully regenerating species may ultimately lead to ways to reactivate similar systems in mammalian progenitor cells, which do not show neurogenesis after spinal injury.

1. Introduction

How animals are capable of reconstructing a functional tissue after a disruptive injury is a fundamental question in regenerative biology. One principle appears to be that mechanisms that regulate cell proliferation, differentiation or death during development are redeployed after injury.

Mammals can functionally regenerate a few organs, such as the liver, but the central nervous system (CNS) regenerates very poorly. Many organ systems can regenerate in species such as teleosts (Rasmussen and Sagasti, 2016). Recently, zebrafish larvae are used to analyse successful regeneration. This shows that many developmental signals are reactivated in successfully regenerating species, which may ultimately lead to ways to reactivate similar systems in mammalian progenitor cells, which do not show neurogenesis after spinal injury.

The cells of the neural plate fuse in the midline giving rise to a structure called neural keel, which reorganises in a neural rod, thus giving rise to BTN by a process of cavitation. Independently of this difference in neurulation among species, the molecular instructions used for NT patterning are evolutionarily conserved to a high degree (Araya et al., 2016; Lowery and Sive, 1998). These gradients establish specific domains of progenitor cells which express distinct combinations of homeodomain proteins (Briscoe et al., 2000). These activate specific transcriptional programs in progenitor cells, so that distinct progenitor domains give rise to different population of neurons (Gouti et al., 2015).

Because regeneration of the spinal cord may recapitulate steps in its development, we briefly summarise major events in spinal cord development. The construction of the spinal cord during initial development requires specific signalling pathways that regionalize and pattern the whole tissue that then grows and gains complexity. Primary neurulation or neural tube (NT) closure occurs during early development, after the specification of the germinal layers. The flat neural plate undergoes a series of morphogenetic changes that end in a dorsal fusion resulting in a closed NT in amniotes. In amphibians and teleosts this process differs (Araya et al., 2016; Lowery and Sive, 2004). The cells of the neural plate fuse in the midline giving rise to a structure called neural keel, which reorganises in a neural rod, thus giving rise to BTN by a process of cavitation. Independently of this difference in neurulation among species, the molecular instructions used for NT patterning are evolutionarily conserved to a high degree (Araya et al., 2016; Lowery and Sive, 2004).

Wnt, FGF and RA signal gradients establish the antero-posterior axis of the CNS (Kudoh et al., 2002; Storey et al., 1998). These gradients also serve as axon guidance cues during development and lead to axonal regeneration along the antero-posterior axis after SCI (Rasmussen and Sagasti, 2016).

Along the dorso-ventral (DV) axis, the patterning of the NT is mainly controlled by Hh, Wnt and BMP signal gradients (Fig. 2; Le Dreu and Marti, 2012). These gradients establish specific domains of progenitor cells which express distinct combinations of homeodomain proteins (Briscoe et al., 2000). These activate specific transcriptional programs in progenitor cells, so that distinct progenitor domains give rise to different population of neurons (Gouti et al., 2015).

Proliferation and differentiation of progenitor cells also requires activity of many of the above signals as well as activity of Notch (Ye and Chitnis, 2007), RA (Wilson et al., 2004), FGF (Diez del Corral and Storey, 2004) signalling and the action of different neurotransmitters like dopamine or serotonin (Barreiro-Iglesias et al., 2015; Reimer et al., 2015).

During successful spinal cord regeneration, molecular pathways...
The non-canonical Wnt/Ca2+ pathway causes an increase in calcium through the activation of Wnt target genes. In the non-canonical Wnt/planar cell polarity (PCP) pathway, the activation of Frizzled and Dvl leads to a signaling cascade resulting in cytoskeleton modifications, leading to the nuclear translocation of canonical and non-canonical. In the canonical pathway, Frizzled, through the activation of Dishevelled (Dvl) protein, promotes the dissociation of β-catenin with heparin sulphate proteoglycan (HSPG). FGFRs are encoded by 4 genes (FGFR1-4) which, by being alternatively spliced, confer ligand-receptor binding specificity in an autocrine, paracrine or endocrine manner. Secreted FGF ligands bind to their receptors (FGFR), a single-pass transmembrane tyrosine kinase molecule, through the interaction with heparan sulphate proteoglycan (HSPG). FGFRs are encoded by 4 genes (FGFR1-4) which, by being alternatively spliced, confer ligand-receptor binding specificity. They activate Smad-dependent or independent pathways like FGF/PLC-β-NFAT and PI3K-AKT signalling pathways to mediate FGF target gene transcription through the activity of the transcription factors FOS, NFAT and FOXO.

Retinoic Acid (RA): Retinol, a form of vitamin A, is transported from the bloodstream to the RA-generating cell by retinol binding protein (RBP) and transthyretin (TTR), entering into the cell through STRA6 receptor. Enzymatic processing of retinol by retinaldehyde dehydrogenases (RALDHs) and retinol dehydrogenases (RDHs) results in the formation of RA. This RA-generating cell releases RA to the neighbouring cells, which enter the cell through STRA6 receptor. This RA enters the nucleus and associates with nuclear RA receptor (RAR) and retinoid X receptor (RXR) to initiate gene transcription. For references see text.
2. Pathways

2.1. Notch

Notch signalling is known as a regulator of neural progenitor cell fate, controlling neurogenesis and gliogenesis (Ables et al., 2011). Notch is important in juxtacrine cell-cell communication (Fig. 1). However, Notch signalling can also occur between non-neighbouring cells by transient basal actin-based filopodial contacts (Cohen et al., 2010).

Delta-Notch signalling participates in NT formation from early developmental stages. Disruption of Notch signalling prevents progenitors cells in Hensen’s node in the chicken from populating the floor plate (Gray and Dale, 2010). Notch activity is necessary to maintain the identity of the floorplate itself in chick hindbrain and spinal cord (le Roux et al., 2003). Mutant studies in zebrafish show that Delta-Notch signalling is required for lateral floor plate and P3 domain development (Schafer et al., 2007). Conditional knock-out of the gene encoding the E3 ligase Mind Bomb-1, which regulates endocytosis of Notch ligands, shows that Notch controls neurogenesis and gliogenesis during NT development in mice (Fig. 2; Kang et al., 2013). notch1 or notch3 are expressed in precursors and immature neurons of the spinal cord in mammals and are important for neuronal differentiation and maturation of the SC (Yamamoto et al., 2001). Indeed, notch1 expression is enhanced in the SC after injury in the ependymal and parenchymal cells and is thought to suppress neurogenesis (Fig. 2; Yamamoto et al., 2001).

In the zebrafish spinal cord, different proliferative progenitors express notch receptor genes, whereas precursors and post-mitotic neurons expressed deltaA and jagged2 ligand genes. A disruption of Delta function causes overproduction of early-specified motor neurons (MNs) in zebrafish which leads to a depletion of progenitors in the motor neuron progenitor domain (pMN) over time (Appel and Eisen, 1998). This is also observed in delta1 and hes1;hes5 double-mutant mice (Hatakeyama et al., 2004; Marklund et al., 2010). jagged2, expressed in the pMN, seems to maintain this cell population in an...
undifferentiated state. The inhibition of Jagged2-mediated signalling by morpholinos (MO) in zebrafish or short-hairpin RNA (shRNA) in chick cause variations in the number of MN and GABAergic Kolmer-Agduhr (KA) cells in the ventral spinal cord (Yeо and Chitnis, 2007). This particular activity of Notch signalling seems important for SC regeneration in adult zebrafish, as notch1a/b, notch2, her4.1, her4.5, her9, jagged1b and deltaC genes are upregulated after SCI (Fig. 2). Indeed, the transgenic over-activation of Notch signalling in ependymo-radial glial (ERG) cells, the progenitor cells in the zebrafish spinal cord (Reimer et al., 2008), during regeneration reduces proliferation of ERGs and the number of new motor neurons generated. Conversely, the blocking of Notch signalling using the gamma-secretase inhibitor DAPT increases motor neuron generation after SCI. Similarly, Notch activity in progenitor cells in the adult zebrafish telencephalon during constitutive neurogenesis also attenuates neurogenesis (Chapouton et al., 2010). These results highlight the potential of modulating Notch signalling in progenitor cells by drug treatments in order to promote generation of motor neurons (Dias et al., 2012). The expression pattern and relationship among Notch signalling proteins in pMN cells and MNs during development and adulthood and the fact that Notch signalling dynamics control asymmetric cell division in the NT (Das and Storey, 2012) raise the question whether altering the mode of division of progenitor cells could lead to motor neurogenesis after spinal cord injury also in mammals.

Notch interacts with other pathways during development and regeneration. For example, Notch1 inactivation specifically in neural progenitor cells results in an increase in the number of V2 interneurons at the expense of MNs and in a gradual disappearance of the ventral central canal in mice (Peng et al., 2007). This is similar to manipulations of the Hh pathway (below and Fig. 3; Yang et al., 2006). Indeed, the transgenic over-activation of Notch signalling in ependymo-radial glial (ERG) cells, the progenitor cells in the zebrafish spinal cord (Reimer et al., 2008), during regeneration reduces proliferation of ERGs and the number of new motor neurons generated. Conversely, the blocking of Notch signalling using the gamma-secretase inhibitor DAPT increases motor neuron generation after SCI. Similarly, Notch activity in progenitor cells in the adult zebrafish telencephalon during constitutive neurogenesis also attenuates neurogenesis (Chapouton et al., 2010). These results highlight the potential of modulating Notch signalling in progenitor cells by drug treatments in order to promote generation of motor neurons (Dias et al., 2012). The expression pattern and relationship among Notch signalling proteins in pMN cells and MNs during development and adulthood and the fact that Notch signalling dynamics control asymmetric cell division in the NT (Das and Storey, 2012) raise the question whether altering the mode of division of progenitor cells could lead to motor neurogenesis after spinal cord injury also in mammals.

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2.2. Hedgehog

Signalling mediated by the morphogen gradient set up by the secreted protein hedgehog (Hh) determines the ventral patterning of the CNS and therefore plays pivotal roles in nervous system development. Its activity is crucial for early specification, regionalization and differentiation of the NT and for subsequent axon guidance and connectivity (Briscoe and Therond, 2013; Fig. 1). During NT development, Shh, expressed in the notochord, activates the signalling pathway in the NT floor plate (Echelard et al., 1993). The floor plate cells, source of many inductive signals, then start to express Shh themselves. The protein diffuses dorsally, thus signalling in a graded manner from ventral to dorsal. This leads to establishing different progenitor domains (Fig. 2; Chamberlain et al., 2008). Shh spreading and responsiveness of neural progenitor cells are both critical for patterning (Dessaud et al., 2008). It has been also shown recently that in addition to diffusion Hh ligand can be transported through filopodia-like structures (Sanders et al., 2013), but it is still unknown whether Notch participates in the regeneration of interneurons during SC regeneration as well as whether and how Notch activity interacts with that of other signalling pathways that are reemployed during regeneration, such as Hh or BMPs.

![Fig. 3. Example of the convergence of signalling pathways in the neural progenitor cells related to Hh - cAMP/PKA modulation. During spinal cord development, Notch augments Shh signalling by increasing the accumulation of Smo in the primary cilium. Notch signalling is inhibited, if the receptor is blocked downstream of BMP signalling. During the coordination of ventral patterning and caudal axis extension, FGF and Hh signalling act in a negative feedback loop by modulating the expression of Shh receptor Patched2. RA downstream pathways inhibit Notch signalling in the pMN cells to induce MN specification. The cross-regulation between RA, FGF and Wnt acts to determine the antero-posterior identity of the progenitors and coordinate the transcriptional programs as the spinal cord matures. In addition, RA is necessary for the modulation of components of neurotransmitter pathways like dopamine or serotonin. Dopamine signalling alters the sensitivity of progenitors to Hh signalling during spinal neurogenesis though the dopamine receptor 4a (D4a) during development and regeneration of the spinal cord. For references see text.](image-url)
particularly important for oligodendrocyte differentiation in zebrafish (Chung et al., 2013).

During regeneration of the axolotl tail, the activity of Hh proteins as ventral organiser is important. Shh expression in the ventral most cells of the SC is required for the establishment of DV progenitor domains in the newly forming ependymal tube. The proliferation of the blastema and the overall tail regeneration also depends on Hh signalling (Schnapp et al., 2005).

After a transection lesion, as has been done in the lesioned spinal cord of adult zebrafish, the patterning activity of the hedgehog pathway may not be required, as the spinal cord progenitor cells maintain their progenitor domain identity from development. However, during regeneration after SCI, shha, pthc2, smo and Hh target genes, like olig2, are upregulated in ependymal cells (Fig. 2) and this is important for injury-induced regeneration of neurons. For example, the generation of new MNs (Reimer et al., 2009) or serotoninergic interneurons (Kusch et al., 2012) after injury is reduced by blocking Hh signalling with cyclopamine. Drug treatment experiments suggest that during MN development and regeneration, the strength of Hh signalling can be modulated by dopamine through the dopamine receptor D4a (Fig. 3) (Reimer et al., 2013). Interestingly, shh is also upregulated after SC compression injury in mice; expressing high levels for up to at least 1 month after injury (Fig. 2; Chen et al., 2005).

Future research is needed to understand how Hh pathway components are configured in adult progenitor cells and how shh expression is upregulated and the protein spreads during spinal cord regeneration. In other tissues like the heart the outflow tract (epicardial layers of the atrium and the bulbous arteriosus) works as a signalling centre and source of Hh ligand to promote epicardial regeneration after cardiac damage (Wang et al., 2015).

During spinal cord development, Hh signalling controls regulators of the cell cycle in neural progenitors (Cayuso et al., 2006), the mode of division of the pMN cells (Saade et al., 2013) and the size and proportions of the NT (Uygur et al., 2016). It remains to be fully established which of the different actions of Hh signalling are recapitulated in the progenitor pool of ependymal cells during SC regeneration.

2.3. BMP

The BMP pathway regulates many fundamental processes during development and adulthood and for that, it was suggested to call it “body” morphogenetic protein pathway, rather than “bone” morphogenetic protein, according to where it had been originally discovered (Reddi, 2005).

The BMP pathway (Fig. 1) is critical for CNS development (Hegarty et al., 2013). During gastrulation, neural induction from the Spemann organizer is promoted by Noggin (Lamb et al., 1993) which binds BMP4 with high affinity blocking BMP signalling activity (Zimmerman et al., 1996). Once the neural tissue is determined, BMP signalling plays important roles during NT development from patterning to generation of post-mitotic neurons, axon guidance, synapse formation and gliogenesis (Le Dreau and Marti, 2013).

BMP gradient formation is crucial for DV body axis patterning, including DV patterning of the NT, and this action is highly conserved among animals (Bier and De Robertis, 2015). The expression of bmp4 and bmp7 in the epidermal ectoderm is important for the dorsal fate acquisition of the prospective NT at neural plate stage (Fig. 2; Liem et al., 1995). BMP activity is required for the entire patterning along the DV axis affecting generation of neurons (Barth et al., 1999). After SCI in adult rats, bmp7 expression is upregulated in glial cells and MNs (Setoguchi et al., 2001). bmp2 is also upregulated after SCI in mouse (Setoguchi et al., 2004). bmp4 is upregulated 1 month after injury in mouse. bmp4 appears upregulated in neurons and GFAP-positive astrocytes. High levels of bmp4 are also found in the ependymal cells, the presumptive spinal progenitor cells, within 1 mm of the lesion site (Fig. 2; Chen et al., 2005). These results suggest an active role of BMPs after injury. Indeed, inhibition of BMP signalling in Xenopus tadpoles prevents regeneration of the tail after amputation. Conversely, the activation of the pathway during a naturally occurring refractive period during which the tail can normally not regenerate, restores regenerative capacity (Beck et al., 2003).

During development, the release of BMP inhibitors like Chordin, Flik, Follistatin and Noggin from the notochord is critical for the ventral cell fate regulation of the developing NT. For instance, noggin mutant mice are characterized by a lack of floor plate cells and lack or reduced number of MNs in the NT (McMahon et al., 1998). During regeneration of the Xenopus tail, Noggin induction reduces the rate of cell division in the SC, suggesting a mitogenic role of BMPs (Beck et al., 2006). Noggin induction by cell transplant experiments in the injured SC of mice promotes the differentiation of β-tubulin positive neurons, oligodendrocytes and astrocytes in correlation with a partial functional recovery of locomotor activity (Setoguchi et al., 2004). However BMP inhibition also increases the lesion volume and the number of macrophages in the injured SC (Enzmann et al., 2005). Moreover, BMP signalling also participates in gliosis and astrocyte differentiation during SCI (Sahni et al., 2010; Xiao et al., 2010). BMP receptor localizes into lipid rafts when β1-integrin is ablated in the ependymal stem cells, which is associated with increased astroglisis after SCI (North et al., 2013). Hence, BMP signalling may have different pro- and anti-regenerative roles after SCI.

Despite the central role of BMPs for nervous system development and regeneration in many species, very little is known about its expression and roles in the zebrafish during SC regeneration. Data from an expression profile indicate that BMP signalling components are differentially expressed after spinal cord crush injury, suggesting specific roles for BMP signalling in regeneration (Hui et al., 2014). Fluorescent fusion proteins could be used in future to visualise BMP transports and gradients of the secreted protein. The genetic toolkits available in zebrafish plus the use of models for neuron ablation using the Nitrroreductase/Metronidazole (NTR/MTz) system (Curado et al., 2007; Ohnmacht et al., 2016) could help to elucidate how this pathway is functionally involved in the regeneration of the spinal cord.

2.4. Wnt

Wnt signalling, a regulator of cell proliferation, growth and fate is critical for development and tissue homeostasis (MacDonald et al., 2009). Its roles during tissue regeneration have been studied in different animal models (Clevers et al., 2014; Wehner and Weidinger, 2015). In the CNS, Wnt signalling components are activated as a response to injury (Lambert et al., 2016), suggesting the importance of Wnt signalling in CNS regeneration.

Wnt signalling (Fig. 1) participates in CNS development from neural induction (Stern, 2001). Once the neural tissue is established, Wnt/β-catenin acts as a morphogen patterning the antero-posterior axis of the CNS (Kiecker and Niehrs, 2001). Wnt signalling induces posterior markers (Kudoh et al., 2002). During subsequent development, Wnt, together with Hh and BMP signalling is responsible for the correct dorso-ventral NT patterning (Fig. 2) (Le Dreau and Marti, 2012). Wnts are expressed dorsally in the NT in an opposing gradient to the Hh ventral signalling (Alvarez-Medina et al., 2008). These opposite gradients are important to pattern the different domains of progenitors along the dorso-ventral axis and also to determine the size of the NT structure by controlling the differentiation rate of the progenitors (Kicheva et al., 2014). Dorsal Wnt is important for proliferation of ventricular progenitor cells and the formation of dorsal neurons (Megasan and McMahon, 2002). Indeed β-catenin, which is essential for canonical Wnt signalling, is required for the maintenance and proliferation of the neuronal progenitors in the entire spinal cord (Zechner et al., 2003). A prominent activity of Wnt signalling in neurogenesis is the control of the cell cycle (Niehrs and Acebron,
2012). Mouse models carrying a stabilized β-catenin in neural precursors develop bigger brains, associated with the control of cell cycle exits of the progenitors (Chenn and Walsh, 2002). During corticogenesis, Wnt modulates the spindle-size asymmetry which lead to the asymmetric cell division; a necessary step for neurogenesis (Delaunay et al., 2014). In adult animals, Wnt signalling controls self-renewal, proliferation and differentiation of stem cell niches in different organs and tissues (Clevers et al., 2014). In the adult CNS, Wnt signalling is necessary for neurogenesis, differentiation and survival of neurons and for synaptogenesis (Inestrosa and Arenas, 2010).

Studies in tail regeneration in urodele amphibians have shown that wnt5a, wnt5b, and wnt10a are expressed in different domains along the anteroposterior axis of the intact adult CNS and after an injury (Caubit et al., 1997a). Wnt10a is strongly expressed after tail amputation, suggesting its importance for the new tissue proliferation and patterning (Caubit et al., 1997b). In Xenopus it has been shown by grafting experiments and the Tet-on conditional transgenic system blocking Wnt-β-catenin in a tissue specific manner, that the Wnt-β-catenin pathway is important for SC regeneration (Lin et al., 2012). In rodents, the expression of Wnt ligands and inhibitory components of the pathway are differently regulated after SCI in comparison to the unlesioned condition (Gonzalez-Fernandez et al., 2014).

During SCI in zebrafish larvae, spinal radial glia exhibit Wnt/β-catenin signalling, which is important for neurogenesis but may also play an important role for axonal regrowth (Briona et al., 2015). After SCI in adult zebrafish, an increase of Wnt/β-catenin signalling is observed, which is necessary for locomotor recovery (Strand et al., 2016).

Studies in zebrafish using conditional knockouts or inducible systems like TetON (Wehner et al., 2015) could help to elucidate cell types and mechanisms by which Wnt and its regulators affect SC regeneration. The strength of imaging in the zebrafish CNS could be used to visualise Wnt protein transport through filopodial structures (Luz et al., 2014) or axons. These technical possibilities and the regenerative ability of the zebrafish makes it particularly interesting to explore Wnt signalling in zebrafish SCI.

2.5. FGF

FGF signalling (Fig. 1) plays important roles in development from cell fate specification to the determination of axis and morphogenetic processes (Dorey and Amaya, 2010). The formation of an FGF gradient is crucial for its morphogenetic activity (Bokel and Brand, 2013). Whether FGF plays a role early during neural induction is still a controversy (discussed in Dorey and Amaya (2010)) During the establishment of the anteroposterior axis of the CNS, FGF acts as a neural morphogen (Kengaku and Okamoto, 1995). High levels of FGF promote expression of posterior markers and conversely, low doses, anterior markers (Storey et al., 1998). Indeed, FGF receptor signalling is required for the elongation of the spinal cord primordium in chick, where FGF works as a posteriorising signal (Fig. 2). FGF signalling maintains the neural progenitor population close to the region of the Hensen’s node (Mathis et al., 2001). Later, FGF is crucial for CNS dorso-ventral patterning, contributing particularly to the specification of the ventral progenitor domains (Lupo et al., 2006) and neurogenesis. FGF promotes proliferation and survival of neuroepithelial cells in vitro and their differentiation into mature neurons and glia depending on ligand concentration (Qian et al., 1997). In the mouse SC, MNs express the FGF ligand FGF1 (Elde et al., 1991) while human and rat MNs express FGF9 (Nakamura et al., 1997). Indeed, the treatment of forebrain-derived neural stem cells with FGF2 induces the generation of MNs which express the MN marker HB9 (Jordan et al., 2009). In addition, different FGF proteins can act as potent survival factors for spinal MNs in culture (Ford-Perriss et al., 2001).

The activity of FGF in glial cells seems important during regenerative processes in the CNS. Brain or SC injury in the salamander Pleurodeles waltl increase FGF2 expression in reactive astrocytes at the lesion site (Fahmy and Moffah, 2010). Tail amputation experiments in Pleurodeles have shown that during regeneration FGF2 expression is upregulated in the ependymal cells, promoting proliferation and neural differentiation from this progenitor cells (Zaky and Moffah, 2014) In other amphibians like Ambystoma mexicanum or Xenopus tadpoles, FGF signalling is also important during the regenerative process of the spinal cord (Lin et al., 2012; Makanee et al., 2016). In zebrafish, different FGF signalling pathway components are upregulated in neurons and glia after SCI. This upregulation of the FGF pathway is important for the formation of a glial bridge after SCI, which has been proposed to acts as a scaffold for the axons crossing the lesion site (Goldshmit et al., 2012). Evidence from mammalian models shows that FGF plays important roles in glial cells during brain or SCI injury (Kang et al., 2014; Tripathi and McGtigue, 2008). In mice, the administration of FGF2 following SCI increases the number of progenitor cells at the lesion site and favours glial bridge formation and axonal regeneration (Goldshmit et al., 2014).

It would be interesting to determine whether cross-regulatory interactions of FGF with other signalling pathways like RA or Shh, which contribute to coordinate transcriptional programs as the spinal cord progressively matures (Briscoe and Novitch, 2008; Diez del Corral and Storey, 2004), are recapitulated during regeneration. For example, FGF signalling promotes spinal cord elongation by controlling cell cycle length through the regulation of cyclins D1 and D2 in concert with Hh signalling (Lobjois et al., 2004). During the coordination of ventral patterning and caudal axis extension, FGF and Hh signalling act in a negative feedback loop by modulating the expression of the Shh receptor Patched2 (Fig. 3; Morales et al., 2015). In the context of limb regeneration, it has been observed recently how the crosstalk between FGF and Shh leads regeneration (Nacu et al., 2016).

During neural differentiation, FGF signalling can modulate chromatin organisation (Patel et al., 2015) pointing to another potential mechanism of FGF action in regeneration. During the transition from multi-potent progenitor to neural progenitor cell in the chick spinal cord, different chromatin modifiers are downregulated. Among them is HDAC1, which depends on FGF signalling activity. (Olivera-Martinez et al., 2014). Interestingly, HDAC1 is able to regulate proliferation in radial glial cells in the Xenopus optic tectum (Tao et al., 2015), indicating a potential mechanism by which FGF controls cell differentiation in the CNS. The capacities of FGF to control chromatin modulators may have implication for the activation of the regeneration-associated gene expression programme in progenitor cells also during neuronal regeneration.

2.6. Retinoic acid

The RA pathway (Fig. 1) is important for cell communication during development and adulthood. Its functions are crucial for spinal cord development (Lara-Ramirez et al., 2013; Maden, 2006). RA has been proposed as an important signal for regeneration of different organs, such as the lungs, limbs, peripheral nervous system (PNS) and CNS (Maden, 2007).

During development, RA is known as a posteriorising agent (Maden and Holder, 1992). The treatment of Xenopus tadpoles with RA promotes the expression of posterior neural genes, such as hoxb3, and suppresses anterior markers, like Xotx2 (Papalois and Kintner, 1996). During NT patterning, the RA receptors (RXRα, RARα and RARβ) are expressed in the NT while Raldh2, the enzyme generating RA, is present in the presomitic mesoderm and somites. The RA signal from the somites is necessary for neural differentiation and ventral patterning (Fig. 2; Diez del Corral et al., 2003). The RA signalling function during NT patterning is conserved in zebrafish (England et al., 2011; Lara-Ramirez et al., 2013). Indeed, a decrease of RA receptor activity is associated with the activation of neural fate (Blumberg et al., 1997). For this posteriorising activity, RA interacts with Wnt and FGF
signalling, which is mediated by the RA hydroxylase Cyp26 in zebrafish. Wnt and FGF signalling inhibit cyp26 expression, which in turn inhibits RA signalling (Kudoh et al., 2002).

The RA pathway is also important for the dorsoventral patterning of the spinal cord (Wilson et al., 2004). In a vitamin A-deficient quail model in which RA is absent, V1 interneuron and MN marker genes are downregulated. RA supports the generation of MNs (Sockanathan and Jessell, 1998) by activating genes necessary for ventral NT patterning and MN specification (Novitch et al., 2003). One retinoid-inducible gene is GDE2 (glycerophosphodiester phosphodiesterase 2) which induces MN differentiation (Rao and Sockanathan, 2005) inhibiting Notch signalling in the pMN cells from the differentiated MNs (Sahbarwal et al., 2011).

RA also promotes the differentiation of a neuronal fate from different types of stem cell lines in vitro and in vivo in the spinal cord (Duester, 2013; Janesiek et al., 2015).

After SCI in rats, RALDH2 activity was found upregulated in cells around the lesion site (Kern et al., 2007) and RARβ agonist treatment reduces the formation of the glial scar and enhances axonal outgrowth capacity (Goncalves et al., 2015). This suggests potential beneficial effects of RA activity after SCI.

In adult nevts, retinoid signalling controls the expression of specific microRNAs, which are expressed in ependymoglial cells during tail and spinal cord regeneration. In turn, these microRNAs control the expression of the RA receptor, RARβ2 (Lepp and Carlone, 2015). These observations are opening new insights into how this pathway is balanced and functions during successful spinal cord regeneration.

Little is known about the effects of RA signalling on neurogenesis during spinal cord regeneration in zebrafish. Expression data indicates that the RA signalling pathway is upregulated after a spinal cord lesion (Reimer et al., 2009). There is no apparent need for a function of RA in patterning of the lesioned adult spinal cord, as this retains its dorso-ventral pattern from development (see above). Further functional experiments, including the visualisation and perturbation of RA gradients (Schilling et al., 2016) will have to clarify the role of RA in spinal cord regeneration. In the developing spinal cord, RA seems to maintain high levels of FGF and Notch signalling in order to drive stem cell differentiation (Paschaki et al., 2012). RA is also necessary for the modulation of components of neurotransmitter pathways like dopamine (Samad et al., 1997) or serotonin, discussed further down (O’Reilly et al., 2007; Fig. 3). These observations open the question if this crosstalk plays an active role during regeneration.

2.7. Dopamine/Serotonin

Neurotransmitters, in addition to their role in transmitting specific neuronal information, also promote neurogenesis in the CNS during development and adulthood. Acetylcholine, dopamine (DA), GABA, glutamate, nitric oxide, neuropeptide Y, noradrenaline and serotonin (5-HT) influence neural cell proliferation and differentiation (Berg et al., 2013). Neurotransmitters are released from producing cells, acting in target cells through transmembrane G-Protein-Coupled Receptors (GPCRs). These common and diverse receptors control cellular processes like proliferation, differentiation and adult neurogenesis (Doze and Perez, 2012).

Different components of DA signalling are expressed in progenitor cells in the CNS (Diaz et al., 1997; Ohtani et al., 2003). Aminergic (DA, 5-HT, noradrenaline) projections to the spinal cord contribute to the maturation of locomotor networks (Sharples et al., 2014). In zebrafish, dopamine from the dopaminergic diencephalo-spinal tract is able to act directly on the spinal progenitor cells during development by promoting the generation of MNs by augmenting Shh signalling (Reimer et al., 2013). Similarly, the depletion of monoamines in vivo affects Hh signalling in the adult rat hippocampus (Rajendran et al., 2009). 5-HT plays a similar role during development; 5-HT depletion in rats delays the differentiation of neurons (Lauder and Krebs, 1978). In zebrafish, 5-HT promotes the embryonic development of MNs by acting on progenitor cell proliferation (Barreiro-Iglesias et al., 2015). The effect and mechanism of action appears to be independent of Shh and therefore different from that of DA.

In the salamander brain, DA controls neurogenesis and regeneration of dopaminergic neurons. DA keeps the stem cells that give rise to DA neurons quiescent in a negative feedback loop (Berg et al., 2011). In the adult spinal cord of zebrafish, dopamine and serotonin augment the number of MNs regenerated after an injury, which is similar to their developmental function (Barreiro-Iglesias et al., 2015; Kuscha et al., 2012; Reimer et al., 2013).

To better understand how neurotransmitters act on neurogenesis, these could be tracked in vivo. Fluorescent false neurotransmitters (FFN), which can be tracked by imaging to study monoamine exocytosis have recently been described (Pereira et al., 2016). For future studies, FFN could be applied in the transparent developing and regenerating zebrafish embryo to understand how neurotransmitters control neurogenesis and modulate regeneration. Also, deciphering the localization and interaction of the different receptors would help to elucidate the molecular code that act in progenitors. The crosstalk with signalling pathways, such as the hedgehog pathway, and changes in gene expression downstream of DA or 5-HT signalling are of interest for future studies (Fig. 3).

3. Discussion/Conclusions

Progenitors in the developing and regenerating spinal cord express a multitude of different receptors and are therefore able to receive a large number of signals. In the regenerating spinal cord, developmental signals derived from neighbouring cells, axons, and the cerebrospinal fluid (CSF) are “reused” and direct the regenerative response of spinal progenitors. While each receptor acts on its own signalling cascade, there is also significant cross-talk between pathways, often integrated onto few effectors (as illustrated for Hh in Fig. 5). It will be interesting to determine how these interactions are altered during regeneration, given that they likely integrate signals unique to regeneration, such as inflammatory mediators from immune cells. The recent progress in genetic and imaging technologies now allows the detailed investigation of these subcellular signalling processes in vivo using the larval zebrafish to investigate successful central nervous system repair.

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References


