Development 134, 479-489 (2007) doi:10.1242/dev.001123

# Distinct Wnt signaling pathways have opposing roles in appendage regeneration

**Cristi L. Stoick-Cooper[1,2,*], Gilbert Weidinger[1,*,†], Kimberly J. Riehle[3,4], Charlotte Hubbert[1], Michael B. Major[1], Nelson Fausto[4] and Randall T. Moon[1,‡]**

In contrast to mammals, lower vertebrates have a remarkable capacity to regenerate complex structures damaged by injury or disease. This process, termed epimorphic regeneration, involves progenitor cells created through the reprogramming of differentiated cells or through the activation of resident stem cells. Wnt/β-catenin signaling regulates progenitor cell fate and proliferation during embryonic development and stem cell function in adults, but its functional involvement in epimorphic regeneration has not been addressed. Using transgenic fish lines, we show that Wnt/β-catenin signaling is activated in the regenerating zebrafish tail fin and is required for formation and subsequent proliferation of the progenitor cells of the blastema. Wnt/β-catenin signaling appears to act upstream of FGF signaling, which has recently been found to be essential for fin regeneration. Intriguingly, increased Wnt/β-catenin signaling is sufficient to augment regeneration, as tail fins regenerate faster in fish heterozygous for a loss-of-function mutation in *axin1*, a negative regulator of the pathway. Likewise, activation of Wnt/β-catenin signaling by overexpression of *wnt8* increases proliferation of progenitor cells in the regenerating fin. By contrast, overexpression of *wnt5b* (*pipetail*) reduces expression of Wnt/β-catenin target genes, impairs proliferation of progenitors and inhibits fin regeneration. Importantly, fin regeneration is accelerated in *wnt5b* mutant fish. These data suggest that Wnt/β-catenin signaling promotes regeneration, whereas a distinct pathway activated by *wnt5b* acts in a negative-feedback loop to limit regeneration.

**KEY WORDS: Wnt, zebrafish, regeneration, β-catenin, dickkopf, wnt8, wnt5, *pipetail*, *axin1*, *masterblind***

## INTRODUCTION

All organisms mount a biological response to damage, but they vary widely in their ability to recover. Humans constantly renew components of blood, skeletal muscle and epithelia. Such homeostatic renewal is thought to be mediated by resident stem cells of a specific lineage. Although humans can regenerate an injured liver and repair limited insults to bone, muscle, digit tips and cornea, they do not regenerate the heart, spinal cord, retina or limbs. Thus, humans and other mammals are somewhat disadvantaged when compared with amphibians and teleost fish, which have a remarkable capacity to regenerate damaged organs including heart, spinal cord, retina and limbs/fins (Akimenko et al., 2003; Brockes and Kumar, 2002; Poss et al., 2003; Poss et al., 2002). A dramatic example of organ regeneration is that of amphibian limbs and fish fins, where intricate structures consisting of multiple cell types that are patterned into complex tissues are faithfully restored after amputation. The mechanisms that enable lower vertebrates to re-establish such structures and the reasons why mammals are not able to do so, are incompletely understood. Elucidation of these mechanisms and an understanding of why regenerative capacity has diminished in vertebrate evolution hold the potential to revolutionize clinical medicine, with practical applications ranging from organ disease and wound treatment to possible alternatives to prosthetics for amputees.

Whereas repair of many organs, such as the chicken retina or mouse liver, is thought to be mediated through activation of resident stem cells or proliferation of normally quiescent differentiated cells, respectively (Fausto et al., 2006; Fischer and Reh, 2001), amphibian and fish appendages regenerate through a process termed 'epimorphic regeneration', sometimes called 'true' regeneration. This occurs in three steps: (1) wound healing and formation of the wound epidermis; (2) formation of a regeneration blastema, a population of mesenchymal progenitor cells that is necessary for proliferation and patterning of the regenerating limb/fin; and (3) regenerative outgrowth and pattern reformation (Akimenko et al., 2003; Poss et al., 2003). Progenitor cells of the blastema in the regenerating axolotl tail can be formed by reprogramming and de-differentiation of differentiated cells (Casimir et al., 1988; Echeverri et al., 2001; Echeverri and Tanaka, 2002; Kintner and Brockes, 1984; Lentz, 1969; Lo et al., 1993). These cells express transcriptional repressors of the *msx* gene family that may help maintain a pluripotent state (Akimenko et al., 1995; Yokoyama et al., 2001). Recently, activation of resident muscle stem cells has been reported in regenerating salamander limbs (Morrison et al., 2006). Thus, it is likely that de-differentiation and stem cell activation both contribute to formation of the blastema. Although de-differentiation of cells has not yet been shown to occur in regenerating structures other than amphibian limbs and tails, the morphology, ontology and gene expression profile of the zebrafish blastema in the regenerating tail fin suggest that zebrafish tail regeneration occurs by similar mechanisms.

[1]Howard Hughes Medical Institute, Department of Pharmacology, Institute for Stem Cell and Regenerative Medicine, [2]Graduate Program in Neurobiology and Behavior, [3]Department of Surgery and [4]Department of Pathology, University of Washington School of Medicine, Seattle, WA 98195, USA.

*These authors contributed equally to this work
†Present address: Biotechnological Center, Technical University of Dresden, Tatzberg 47, 01307 Dresden, Germany
‡Author for correspondence (e-mail: rtmoon@u.washington.edu)

**Accepted 21 November 2006**

A major question that remains incompletely answered involves the identification of the extracellular signals that regulate the formation or activation of stem cells during regeneration. Although hedgehog signaling has been implicated in newt tail and chick retina regeneration (Schnapp et al., 2005; Spence et al., 2004), and BMP signaling in newt lens and *Xenopus* tail regeneration (Beck et al., 2003; Grogg et al., 2005), the strongest evidence to date points to FGF signaling as an essential regulator of progenitor cell formation in limb and fin regeneration. FGF-10 is sufficient to reactivate regeneration in *Xenopus* limbs at later stages of development where limbs have lost their regenerative capacity (Yokoyama et al., 2001), and FGF-2-soaked beads can stimulate chick limbs, which normally do not regenerate, to do so (Taylor et al., 1994). Inhibition of FGF signaling by pharmacological inhibitors or expression of a dominant-negative FGF receptor blocks blastema formation in zebrafish caudal fin regeneration (Lee et al., 2005; Poss et al., 2000b), and a mutation in zebrafish *fgf20a* causes an early block in blastema formation (Whitehead et al., 2005).

Wnt/β-catenin signaling regulates progenitor cell fate and proliferation during embryonic development and in adult tissue homeostasis (Logan and Nusse, 2004; Reya and Clevers, 2005), raising the possibility that it is also involved in progenitor cell function during regeneration. Several studies have documented expression of Wnt ligands and components of the β-catenin signaling pathway in regenerating amphibian and fish appendages (Caubit et al., 1997a; Caubit et al., 1997b; Poss et al., 2000a), and other studies have suggested that Wnt/β-catenin signaling is functionally involved in the proliferation of cells during regeneration of mammalian muscle, liver and bone (Polesskaya et al., 2003; Sodhi et al., 2005; Zhong et al., 2006). However, whether Wnt/β-catenin signaling plays an essential role in the epimorphic, 'true' regeneration of complex structures has not been tested.

Many Wnt ligands can activate β-catenin-independent ('noncanonical') signaling pathways (Slusarski et al., 1997; Veeman et al., 2003) that are well documented to regulate cell polarity and cell migration during embryonic development (Veeman et al., 2003). However, other than reports which indicate that β-catenin-independent Wnt signaling might act to suppress tumor formation (Dejmek et al., 2005; Jonsson et al., 2002; Kremenevskaja et al., 2005), nothing is known about its role in adults. Here, we provide evidence that both β-catenin-dependent and -independent Wnt signaling pathways regulate zebrafish fin regeneration.

## MATERIALS AND METHODS

### Zebrafish surgeries

Zebrafish of ~6-12 months of age were used for all studies. Zebrafish heart and fin amputations were performed as previously described (Poss et al., 2000a; Raya et al., 2004), after which fish were returned to 28-30°C water.

### Partial hepatectomy in TOPGAL mice

TOPGAL mice (a gift from E. Fuchs, Rockefeller University, NY) have been described previously (DasGupta and Fuchs, 1999). We performed 2/3 partial hepatectomy (Campbell et al., 2006) and sham laparotomy on 8- to 11-week-old male TOPGAL mice in the morning after a night of fasting. Resected lobes were collected and served as control tissue for subsequent experiments; remnant livers were harvested 48 hours later. β-galactosidase activity was determined in whole liver lysates as per manufacturer's instructions (Promega, Madison, WI), and normalized to total protein concentration as determined by the Bradford assay (Bio-Rad, Hercules, CA). X-Gal staining was performed on glutaraldehyde-fixed 5 μm frozen liver sections as per manufacturer's instructions (Gold Biotechnology, St Louis, MO).

### Cloning of zebrafish *wnt5a*

Zebrafish genomic sequence was searched for sequences homologous to the previously known zebrafish Wnt5 ortholog, *pipetail* (*ppt*). A sequence distinct from *ppt* was identified and a partial cDNA coding for this *wnt5* paralog cloned by RT-PCR from a mixture of RNA isolated at different stages of embryonic development. The 5′ end of the cDNA was defined by RACE and by homology to EST 052-H12-2. The very 3′ end of the open reading frame and a putative 3′UTR were predicted from genomic sequences, but have not been experimentally verified. BLAST searches, multiple sequence alignments of the predicted protein sequence with Wnt5 paralogs from other species and phylogenetic analysis using the PAUP program support the conclusion that the previously described zebrafish *wnt5* paralog *ppt* is the zebrafish ortholog of *wnt5b*, whereas the newly cloned paralog described here is most likely to be the ortholog of *wnt5a* (see Fig. S2 in the supplementary material). We thus deposited the new sequence as *wnt5a* in GenBank (accession number DQ465921) and suggested that *wnt5* (*pipetail*; *ppt*) should be renamed *wnt5b*, which has now been done.

### In situ hybridization

Whole-mount in situ hybridization was performed on amputated fins and hearts as described previously (Poss et al., 2000a). For Digoxigenin-labeled probe synthesis, published templates were used, except for *wnt5a* cDNA, which was cloned by RT-PCR from RNA isolated from embryos at different stages of development. When assaying for differences in expression, the development of the staining reaction was monitored carefully and fins or hearts of the same comparative groups were stopped at exactly the same time. Cryosectioning of the fins was performed as described previously (Poss et al., 2000b).

### Heat-shock inducible transgenic zebrafish lines

The hsDkk1GFP and hsWnt5bGFP lines were established as follows (see Fig. S3 in the supplementary material). mmGPF5 (Siemering et al., 1996) was fused to the C-terminus of zebrafish *dkk1* (Genbank accession # AB023488). Upon injection into zebrafish embryos, RNA encoding this fusion protein was found to cause posterior truncations, and increased the size of eyes and forebrain at similar doses as the wild-type *dkk1* RNA (data not shown). Likewise, mmGFP5 was fused to the C-terminus of zebrafish *wnt5b/pipetail* (see Fig. S2 in the supplementary material for nomenclature; Genbank accession # DRU51268). Injection of RNA coding for this fusion protein into early zebrafish embryos caused similar gastrulation defects as RNA coding for the wild-type Wnt5b protein, but the fusion protein appeared to be significantly less active (data not shown). Both fusion proteins were cloned downstream of a 1.5 kb fragment of the zebrafish hsp70-4 promoter (Halloran et al., 2000) and upstream of the SV40 polyadenylation signal of the vector pCS2+. An I-*Sce*I meganuclease restriction site was inserted 5′ of the transgene. Supercoiled plasmid DNA containing the transgenes was injected together with I-*Sce*I meganuclease (Thermes et al., 2002) into one-cell-stage embryos to create mosaic G0 founder fish. Founders that transmitted a functional transgene through their germline were identified by crossing them to wild-type fish, heat shocking the resulting F1 embryos and screening them for GFP expression. Transgenic F1 embryos were found to be viable when heat shocked at 24 hpf or later and therefore could be raised to adulthood. To establish transgenic lines, identified heterozygous F1 fish were crossed to wild-type fish and the F2 generation raised. For most experiments on adult fish, wild-type siblings from such crosses served as controls. When siblings could not be used, age-matched wild types served as controls.

Heat shocks for these lines and the hsΔTCFGFP and hsWnt8GFP lines were performed twice daily by transferring fish from 28-30°C water to water preheated to 38°C with subsequent incubation in an air incubator at 39°C for 1 hour.

### Tissue sectioning and histology

Hematoxylin staining and histology were performed as previously described (Poss et al., 2002) on 20 μM cryostat sections.

### BrdU incorporation and mitosis analysis

BrdU incorporation and mitosis analysis were performed as previously described (Nechiporuk and Keating, 2002). All BrdU incorporations were performed for the final 1-2 hours of the experiment. Sections were rinsed

three times in PBS, then incubated in 2N HCl for 30 minutes at 37°C. Sections were then briefly rinsed in PBS three times and incubated in blocking solution (1% Triton X-100 and 0.25% BSA in PBS) for at least 1 hour. Slides were incubated in mouse anti-BrdU (1:200; Sigma, St Louis, MO) and rabbit anti-phosphorylated histone H3 (PH3; 1:200, Upstate Biotechnology, Charlottesville, VA) antibodies overnight at room temperature. Slides were then washed all day with multiple changes of PBS and then incubated in secondary antibodies (goat anti-mouse Alexa-fluor-546; goat anti-rabbit Alexa-fluor-488, Molecular Probes) for 1-2 hours at room temperature. Slides were rinsed three times in PBS (20 minutes each) and mounted with DAPI mounting media and coverslipped. DAPI-stained nuclei, BrdU-positive cells and PH3-positive cells were counted from 3-6 sections per fin from three fins per wild-type or transgenic sample. *n*=number of blastemas counted per experiment.

#### Fin length measurements in *axin1* and *wnt5b* mutant fish

Heterozygous carriers of the *axin1* mutation *masterblind* (*mbl*$^{tm013}$) and wild-type sibling fish were identified by genotyping using allele-specific PCR. *ppt*$^{ta98}$ (*wnt5b*) homozygous mutant embryos were identified by their phenotype in an incross of heterozygous carriers. Because some homozygous embryos survive, identified embryos could be raised to adulthood. At different times during regeneration, fins were photographed and photographs were blinded before analysis. The length of the regenerate (from the amputation plane to the distal tip of the fin) at the third, fourth and fifth dorsal fin ray was measured using IMAGE J software (NIH, http://rsb.info.nih.gov/ij/) and the average length of the regenerate calculated for each fish. To exclude that variations in the position of the amputation plane might have caused differences in regenerative speed, the exact position of the amputation plane was measured in each fish. We found that there was no significant difference in the position of the amputation plane between wild-type and *mbl* or *ppt* fish.

#### Semi-quantitative and quantitative RT-PCR

Total RNA was extracted from zebrafish fin regenerates using TRIZOL according to the manufacturer's protocol (Invitrogen). RNA was digested with DNase and purified using the Qiagen RNeasy Kit. Equal amounts of total RNA from each sample were reverse transcribed with Thermoscript reverse transcriptase (Invitrogen) using oligo(dT) and random hexamer primers. For semi-quantitative PCR, amplification of ornithine decarboxylase (*odc1*) was used as the loading control. *fgf20a* (primers 5′-GCAGATTTGGTATATTGGAATTCAT-3′ and 5′-CTAGAACATCC-TTGTAAAGCTCAGG-3′) and *odc1* (primers 5′-ACTTTGACTTCGC-CTTCCTG-3′ and 5′-CACCTTCATGAGCTCCACCT-3′) PCR products were detected on Ethidium Bromide-stained agarose gels. Quantitative PCR was performed using a Roche Lightcycler and the SYBR Green Labeling System. *wnt10a* was amplified using primers 5′-ATTCACTCCAG-GATGAGACTTCATA-3′ and 5′-GTTTCTGTTGTGGGCTTTGATTAG-3′. *wnt10a* expression levels were normalized to β-actin (primers 5′-GGTATGGGACAGAAAGACAG-3′ and 5′-AGAGTCCATCACGATAC-CAG-3′) or 18S rRNA (primers 5′-CGCTATTGGAGCTGGAATTACC-3′ and 5′-GAAACGGCTACCACATCCAA-3′) levels. Primers for quantitative PCR of *fgf20a* were 5′-CAGCTTCTCTCACGGCTTGG-3′ and 5′-AAAGCTCAGGAACTCGCTCTG-3′ (Whitehead et al., 2005).

## RESULTS

### Wnt/β-catenin signaling is activated during regeneration

Since the zebrafish tail fin is a good model for epimorphic regeneration (Poss et al., 2003) and is highly amenable to experimental manipulation, we studied the role of Wnt signaling in regeneration using the zebrafish fin model. Expression of Wnt ligands and of components of the β-catenin signaling pathway has been reported in regenerating amphibian and fish appendages (Caubit et al., 1997a; Caubit et al., 1997b; Poss et al., 2000a), suggesting that Wnt/β-catenin signaling is upregulated during regeneration. The endpoint of Wnt/β-catenin signaling is transcriptional regulation of target genes; however, because Wnt signaling is tightly regulated by extracellular, cytoplasmic and nuclear inhibitors, expression of Wnt ligands does not necessarily result in activation of transcription. Thus, to test whether the Wnt/β-catenin pathway is functional during zebrafish fin regeneration, we asked whether a transcriptional reporter of Wnt/β-catenin signaling, TOPdGFP (Dorsky et al., 2002), is activated in response to fin amputation in TOPdGFP transgenic zebrafish. We found that TOPdGFP is detectable in the blastema of the regenerating fin at 2 days post-amputation (dpa) (Fig. 1A). We also found that the expression of *axin2*, which has been shown to be a direct Wnt target gene in several systems (Jho et al., 2002; Leung et al., 2002; Lustig et al., 2002; Weidinger et al., 2005) and of *sp8*, which is regulated by Wnt/β-catenin signaling in fin and limb development (Kawakami et al., 2004), were upregulated in regenerating zebrafish tail fins (Fig. 1B).

We then investigated which Wnt ligands might be responsible for activation of Wnt/β-catenin signaling during regeneration of the tail fin. We found that *wnt10a*, which has been shown to activate Wnt/β-catenin signaling during limb development (Narita et al., 2005), is expressed early during regeneration. Expression of *wnt10a* was detected in the distal tip of the blastema (Fig. 1B). Using quantitative PCR, we found that expression of *wnt10a* was upregulated very early during regeneration, expression being 2.3-fold higher than in uncut fins 3 hours post-amputation (hpa) and 5.3-fold higher at 6 hpa (Fig. 1C). Thus, *wnt10a* is an excellent candidate for a Wnt ligand responsible for early activation of the β-catenin signaling pathway during fin regeneration. Interestingly, we found that Wnt signaling activity, as detected by transgenic reporters, is also upregulated during zebrafish heart and mouse liver regeneration (see Fig. S1 in the supplementary material), suggesting that activation of Wnt/β-catenin signaling may be a conserved feature of regeneration.

We also tested whether Wnts that have been shown to signal via β-catenin-independent pathways in other systems (Slusarski et al., 1997; Veeman et al., 2003), are expressed during zebrafish fin regeneration. We cloned the zebrafish ortholog of *wnt5a* (see Fig. S2 in the supplementary material) and found that its expression is induced after the blastema has formed and is maintained throughout regeneration. We observed *wnt5a* expression in the basal epithelial layer of the regeneration epidermis as well as in the distal tip of the blastema (Fig. 1B). *wnt5b* (*pipetail*; for nomenclature, see Fig. S2 in the supplementary material) which, like *wnt5a*, has been shown to signal via β-catenin-independent pathways in other systems (Westfall et al., 2003), was also expressed in the basal epithelial layer of the epidermis, albeit only at the very tip of the regenerate, as well as in the distal tip of the blastemal mesenchyme (Fig. 1B). These data suggest that β-catenin-independent Wnt signaling pathways, activated by Wnt5 paralogs, play a role in fin regeneration.

### Wnt/β-catenin signaling is required for fin regeneration

To test the requirement of Wnt/β-catenin signaling for fin regeneration we created a line of zebrafish that are transgenic for heat-shock inducible Dickkopf1 (hsDkk1GFP; see Fig. S3 in the supplementary material), a secreted inhibitor of Wnt/β-catenin signaling (Glinka et al., 1998). Activation of the transgene during embryogenesis phenocopies the effects of *wnt8* loss-of-function (see Fig. S3G-I in the supplementary material) and is sufficient to suppress expression of the TOPdGFP Wnt/β-catenin reporter in doubly transgenic embryos 3 hours after induction (see Fig. S3J-K in the supplementary material). Heat shock induces ubiquitous

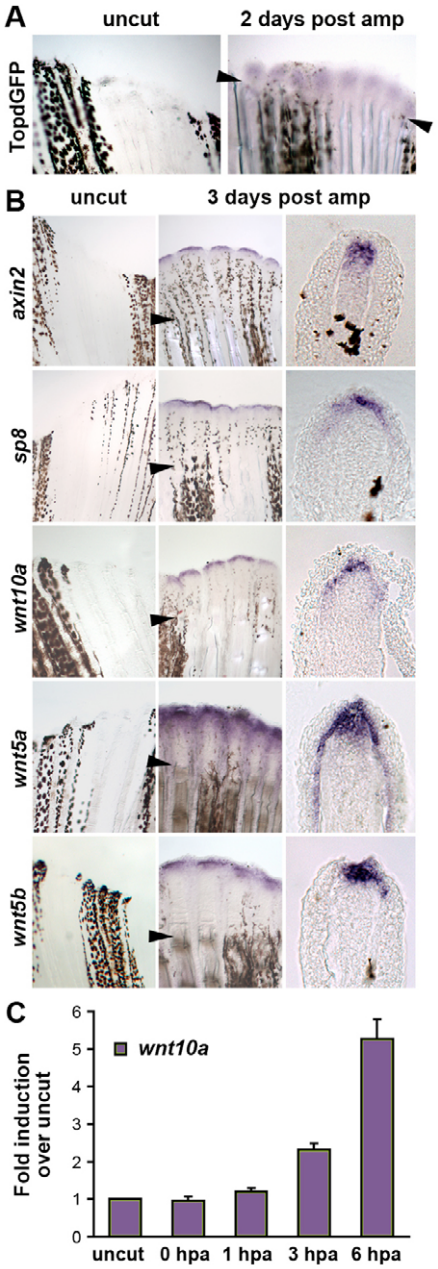


**Fig. 1. Wnt/β-catenin signaling is upregulated in regenerating zebrafish tail fins.** (**A**) Wnt/β-catenin reporter (TOPdGFP) activity, detected by in situ hybridization for GFP RNA (blue), is upregulated in the blastema of regenerating fins of zebrafish homozygous for the transgene at 48 hpa (*n*=5; arrowheads indicate the amputation plane). Control is a non-amputated TOPdGFP fin. At 3 dpa (*n*=3) and 5 dpa (*n*=3), TOPdGFP was still upregulated (not shown). (**B**) In situ hybridization of control non-amputated fins (left panels), regenerating fins at 3 dpa (middle panels), and cross-sections of fins at the same stage (right panels). The Wnt/β-catenin target genes *axin2* and *sp8* are expressed in the distal tip of the blastemal mesenchyme and in the basal epithelial layer of the regeneration epidermis, respectively. *wnt10a* is expressed in the distal tip of the blastema. Both *wnt5a* (for nomenclature, see Fig. S2 in the supplementary material) and *wnt5b* are expressed in the basal epithelial layer of the regeneration epidermis and in the distal tip of the blastema, with *wnt5a* extending far proximally in the basal epithelium. (**C**) *wnt10a* expression levels in uncut control and regenerating fins at 0 hpa (sample isolated immediately after fin amputation), 1 hpa, 3 hpa and 6 hpa as determined by quantitative PCR. RNA was isolated from the tips of fins of 10 wild-type fish for each time point. Expression levels were normalized to β-actin levels (normalization to 18S rRNA levels produced very similar results) and fold-induction calculated by setting the level of uncut fins to 1. Quantitative PCR was performed four times on the same samples; error bars represent the s.e.m.

expression of the transgene (as monitored by GFP expression) in embryos and regenerating adult tail fins (see Fig. S3C-F in the supplementary material). Thus, this transgenic line represents an excellent tool to study the functions of Wnt/β-catenin signaling during late embryogenesis and in adults. Additionally, we employed a zebrafish line transgenic for a heat-shock inducible dominant-negative form of the transcription factor Tcf3 (T-cell factor 3) (hsΔTcfGFP), which has been shown to efficiently inhibit expression of Wnt/β-catenin target genes (Lewis et al., 2004). When we heat shocked the fish 2 hours before fin amputation and continued to heat shock twice daily for 7 days, we found that regeneration was completely blocked in both hsDkk1GFP and hsΔTcfGFP transgenic fish, whereas regeneration in heat-shocked wild-type fish was unperturbed (Fig. 2A,B).

Fin regeneration can be divided into three phases: wound healing, which happens within 24 hpa at 29°C; blastema formation (approximately 24-48 hpa); and regenerative outgrowth (starting around 48 hpa). Our inducible transgenic system allowed us to test when Wnt/β-catenin signaling is required during regeneration. Interestingly, when we started to inhibit Wnt/β-catenin signaling by heat shock after wound healing had taken place, but before the regeneration blastema had formed (24 hpa, Fig. 2A), regeneration was again completely blocked (Fig. 2C, left panel). Thus, impaired regeneration in Dkk1-overexpressing fish is not a consequence of failed wound healing, but instead is due to a specific requirement for Wnt/β-catenin signaling during blastema formation. We also asked whether Wnt/β-catenin signaling is important for the outgrowth phase of fin regeneration. To do this, we began heat shocking hsDkk1GFP transgenic fish at 72 hpa (Fig. 2A). These fish displayed incomplete regeneration (Fig. 2C, right panel), indicating that Wnt/β-catenin signaling is not only required for formation of the blastema, but subsequently for blastema maintenance and/or proliferation.

## Wnt/β-catenin signaling regulates blastema formation and subsequent proliferation

To characterize the cell biological functions of Wnt/β-catenin during fin regeneration, we carried out assays to test for specific effects of Dkk1 overexpression on cell specification and proliferation. Heat shock of hsDkk1GFP fish starting shortly before amputation resulted in a loss of expression of *lef1*, a marker for the basal epidermis (Poss et al., 2000a), by 24 hpa, indicating that the basal layer of the wound epidermis was not being specified correctly (Fig. 3A). We also found that expression of *msxb*, a marker for the mesenchymal progenitor cells of the regeneration blastema (Poss et al., 2000b), and of *shh*, which is normally expressed within basal epidermal cells (Poss et al., 2000b), was lost by 72 hpa in Dkk1-expressing fins (Fig. 3A). Histological examination confirmed that formation of the regeneration blastema was severely impaired in hsDkk1GFP fish, although the wound healed properly (Fig. 3B). These data show that neither the blastema mesenchyme nor the overlying epithelium are specified correctly following loss of Wnt/β-catenin signaling.

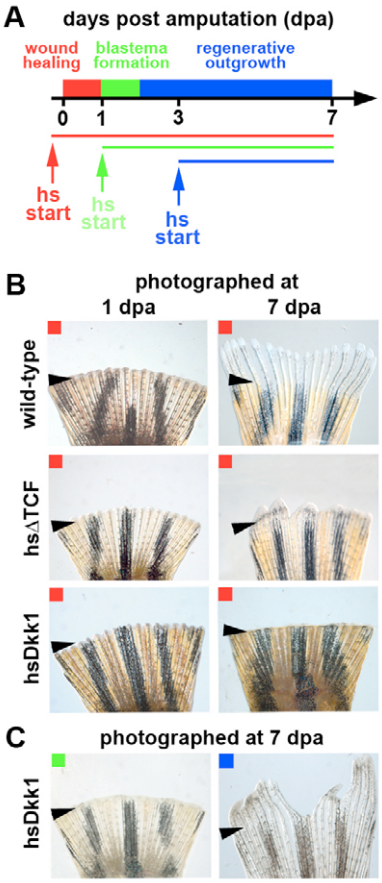


**Fig. 2. Wnt/β-catenin signaling is required for zebrafish tail fin regeneration.** (**A**) Experimental scheme. Tail fins were amputated from wild-type, hsDkk1GFP or hsΔTcfGFP transgenic zebrafish and heat shocks were applied twice daily for the time periods indicated by the colored lines. (**B**) Continuous suppression of Wnt target gene expression in hsΔTcfGFP (*n*=15), or reduction of Wnt/β-catenin signaling in hsDkk1GFP transgenic fish (*n*=19), for 7 days starting shortly before amputation inhibits fin regeneration. Live fins were photographed at 1 dpa (left panels) and 7 dpa (right panels). (**C**) Overexpression of Dkk1 starting at 1 dpa inhibits fin regeneration (left panel; *n*=18); overexpression from 3 dpa results in partial inhibition of regeneration (right panel; 11 of 15 fins). Live fins were photographed at 7 dpa; corresponding wild-type controls regenerated normally (not shown).

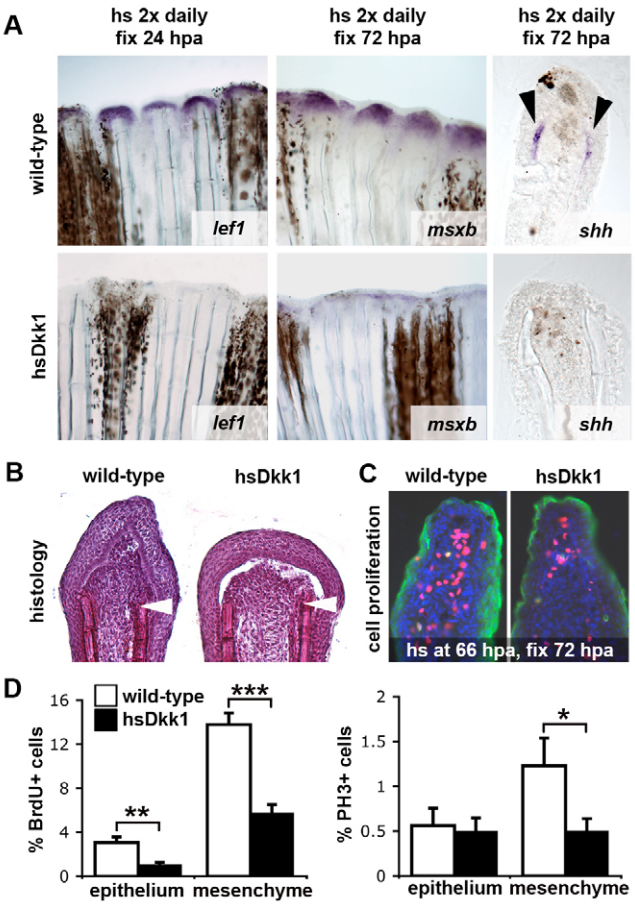


**Fig. 3. Wnt/β-catenin signaling regulates specification and proliferation of the regeneration blastema.** (**A**) Expression of *lef1*, a marker for the basal epidermal layer of the regeneration epithelium, *msxb*, marking the mesenchymal progenitor cells of the blastema, and *shh*, expressed in basal epidermal cells (shown in thick sections), is strongly reduced in Dkk1-overexpressing fins. *lef1* is shown at 24 hpa (*n*=4), *msxb* (*n*=4) and *shh* (*n*=4) at 72 hpa. Fish were heat shocked twice daily starting shortly before amputation. (**B**) Hematoxylin-stained sections of tail fin regenerates at 48 hpa. Dkk1-overexpressing fins (right panel; *n*=6) display reduced numbers of deep mesenchymal cells of the blastema. Fish were heat shocked twice daily starting shortly before amputation. Arrowheads indicate the plane of amputation. (**C**) 72 hpa regenerates stained for BrdU (red), phosphorylated histone H3 (PH3, green) and DAPI (blue). Cell proliferation in both the mesenchyme and epithelium is decreased in Dkk1-overexpressing fins. Fish were heat shocked once at 66 hpa and fixed at 72 hpa. (**D**) Quantification of the cell proliferation defects in Dkk1-overexpressing regenerating fins. The fraction of BrdU-positive (left) and PH3-positive (right) cells relative to the total number of cells (DAPI-positive) is shown in percent (*n*=11). Error bars represent the s.e.m; **P*=0.0495; ***P*=0.0025; ****P*=7.076×10$^{-6}$ (two-tailed).

To test whether Wnt/β-catenin signaling is required for proliferation of the blastema, we inhibited Wnt signaling by a single pulse of Dkk1 expression in regenerating fins during the outgrowth phase of regeneration at 3 dpa. We assayed for cell proliferation 6 hours after heat shock using BrdU incorporation and staining for phosphorylated histones. We observed that loss of Wnt/β-catenin signaling lead to a reduction in proliferation of both the blastema mesenchyme and the overlying epithelium (Fig. 3C,D). Thus, Wnt/β-catenin signaling is required for the formation and subsequent proliferation of the blastema.

## Wnt/β-catenin signaling is sufficient to enhance regeneration

We next investigated whether enhanced Wnt/β-catenin signaling is sufficient to augment regeneration. To activate Wnt/β-catenin signaling we used transgenic fish that overexpress Wnt8 after heat shock (hsWnt8GFP) (Weidinger et al., 2005). During embryogenesis, heat shock of these fish causes characteristic Wnt/β-catenin gain-of-function phenotypes (Weidinger et al., 2005).

Induction of Wnt8 during fin regeneration increased expression of the Wnt/β-catenin target gene *axin2* (Fig. 4A), showing that overexpression of Wnt8 in the fin is sufficient to augment β-catenin signaling. Importantly, overexpression of Wnt8 at 72 hpa significantly increased proliferation of the blastema mesenchyme and overlying epithelium 6 hours after induction of the transgene, as

detected by BrdU incorporation and anti-phosphorylated histone H3 antibody staining (Fig. 4B). Despite its ability to increase proliferation, overexpression of Wnt8 had no consistent effect on fin length by 10 dpa (Fig. 4C). However, the short half-life of Wnt proteins and the pulsed activation of the transgene raise the question of whether a more prolonged and consistent activation of the pathway might be sufficient to augment overall fin regeneration.

To test this, we made use of fish in which one copy of *axin1*, an inhibitor of the Wnt/β-catenin signaling pathway, is mutated (Heisenberg et al., 2001), and asked whether *axin1*$^{+/-}$ fins regenerate more rapidly. To minimize effects of the genetic background, we used wild-type and *axin1*$^{+/-}$ fish that were siblings derived from a cross of a wild-type fish with an *axin1* heterozygous carrier. We genotyped the fish, amputated fins of 12 wild-type and 9 *axin1* heterozygous mutant fish, allowed them to regenerate for 7 days, photographed the fins, blinded the photographs, measured the length of the regenerate (from the amputation plane to the distal tip of the fin) in the third, fourth and fifth dorsal fin ray in each fish and calculated the average length of the regenerate of each fish (experiment 1). The same fish were

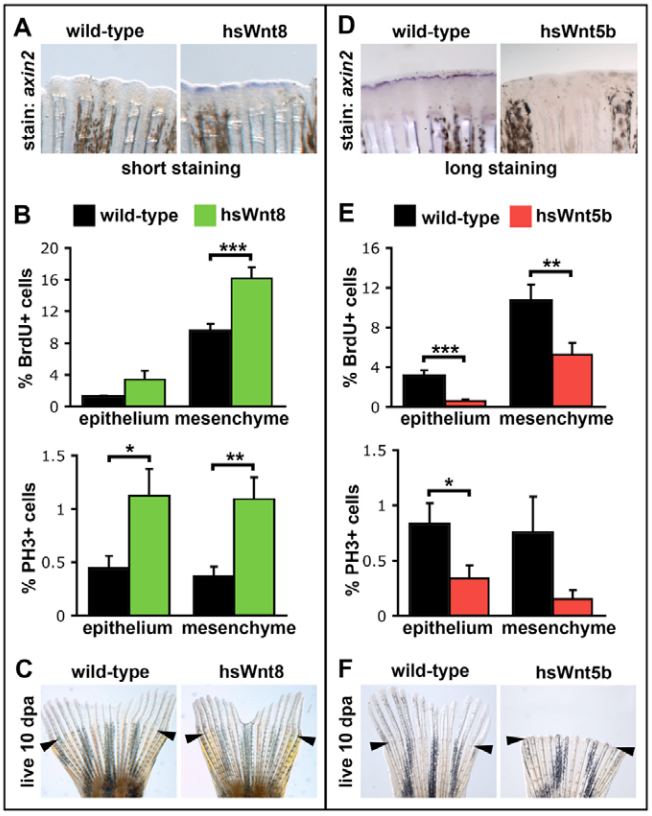


**Fig. 4. β-catenin-dependent and β-catenin-independent Wnt signaling pathways have opposing roles in zebrafish fin regeneration.** (**A**,**D**) Overexpression of Wnt8 in hsWnt8GFP transgenic fish induces the Wnt/β-catenin target gene *axin2* in regenerating fins 6 hours after heat shock at 3 dpa (A; 3 of 4 fins), whereas overexpression of Wnt5b in hsWnt5bGFP transgenic fish represses *axin2* expression (D; *n*=4). Note that staining reactions were stopped as soon as a robust signal could be detected in most samples of one experimental group. Robust signal was first detected in hsWnt8GFP fins (versus wild-type controls) after a short amount of time and reactions were stopped (A), whereas robust signal was first detected in wild-type controls (versus hsWnt5GFP fins) after a longer staining reaction (D), thus accounting for the difference in wild-type signal between groups. (**B**,**E**) Cell proliferation in regenerating fins, as detected by BrdU incorporation and staining with an anti-PH3 antibody, is increased by overexpression of Wnt8 (B; *n*=14), and repressed by overexpression of Wnt5b (E; *n*=10). Fish were heat shocked once at 66 hpa and fixed at 72 hpa. The percentage of BrdU-positive or PH3-positive cells relative to the total number of cells in sections of regenerating fins is shown. Error bars represent the s.e.m. (**C**,**F**) Whereas overexpression of Wnt8 for 10 days starting shortly before amputation has no obvious effect on overall length of the regenerate (C; *n*=16), overexpression of Wnt5b completely inhibits regeneration (F; *n*=16). (B) **P*=0.0579; ***P*=0.0082; ****P*=0.0002 (two-tailed). (E) **P*=0.0377; ***P*=0.0123; ****P*=0.0006 (two-tailed).

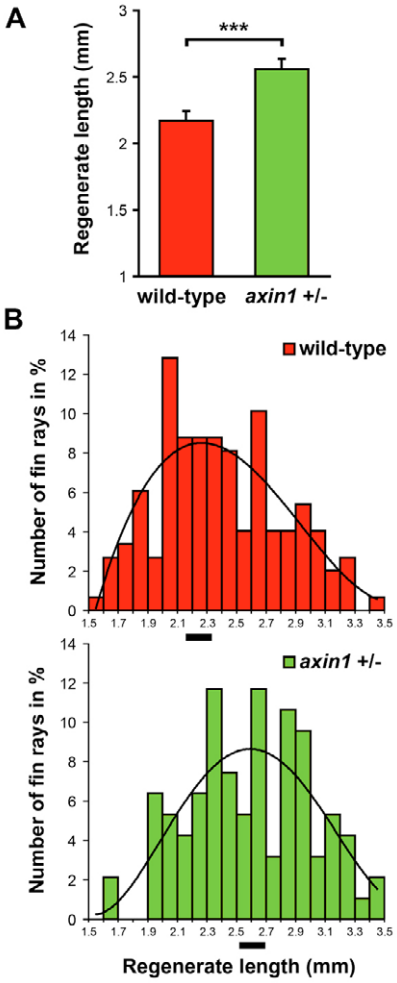


**Fig. 5. Fins regenerate faster in fish heterozygous for a loss-of-function mutation in *axin1*.** (**A**) Average length of regenerating tail fins at 7 dpa is increased in fish heterozygous for an *axin1* loss-of-function mutation (*mbl*$^{tm013}$) compared with wild-type siblings. Results of one representative experiment of three are shown. To determine the length of the regenerate for individual fish, the average length of the third, fourth and fifth dorsal regenerating fin ray was calculated. *n*=12 wild-type fish and 9 *mbl* heterozygous fish; error bars represent the s.e.m. of the average regenerate lengths; ***, *P*=0.0009 (one-tailed). (**B**) The number of fin rays (in percent of the total number counted) is plotted against the length of the regenerate (in 0.1 mm intervals) for wild-type (upper bar graph) and *axin1* heterozygous fish (lower bar graph). The curves represent a fifth-order polynomial trendline. The average regenerate length is marked by black bars at the *x*-axis. 148 fin rays were counted (combined results from three experiments) in 19 wild-type fish and 94 rays were counted in 10 *axin1*$^{+/-}$ fish.

re-amputated and remeasured twice (experiments 2 and 3, respectively) after a 2- to 3-week recovery period. In the third experiment, several additional fish were included.

Intriguingly, in all three experiments, the regenerates of *axin1*$^{+/-}$ fins were significantly longer (as determined by a Student's *t*-test) than those of wild-type siblings at 7 dpa (9.5%, 15.1% and 7.1% longer, respectively). Fig. 5A shows the average length of the regenerates in wild-type and *axin1*$^{+/-}$ fish as measured in the second experiment (for data from all three experiments, see Table S1 in the supplementary material). To assess the error rate of measurement, we repeatedly measured the same pictures blinded by a colleague. The average error between repeated measurements was 0.87%, insignificant compared with the differences measured between the wild-type and *axin1*$^{+/-}$ fins. When we combine the measurements of individual wild-type fin rays from all three experiments and create a frequency histogram of the data, we find that the length of wild-type regenerates ranges from 1.48 to 3.36 mm, with the average length being 2.29 mm (Fig. 5B). *axin1* regenerates exhibit the same length range as wild-type fins (1.52 to 3.33 mm). However, the distribution in the length of *axin1* fin rays is shifted towards longer regenerates, with an average length of 2.49 mm (Fig. 5B). A Mann-Whitney test shows that the difference in fin ray length is highly significant ($P$=0.0003).

In summary, these findings not only indicate that increased Wnt/β-catenin signaling results in faster regeneration, but also provide genetic evidence for the involvement of Wnt signaling in regenerative processes, which has not been previously addressed in any system.

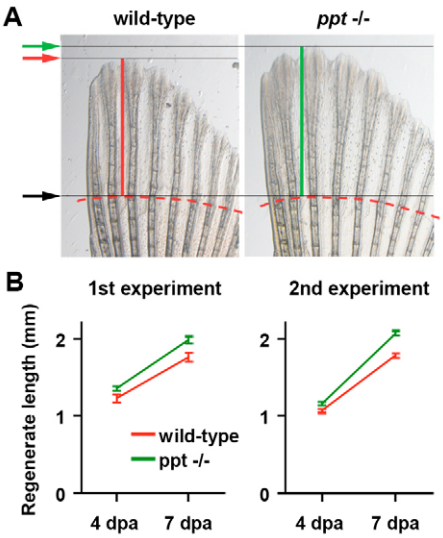


**Fig. 6. Fins regenerate faster in *wnt5b* mutant fish.** (**A**) Dorsal half of regenerating tail fins of wild-type and *wnt5b* (*ppt*) homozygous mutant fish at 7 dpa. The amputation plane is indicated by a dashed red line, the length of the third fin ray by red or green bars and arrows. Note that the regenerate is longer in *ppt* than in wild-type fish. (**B**) The average length of the regenerate of wild-type and *ppt* mutant fish at 4 and 7 dpa in two independent experiments. To determine the length of the regenerate for individual fish, the average length of the third, fourth and fifth dorsal regenerating fin ray was calculated. Experiment 1: $n$=14 wild-type, 12 *ppt* fish. Experiment 2: $n$=12 wild-type, 11 *ppt* fish. Error bars represent the s.e.m. of the average regenerate lengths. For $P$ values, see Table S2 in the supplementary material. Note that absolute fin lengths cannot be compared between experiments because water temperatures and thus regenerative speed and exact times of photography varied between experiments.

## *wnt5b* overexpression inhibits fin regeneration

As Wnts that can act through the Wnt/β-catenin pathway (*wnt10a*) and through β-catenin-independent pathways (*wnt5a*, *wnt5b*) are expressed during fin regeneration (Fig. 1), we next tested whether these distinct Wnt pathways might have different roles in fin regeneration. We compared the effects of activation of Wnt/β-catenin signaling with those produced by activation of β-catenin-independent Wnt signaling. To this end, we generated a transgenic zebrafish line carrying a heat-shock inducible Wnt5bGFP transgene (hsWnt5bGFP; see Fig. S3 in the supplementary material). Wnt5b has been shown to activate β-catenin-independent signaling pathways in zebrafish embryos (Westfall et al., 2003). Accordingly, heat-shocked hsWnt5bGFP embryos display the characteristic phenotypes associated with gain-of-function of β-catenin-independent Wnt pathways, namely defects in convergence-extension cell movements during gastrulation and somitogenesis (see Fig. S3L,M in the supplementary material).

Interestingly, whereas overactivation of Wnt/β-catenin signaling enhances regeneration, overexpression of Wnt5b represses regeneration. Heat shock of hsWnt5bGFP transgenic fish for 10 days starting shortly before fin amputation completely inhibited fin regeneration (Fig. 4F). This is in marked contrast to the effects of overexpressing Wnt8, which had no obvious effect on overall fin morphology (Fig. 4C), but closely resembled the defects caused by inhibition of Wnt/β-catenin signaling via Dkk1 overexpression (Fig. 2B). As with overexpression of Dkk1, but in contrast to Wnt8, overexpression of Wnt5b significantly reduced proliferation of the blastema mesenchyme and overlying epithelium 6 hours after induction of the transgene, as detected by BrdU incorporation and anti-phosphorylated histone H3 antibody staining (Fig. 4E). Thus, activation of Wnt5b inhibits fin regeneration.

Although it is difficult to test which signaling pathways Wnt5b activates in the regenerating fin, the fact that it causes dramatically different effects than Wnt8, which signals via β-catenin, suggests that it is likely to act through β-catenin-independent pathways. Since Wnt5b overexpression causes the same phenotypes as Wnt/β-catenin loss-of-function, and because β-catenin-independent Wnt signaling has been reported to be able to inhibit Wnt/β-catenin signaling in other systems (Weidinger and Moon, 2003), we hypothesize that Wnt5b overexpression inhibits fin regeneration by repressing Wnt/β-catenin signaling. In support of this model, we found that Wnt5b overexpression abolished expression of the direct Wnt/β-catenin target gene *axin2* 6 hours after heat shock at 3 dpa (Fig. 4D).

## *wnt5b* loss-of-function augments fin regeneration

We next tested whether endogenous *wnt5b* acts as an essential modulator of fin regeneration. If non-canonical Wnt signaling activated by *wnt5b* inhibits regeneration in vivo, loss of *wnt5b* function in the regenerating fin might result in enhanced or faster regeneration. To test this prediction, we made use of homozygous adult *wnt5b* (*pipetail*) mutant fish. We amputated tail fins of *wnt5b* mutant and age- and size-matched wild-type fish of the same genetic background, measured the length of the third, fourth and fifth dorsal fin ray at 4 and 7 dpa, and calculated the average length of the regenerate for each fish (Fig. 6A). In two independent sets of experiments using different fish (experiments 1 and 2), we found that *wnt5b* mutants had significantly longer regenerates than wild types at both 4 and 7 dpa (Fig. 6A,B and see Table S2 in the supplementary material). The difference in length between wild-type and *wnt5b* mutant regenerates increased between 4 and 7 dpa,

showing that *wnt5b* mutant fins regenerate faster (Fig. 6B). These data provide genetic evidence that *wnt5b* acts as a negative modulator of fin regeneration. *Wnt5b* mutant regenerating fins did not show any obvious patterning defects or indications of tumor formation or other signs of inappropriate growth (Fig. 6A), suggesting that *wnt5b* is only required to modulate the overall rate of regeneration.

It is tempting to speculate that this antagonistic role of β-catenin-independent signaling activated by *wnt5b* (and possibly *wnt5a*) during fin regeneration represents a negative feedback mechanism that regulates the levels and/or duration of Wnt/β-catenin signaling. If so, we would expect the expression of *wnt5* paralogs to be regulated by Wnt/β-catenin signaling in the regenerating fin. Indeed, we found that *wnt5b* expression is downregulated in Dkk1-overexpressing fins 6 hours after heat shock at 3 dpa (see Fig. S4 in the supplementary material). Taken together, these data strongly suggest that β-catenin-independent Wnt signaling activated by *wnt5b* and possibly *wnt5a* acts in a negative feedback loop to inhibit Wnt/β-catenin signaling during fin regeneration (Fig. 8).

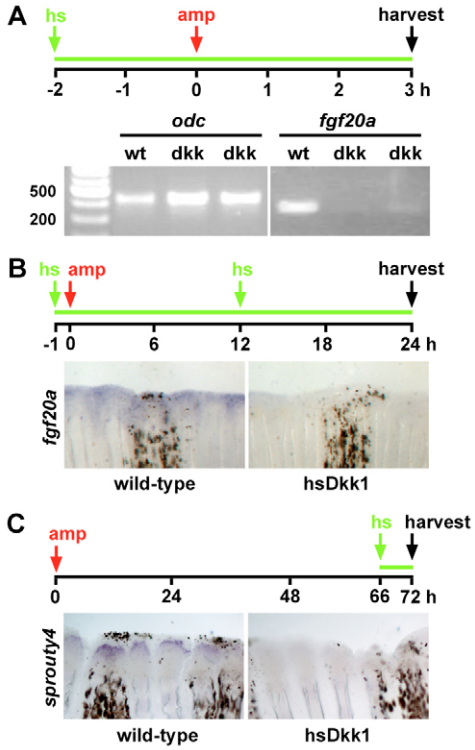


**Fig. 7. Wnt/β-catenin signaling regulates FGF signaling during fin regeneration.** (**A**) *fgf20a* expression as detected by semi-quantitative RT-PCR is greatly reduced in Dkk1-overexpressing fins at 3 hpa. Wild-type and hsDkk1GFP transgenic fish were treated according to the schematic (hs, heat shock; amp, amputation; the green line indicates inhibition of Wnt/β-catenin signaling), and RNA was harvested from the tissue adjacent to the amputation plane of nine wild-type and two groups of nine hsDkk1GFP transgenic fins. *odc1* amplification serves as a loading control. The experiment was repeated four times using two sets of biological samples and representative results are shown. (**B**) *fgf20a* expression is greatly reduced as detected by in situ hybridization in hsDkk1GFP transgenic fins (5 of 6 fins) at 24 hpa as compared with wild-type fins. (**C**) *sprouty4* expression is greatly reduced 6 hours after heat shock in hsDkk1GFP fins ($n$=3) at 72 hpa.

## Wnt/β-catenin signaling regulates FGF signaling during fin regeneration

FGF signaling has been shown to be required for regeneration of amphibian and fish appendages (Lee et al., 2005; Poss et al., 2000b; Yokoyama et al., 2001) and recently *fgf20a* was found to be induced early during zebrafish fin regeneration and to be required for blastema formation (Whitehead et al., 2005). Similarly, we observe that *wnt10a* is induced very early in regenerating fins and that Wnt/β-catenin signaling is essential for formation of the blastema. Therefore, to gain more mechanistic insight into the role of Wnt/β-catenin signaling in fin regeneration, we investigated whether Wnt/β-catenin signaling regulates FGF signaling during regeneration. Strikingly, we found that levels of *fgf20a* transcripts are suppressed 3 hours after amputation in Dkk1-overexpressing fins (Fig. 7A), and that *fgf20a* expression is still not detectable in hsDkk1GFP fins at 24 hpa (Fig. 7B). Quantitative PCR revealed that induction of Dkk1 2 hours prior to amputation resulted in severe downregulation of the baseline of *fgf20a* expression at the time of amputation and in the suppression of *fgf20a* upregulation during the first 48 hours of regeneration (see Fig. S5 in the supplementary material). These findings show that Wnt/β-catenin signaling is required for initiation of *fgf20a* expression during regeneration. The fast response and the repression of basic *fgf20a* levels in hsDkk1 fins indicate that *fgf20a* downregulation is not an indirect consequence of a failure of these fins to regenerate, but is likely to reflect a more direct regulation of *fgf20a* expression by Wnt/β-catenin signaling.

In addition, we observed that in fins that have been allowed to regenerate normally for 72 hours, a single pulse of Dkk1 expression quickly results in the repression of *sprouty4*, an FGF target gene (Lee et al., 2005) (Fig. 7C). We conclude that Wnt/β-catenin signaling is also required for the maintenance of FGF signaling. These findings indicate that Wnt/β-catenin signaling acts upstream

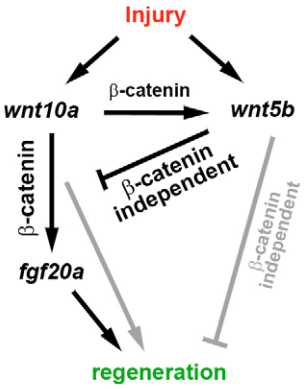


**Fig. 8. A model of signaling events regulating zebrafish fin regeneration.** We propose that injury of the tail fin activates as yet unknown signals that result in upregulation of *wnt10a* and *wnt5b*. *wnt5b* expression is also regulated by Wnt/β-catenin signaling activated by *wnt10a*. *Wnt10a* activates a β-catenin-dependent signaling pathway that positively regulates *fgf20a* expression, which has been shown to be required for blastema formation and subsequent regeneration (Whitehead et al., 2005). In addition to its role in regulating *fgf20a* expression, Wnt/β-catenin signaling might also regulate other genes that are required for blastema formation and proliferation (gray arrow). We propose that *wnt5b* employs a β-catenin-independent signaling pathway that antagonizes Wnt/β-catenin signaling. However, we cannot exclude the possibility that such β-catenin-independent pathways also inhibit regeneration without impairing Wnt/β-catenin signaling (gray arrow). Arrows do not imply direct events.

of FGF signaling during regeneration, placing Wnt/β-catenin signaling at the top of the hierarchy of signaling pathways known to be required for epimorphic regeneration (Fig. 8).

## DISCUSSION

Our findings further an understanding of the molecular events that initiate regenerative processes by demonstrating a crucial role for Wnt/β-catenin signaling in epimophic regeneration of the zebrafish tail fin, and an antagonistic role for β-catenin-independent Wnt signaling. Based on our results and those of others, we propose the following model for signaling pathways regulating zebrafish fin regeneration (Fig. 8). Injury of the fin activates signal(s) that rapidly induce expression of *wnt10a* and possibly other Wnt ligands that activate the β-catenin signaling pathway. The nature of these signals and whether they directly or indirectly regulate expression of Wnt ligands is unknown. One potential candidate that might indirectly activate Wnt expression is thrombin, which is activated by the wound-healing response and which has been shown to be involved in regeneration of newt lens and limb myotubes (Imokawa and Brockes, 2003; Imokawa et al., 2004; Tanaka et al., 1999). Wnt10a activates the β-catenin signaling pathway, which directly or indirectly activates expression of *fgf20a*, which in turn activates (directly or indirectly) the events resulting in blastema formation and thus regeneration (Whitehead et al., 2005). Although we have not tested whether *wnt10a* activates *fgf20a* expression directly in the regenerating fin, it is intriguing that *fgf20a* has been found to be a direct target of Wnt/β-catenin signaling in cultured human cells (Chamorro et al., 2005). Since we have not tested whether Wnt/β-catenin signaling acts solely through *fgf20a* to regulate blastema formation, we cannot exclude the possibility that β-catenin signaling also controls regeneration in parallel to FGF signaling (gray arrow in Fig. 8).

The same injury-activated signal(s) that regulate *wnt10a* expression might also activate expression of *wnt5a* and *wnt5b* and potentially other Wnt ligands that activate β-catenin-independent signaling. We postulate that these signaling pathways modulate regeneration by negatively regulating Wnt/β-catenin signaling. However, we cannot exclude the possibility that β-catenin-independent Wnt signaling also represses regeneration independently of its antagonistic effect on β-catenin signaling (gray arrow in Fig. 8). Because we find that expression of *wnt5b* is regulated by Wnt/β-catenin signaling, we hypothesize that these separate Wnt pathways establish a negative feedback loop whose function might be to ensure proper levels, duration or location of β-catenin signaling in the regenerating fin.

In addition to its role in blastema formation, FGF signaling appears to be absolutely required for the regenerative outgrowth of the fin, as drugs that block FGF signaling can inhibit fin regeneration during this phase (Poss et al., 2000b). Our experiments indicate that Wnt/β-catenin signaling is also required for regenerative outgrowth. However, overexpression of Dickkopf1 does not cause a complete inhibition of outgrowth. It is possible that the expression levels of Dkk1 are not sufficient to completely block β-catenin signaling during this regenerative phase. Alternatively, other signals that are partially redundant with Wnt/β-catenin signaling might compensate for the loss of Wnt signaling. We have found that Wnt/β-catenin signaling regulates FGF signaling during regenerative outgrowth, and thus it appears likely that β-catenin signaling acts through FGF signaling in this phase of regeneration as well.

Elucidation of the exact cell biological role of Wnt/β-catenin and FGF signaling in blastema formation awaits further experiments. Whereas regeneration of the zebrafish tail fin occurs in similar steps to salamander limb regeneration, blastema formation by de-differentiation of differentiated cells has so far only been reported in salamanders. Interestingly, a recent report has shown that resident muscle stem cells are activated during salamander limb regeneration and that progeny of these cells take part in the formation of the blastema (Morrison et al., 2006). It is likely that the relative contribution of de-differentiation and resident stem cell activation to the formation of progenitor cells during regeneration varies between organs and organisms, with amphibian limbs likely to represent one end of the spectrum where de-differentiation is prominent and, at the other end, processes like mammalian muscle or bone regeneration being driven only by activation of resident stem cells. Whether Wnt/β-catenin and FGF signaling regulate de-differentiation or stem cell activation or both in blastema formation is at present unclear. Interestingly, Wnt/β-catenin signaling has been shown to be important for regeneration or repair of systems that are thought to rely largely or solely on activation of resident stem cells. Inhibition of Wnt/β-catenin signaling reduces proliferation of CD45+ resident stem cells in mammalian muscle regeneration (Polesskaya et al., 2003) and inhibits proliferation of osteoblasts, which drive bone repair, in culture (Zhong et al., 2006). Wnt/β-catenin signaling has also been reported to be active during regeneration of deer antlers and to be required for survival of antler bone progenitor cells in culture (Mount et al., 2006). Very recently, Hayashi et al. have shown that Wnt/β-catenin signaling is necessary and sufficient for regeneration of newt lenses in culture (Hayashi et al., 2006). More specifically, Wnt signaling appears to regulate the second step of regeneration in which, subsequent to proliferation of the iris pigmented epithelium and activation of early lens genes in the whole iris, only the dorsal iris continues to develop (Hayashi et al., 2006). Thus, together with our results showing that β-catenin signaling is required for fin regeneration and our data showing that β-catenin signaling is activated during mouse liver and zebrafish heart regeneration, evidence is beginning to emerge that Wnt/β-catenin signaling might play central roles in many regenerative processes. However, the specific function of Wnt signaling in the regeneration of different organs is most likely to differ. For example, in the newt lens, Wnt signaling is only activated after the initial phase of proliferation and gene expression and is required for the second step of regeneration. By contrast, we have shown that Wnt signaling regulates gene expression very early in fin regeneration and that it is required for the early events of blastema formation.

A better understanding of the role of Wnt/β-catenin and FGF signaling in de-differentiation and/or stem cell activation during epimorphic regeneration is hampered by the fact that our insights into signaling events that regulate epimorphic regeneration come mainly from systems such as zebrafish, where de-differentiation has not been reported. Thus, further insights into the role of these pathways awaits better characterization of the cell biological events of blastema formation in zebrafish or the development of tools that facilitate genetic and other in vivo functional studies in salamanders.

Our study not only demonstrates an important role for Wnt/β-catenin signaling during regeneration, but also adds to our knowledge about the functions of β-catenin-independent Wnt signaling in adults. In vertebrates, it is well established that β-catenin-independent Wnt signaling is required for cell polarity and cell movements during gastrulation, and has also been implicated in endoderm cell migration, pancreas cell migration, the migration of neurons and organization of hair cell polarity in the inner ear (Bingham et al., 2002; Carreira-Barbosa et al., 2003; Curtin et al., 2003; Jessen et al., 2002; Kim et al., 2005; Matsui et al., 2005; Wada et al., 2005). It is less clear whether β-catenin-independent Wnt

signaling plays roles in cell fate determination. Interestingly, however, it has been shown that β-catenin-independent Wnt signaling can inhibit Wnt/β-catenin signaling and thus can, indirectly at least, regulate cell fate. For example, overexpression of β-catenin-independent Wnt ligands in *Xenopus* blocks the ability of 'canonical' Wnt ligands to activate β-catenin signaling and to induce a secondary body axis. Genetic evidence for the existence of such opposing roles of β-catenin-independent Wnt signaling on Wnt/β-catenin signaling comes from zebrafish, where maternal loss of *wnt5b* has been reported to result in ectopic β-catenin signaling and a consequent increase in dorsal cell fates (Weidinger and Moon, 2003; Westfall et al., 2003). Furthermore, loss of *wnt5a* in mouse limb buds likewise results in ectopic β-catenin signalling, causing defective chondrocyte differentiation (Topol et al., 2003). We propose that β-catenin-independent Wnt signaling, activated by *wnt5a* and *wnt5b*, plays a similar antagonistic role in fin regeneration. Our finding that *wnt5b* expression appears to be regulated by β-catenin signaling suggests the existence of a negative feedback loop. Such a loop represents a mechanism for regulation of β-catenin signaling that, to our knowledge, has not been described before. It will be interesting to see whether the transcriptional activation of Wnt ligands that activate antagonistic β-catenin-independent pathways is a more widespread regulatory mechanism employed by organisms to keep β-catenin signaling in check.

Taken together, our findings add to our mechanistic insight into the regulation of regeneration by demonstrating separate and opposing roles for β-catenin-dependent and β-catenin-independent signaling pathways during fin regeneration. Furthermore, although regeneration of the mammalian liver and the zebrafish heart employ different cellular mechanisms than regeneration of the zebrafish fin or amphibian limbs (with only the latter two involving formation of a blastema), it is intriguing that Wnt/β-catenin signaling is upregulated during regeneration of all three organs. Although beyond the scope of the present study, it will be very interesting to test what role Wnt signaling plays in regeneration of these organs. It is conceivable that our findings will prove to be important for the goals of regenerative medicine, as the modulation of Wnt signaling pathways might augment the regeneration of human tissues.

We thank Laurel Rohde and Carl-Philipp Heisenberg for *ppt* homozygous fish; Thuy Tran, Jerry Ament and Jeanot Muster for fish care and technical assistance; and Steve Springer for assistance with phylogenetic analyses. C.S.-C. is a recipient of a NIH-funded Cardiovascular Pathology Training Grant. G.W. and M.B.M. are associates and R.T.M. is an investigator of the Howard Hughes Medical Institute, which supported this research. N.F. and R.T.M. also receive grants from the National Institutes of Health. K.J.R. is supported by an American College of Surgeons Resident Research scholarship and C.H. is supported by a post-doctoral F32 NRSA NIH training grant.

**Supplementary material**

Supplementary material for this article is available at http://dev.biologists.org/cgi/content/full/134/3/479/DC1

**References**

**Akimenko, M. A., Johnson, S. L., Westerfield, M. and Ekker, M.** (1995). Differential induction of four msx homeobox genes during fin development and regeneration in zebrafish. *Development* **121**, 347-357.

**Akimenko, M. A., Mari-Beffa, M., Becerra, J. and Geraudie, J.** (2003). Old questions, new tools, and some answers to the mystery of fin regeneration. *Dev. Dyn.* **226**, 190-201.

**Beck, C. W., Christen, B. and Slack, J. M.** (2003). Molecular pathways needed for regeneration of spinal cord and muscle in a vertebrate. *Dev. Cell* **5**, 429-439.

**Bingham, S., Higashijima, S., Okamoto, H. and Chandrasekhar, A.** (2002). The Zebrafish trilobite gene is essential for tangential migration of branchiomotor neurons. *Dev. Biol.* **242**, 149-160.

**Brockes, J. P. and Kumar, A.** (2002). Plasticity and reprogramming of differentiated cells in amphibian regeneration. *Nat. Rev. Mol. Cell Biol.* **3**, 566-574.

**Campbell, J. S., Riehle, K. J., Brooling, J. T., Bauer, R. L., Mitchell, C. and Fausto, N.** (2006). Proinflammatory cytokine production in liver regeneration is Myd88-dependent, but independent of Cd14, Tlr2, and Tlr4. *J. Immunol.* **176**, 2522-2528.

**Carreira-Barbosa, F., Concha, M. L., Takeuchi, M., Ueno, N., Wilson, S. W. and Tada, M.** (2003). Prickle 1 regulates cell movements during gastrulation and neuronal migration in zebrafish. *Development* **130**, 4037-4046.

**Casimir, C. M., Gates, P. B., Patient, R. K. and Brockes, J. P.** (1988). Evidence for dedifferentiation and metaplasia in amphibian limb regeneration from inheritance of DNA methylation. *Development* **104**, 657-668.

**Caubit, X., Nicolas, S. and Le Parco, Y.** (1997a). Possible roles for Wnt genes in growth and axial patterning during regeneration of the tail in urodele amphibians. *Dev. Dyn.* **210**, 1-10.

**Caubit, X., Nicolas, S., Shi, D. L. and Le Parco, Y.** (1997b). Reactivation and graded axial expression pattern of Wnt-10a gene during early regeneration stages of adult tail in amphibian urodele Pleurodeles waltl. *Dev. Dyn.* **208**, 139-148.

**Chamorro, M. N., Schwartz, D. R., Vonica, A., Brivanlou, A. H., Cho, K. R. and Varmus, H. E.** (2005). FGF-20 and DKK1 are transcriptional targets of beta-catenin and FGF-20 is implicated in cancer and development. *EMBO J.* **24**, 73-84.

**Curtin, J. A., Quint, E., Tsipouri, V., Arkell, R. M., Cattanach, B., Copp, A. J., Henderson, D. J., Spurr, N., Stanier, P., Fisher, E. M. et al.** (2003). Mutation of Celsr1 disrupts planar polarity of inner ear hair cells and causes severe neural tube defects in the mouse. *Curr. Biol.* **13**, 1129-1133.

**DasGupta, R. and Fuchs, E.** (1999). Multiple roles for activated LEF/TCF transcription complexes during hair follicle development and differentiation. *Development* **126**, 4557-4568.

**Dejmek, J., Dejmek, A., Safholm, A., Sjolander, A. and Andersson, T.** (2005). Wnt-5a protein expression in primary dukes B colon cancers identifies a subgroup of patients with good prognosis. *Cancer Res.* **65**, 9142-9146.

**Dorsky, R. I., Sheldahl, L. C. and Moon, R. T.** (2002). A transgenic Lef1/beta-catenin-dependent reporter is expressed in spatially restricted domains throughout zebrafish development. *Dev. Biol.* **241**, 229-237.

**Echeverri, K. and Tanaka, E. M.** (2002). Ectoderm to mesoderm lineage switching during axolotl tail regeneration. *Science* **298**, 1993-1996.

**Echeverri, K., Clarke, J. D. and Tanaka, E. M.** (2001). In vivo imaging indicates muscle fiber dedifferentiation is a major contributor to the regenerating tail blastema. *Dev. Biol.* **236**, 151-164.

**Fausto, N., Campbell, J. S. and Riehle, K. J.** (2006). Liver regeneration. *Hepatology* **43**, S45-S53.

**Fischer, A. J. and Reh, T. A.** (2001). Muller glia are a potential source of neural regeneration in the postnatal chicken retina. *Nat. Neurosci.* **4**, 247-252.

**Glinka, A., Wu, W., Delius, H., Monaghan, A. P., Blumenstock, C. and Niehrs, C.** (1998). Dickkopf-1 is a member of a new family of secreted proteins and functions in head induction. *Nature* **391**, 357-362.

**Grogg, M. W., Call, M. K., Okamoto, M., Vergara, M. N., Del Rio-Tsonis, K. and Tsonis, P. A.** (2005). BMP inhibition-driven regulation of six-3 underlies induction of newt lens regeneration. *Nature* **438**, 858-862.

**Halloran, M. C., Sato-Maeda, M., Warren, J. T., Su, F., Lele, Z., Krone, P. H., Kuwada, J. Y. and Shoji, W.** (2000). Laser-induced gene expression in specific cells of transgenic zebrafish. *Development* **127**, 1953-1960.

**Hayashi, T., Mizuno, N., Takada, R., Takada, S. and Kondoh, H.** (2006). Determinative role of Wnt signals in dorsal iris-derived lens regeneration in newt eye. *Mech. Dev.* **123**, 793-800.

**Heisenberg, C. P., Houart, C., Take-Uchi, M., Rauch, G. J., Young, N., Coutinho, P., Masai, I., Caneparo, L., Concha, M. L., Geisler, R. et al.** (2001). A mutation in the Gsk3-binding domain of zebrafish Masterblind/Axin1 leads to a fate transformation of telencephalon and eyes to diencephalon. *Genes Dev.* **15**, 1427-1434.

**Imokawa, Y. and Brockes, J. P.** (2003). Selective activation of thrombin is a critical determinant for vertebrate lens regeneration. *Curr. Biol.* **13**, 877-881.

**Imokawa, Y., Simon, A. and Brockes, J. P.** (2004). A critical role for thrombin in vertebrate lens regeneration. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **359**, 765-776.

**Jessen, J. R., Topczewski, J., Bingham, S., Sepich, D. S., Marlow, F., Chandrasekhar, A. and Solnica-Krezel, L.** (2002). Zebrafish trilobite identifies new roles for Strabismus in gastrulation and neuronal movements. *Nat. Cell Biol.* **4**, 610-615.

**Jho, E. H., Zhang, T., Domon, C., Joo, C. K., Freund, J. N. and Costantini, F.** (2002). Wnt/beta-catenin/Tcf signaling induces the transcription of Axin2, a negative regulator of the signaling pathway. *Mol. Cell. Biol.* **22**, 1172-1183.

**Jonsson, M., Dejmek, J., Bendahl, P. O. and Andersson, T.** (2002). Loss of Wnt-5a protein is associated with early relapse in invasive ductal breast carcinomas. *Cancer Res.* **62**, 409-416.

**Kawakami, Y., Esteban, C. R., Matsui, T., Rodriguez-Leon, J., Kato, S. and Belmonte, J. C.** (2004). Sp8 and Sp9, two closely related buttonhead-like transcription factors, regulate Fgf8 expression and limb outgrowth in vertebrate embryos. *Development* **131**, 4763-4774.

**Kim, H. J., Schleiffarth, J. R., Jessurun, J., Sumanas, S., Petryk, A., Lin, S. and**

**Ekker, S. C.** (2005). Wnt5 signaling in vertebrate pancreas development. *BMC Biol.* **3**, 23.
**Kintner, C. R. and Brockes, J. P.** (1984). Monoclonal antibodies identify blastemal cells derived from dedifferentiating limb regeneration. *Nature* **308**, 67-69.
**Kremenevskaja, N., von Wasielewski, R., Rao, A. S., Schofl, C., Andersson, T. and Brabant, G.** (2005). Wnt-5a has tumor suppressor activity in thyroid carcinoma. *Oncogene* **24**, 2144-2154.
**Lee, Y., Grill, S., Sanchez, A., Murphy-Ryan, M. and Poss, K. D.** (2005). Fgf signaling instructs position-dependent growth rate during zebrafish fin regeneration. *Development* **132**, 5173-5183.
**Lentz, T. L.** (1969). Cytological studies of muscle dedifferentiation and differentiation during limb regeneration of the newt Triturus. *Am. J. Anat.* **124**, 447-479.
**Leung, J. Y., Kolligs, F. T., Wu, R., Zhai, Y., Kuick, R., Hanash, S., Cho, K. R. and Fearon, E. R.** (2002). Activation of AXIN2 expression by beta-catenin-T cell factor. A feedback repressor pathway regulating Wnt signaling. *J. Biol. Chem.* **277**, 21657-21665.
**Lewis, J. L., Bonner, J., Modrell, M., Ragland, J. W., Moon, R. T., Dorsky, R. I. and Raible, D. W.** (2004). Reiterated Wnt signaling during zebrafish neural crest development. *Development* **131**, 1299-1308.
**Lo, D. C., Allen, F. and Brockes, J. P.** (1993). Reversal of muscle differentiation during urodele limb regeneration. *Proc. Natl. Acad. Sci. USA* **90**, 7230-7234.
**Logan, C. Y. and Nusse, R.** (2004). The Wnt signaling pathway in development and disease. *Annu. Rev. Cell Dev. Biol.* **20**, 781-810.
**Lustig, B., Jerchow, B., Sachs, M., Weiler, S., Pietsch, T., Karsten, U., van de Wetering, M., Clevers, H., Schlag, P. M., Birchmeier, W. et al.** (2002). Negative feedback loop of Wnt signaling through upregulation of conductin/axin2 in colorectal and liver tumors. *Mol. Cell. Biol.* **22**, 1184-1193.
**Matsui, T., Raya, A., Kawakami, Y., Callol-Massot, C., Capdevila, J., Rodriguez-Esteban, C. and Izpisua Belmonte, J. C.** (2005). Noncanonical Wnt signaling regulates midline convergence of organ primordia during zebrafish development. *Genes Dev.* **19**, 164-175.
**Morrison, J. I., Loof, S., He, P. and Simon, A.** (2006). Salamander limb regeneration involves the activation of a multipotent skeletal muscle satellite cell population. *J. Cell Biol.* **172**, 433-440.
**Mount, J. G., Muzylak, M., Allen, S., Althnaian, T., McGonnell, I. M. and Price, J. S.** (2006). Evidence that the canonical Wnt signalling pathway regulates deer antler regeneration. *Dev. Dyn.* **235**, 1390-1399.
**Narita, T., Sasaoka, S., Udagawa, K., Ohyama, T., Wada, N., Nishimatsu, S., Takada, S. and Nohno, T.** (2005). Wnt10a is involved in AER formation during chick limb development. *Dev. Dyn.* **233**, 282-287.
**Nechiporuk, A. and Keating, M. T.** (2002). A proliferation gradient between proximal and msxb-expressing distal blastema directs zebrafish fin regeneration. *Development* **129**, 2607-2617.
**Polesskaya, A., Seale, P. and Rudnicki, M. A.** (2003). Wnt signaling induces the myogenic specification of resident CD45+ adult stem cells during muscle regeneration. *Cell* **113**, 841-852.
**Poss, K. D., Shen, J. and Keating, M. T.** (2000a). Induction of lef1 during zebrafish fin regeneration. *Dev. Dyn.* **219**, 282-286.
**Poss, K. D., Shen, J., Nechiporuk, A., McMahon, G., Thisse, B., Thisse, C. and Keating, M. T.** (2000b). Roles for Fgf signaling during zebrafish fin regeneration. *Dev. Biol.* **222**, 347-358.
**Poss, K. D., Wilson, L. G. and Keating, M. T.** (2002). Heart regeneration in zebrafish. *Science* **298**, 2188-2190.
**Poss, K. D., Keating, M. T. and Nechiporuk, A.** (2003). Tales of regeneration in zebrafish. *Dev. Dyn.* **226**, 202-210.
**Raya, A., Consiglio, A., Kawakami, Y., Rodriguez-Esteban, C. and Izpisua-Belmonte, J. C.** (2004). The zebrafish as a model of heart regeneration. *Cloning Stem Cells* **6**, 345-351.
**Reya, T. and Clevers, H.** (2005). Wnt signalling in stem cells and cancer. *Nature* **434**, 843-850.
**Schnapp, E., Kragl, M., Rubin, L. and Tanaka, E. M.** (2005). Hedgehog signaling controls dorsoventral patterning, blastema cell proliferation and cartilage induction during axolotl tail regeneration. *Development* **132**, 3243-3253.
**Siemering, K. R., Golbik, R., Sever, R. and Haseloff, J.** (1996). Mutations that suppress the thermosensitivity of green fluorescent protein. *Curr. Biol.* **6**, 1653-1663.
**Slusarski, D. C., Yang-Snyder, J., Busa, W. B. and Moon, R. T.** (1997). Modulation of embryonic intracellular $Ca^{2+}$ signaling by Wnt-5A. *Dev. Biol.* **182**, 114-120.
**Sodhi, D., Micsenyi, A., Bowen, W. C., Monga, D. K., Talavera, J. C. and Monga, S. P.** (2005). Morpholino oligonucleotide-triggered beta-catenin knockdown compromises normal liver regeneration. *J. Hepatol.* **43**, 132-141.
**Spence, J. R., Madhavan, M., Ewing, J. D., Jones, D. K., Lehman, B. M. and Del Rio-Tsonis, K.** (2004). The hedgehog pathway is a modulator of retina regeneration. *Development* **131**, 4607-4621.
**Tanaka, E. M., Drechsel, D. N. and Brockes, J. P.** (1999). Thrombin regulates S-phase re-entry by cultured newt myotubes. *Curr. Biol.* **9**, 792-799.
**Taylor, G. P., Anderson, R., Reginelli, A. D. and Muneoka, K.** (1994). FGF-2 induces regeneration of the chick limb bud. *Dev. Biol.* **163**, 282-284.
**Thermes, V., Grabher, C., Ristoratore, F., Bourrat, F., Choulika, A., Wittbrodt, J. and Joly, J. S.** (2002). I-SceI meganuclease mediates highly efficient transgenesis in fish. *Mech. Dev.* **118**, 91-98.
**Topol, L., Jiang, X., Choi, H., Garrett-Beal, L., Carolan, P. J. and Yang, Y.** (2003). Wnt-5a inhibits the canonical Wnt pathway by promoting GSK-3-independent beta-catenin degradation. *J. Cell Biol.* **162**, 899-908.
**Veeman, M. T., Axelrod, J. D. and Moon, R. T.** (2003). A second canon. Functions and mechanisms of beta-catenin-independent Wnt signaling. *Dev. Cell* **5**, 367-377.
**Wada, H., Iwasaki, M., Sato, T., Masai, I., Nishiwaki, Y., Tanaka, H., Sato, A., Nojima, Y. and Okamoto, H.** (2005). Dual roles of zygotic and maternal Scribble1 in neural migration and convergent extension movements in zebrafish embryos. *Development* **132**, 2273-2285.
**Weidinger, G. and Moon, R. T.** (2003). When Wnts antagonize Wnts. *J. Cell Biol.* **162**, 753-755.
**Weidinger, G., Thorpe, C. J., Wuennenberg-Stapleton, K., Ngai, J. and Moon, R. T.** (2005). The Sp1-related transcription factors sp5 and sp5-like act downstream of Wnt/beta-catenin signaling in mesoderm and neuroectoderm patterning. *Curr. Biol.* **15**, 489-500.
**Westfall, T. A., Brimeyer, R., Twedt, J., Gladon, J., Olberding, A., Furutani-Seiki, M. and Slusarski, D. C.** (2003). Wnt-5/pipetail functions in vertebrate axis formation as a negative regulator of Wnt/beta-catenin activity. *J. Cell Biol.* **162**, 889-898.
**Whitehead, G. G., Makino, S., Lien, C. L. and Keating, M. T.** (2005). fgf20 is essential for initiating zebrafish fin regeneration. *Science* **310**, 1957-1960.
**Yokoyama, H., Ide, H. and Tamura, K.** (2001). FGF-10 stimulates limb regeneration ability in Xenopus laevis. *Dev. Biol.* **233**, 72-79.
**Zhong, N., Gersch, R. P. and Hadjiargyrou, M.** (2006). Wnt signaling activation during bone regeneration and the role of Dishevelled in chondrocyte proliferation and differentiation. *Bone* **39**, 5-16.