THE ROLE OF HYDRODYNAMICS IN THE DEVELOPMENT OF THE ZEBRAFISH CAUDAL FIN

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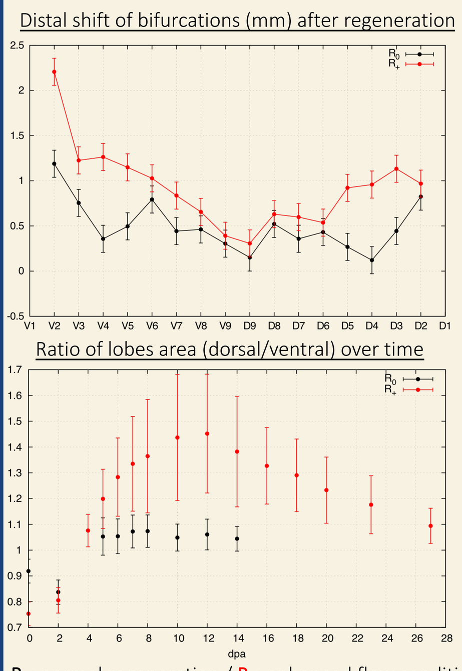
model organism

danio rerio

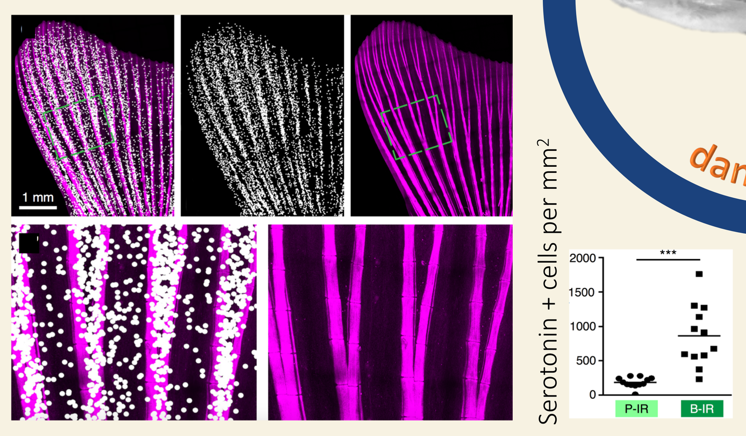
INTRODUCTION



R_0: normal regeneration / R_1: enhanced flow conditions

Plasticity

Variations in development result from variations in environmental conditions. Different hydrodynamic stresses on the fin induce different branching patterns (top) and growth rate asymmetry between the lobes (bottom).



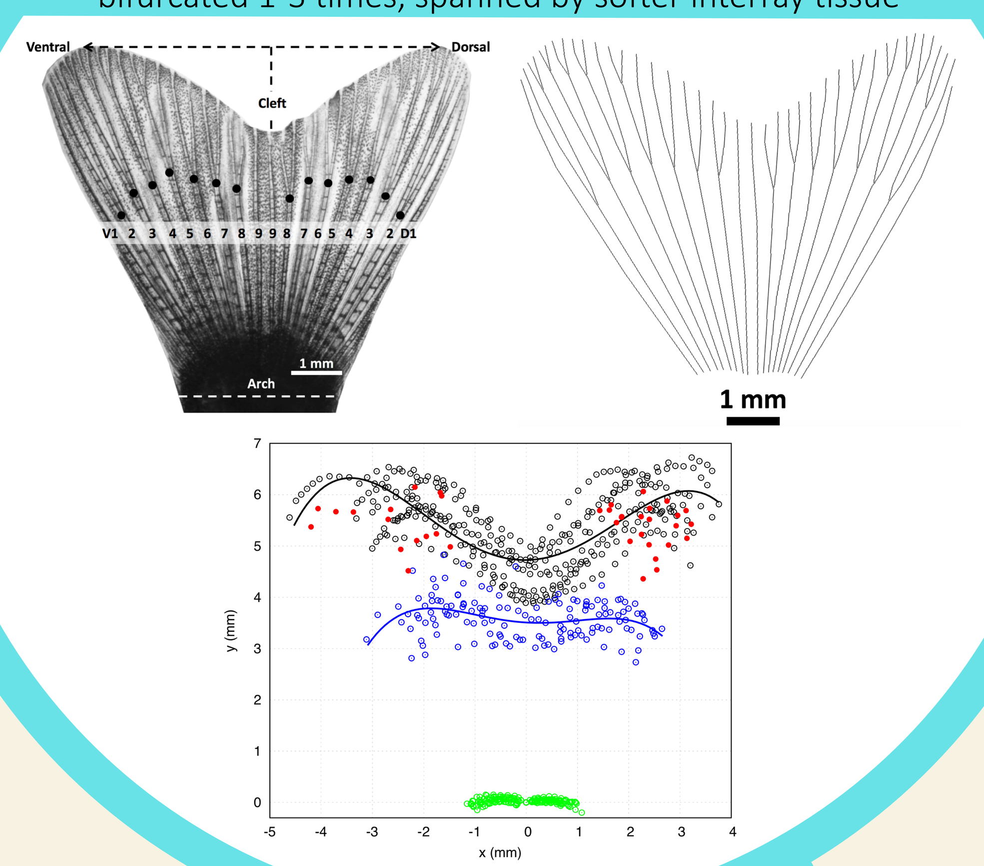
Chemoreceptive system

Enrichment of solitary chemosensory cells (SCC) in bifurcation interrays (BI) as compared to primary interrays (PI)

D. König *et al.*, 2018

Caudal fin morphology

Non-muscularized dermal appendage composed of regularly segmented hemirays (lepidotrichia), mostly bifurcated 1-3 times, spanned by softer interray tissue



Motivation

The goal is to study the interplay between the mechanical environment of biological structures and their morphogenesis. Evidences of plasticity in the zebrafish caudal fin include the distal shift of ray bifurcation points following regeneration. The ray branching pattern is correlated to hydrodynamic stress curves acting on the surface of an oscillating synthetic fin. Additionally, the spatial distribution of chemosensory cells on the fin is correlated with particular flow profiles in the bifurcation interray region.

METHODS

Calculations

Hydrodynamic pressure and shear stress

i-component of the stress (force per unit area) acting on any $\vec{n}$ oriented surface

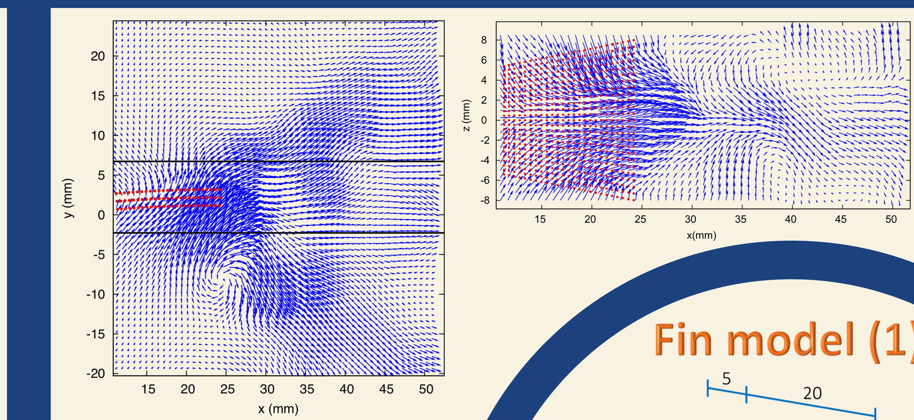
$$\sigma_i(\vec{r},t,\vec{n}) = s_{ij}(\vec{r},t)n_j$$

total stress tensor = PRESSURE + VISCOUS stress tensor

$$\boldsymbol{s} = -p\boldsymbol{I} + \boldsymbol{\tau} \qquad \tau_{ik} = \mu\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right)$$

$$\vec{\nabla}p = -\rho\left(\frac{D\vec{u}}{Dt} - \nu\nabla^2\vec{u}\right) \qquad p_2 - p_1 = \int_{\vec{r}_1}^{\vec{r}_2} \vec{\nabla}p \cdot d\vec{r}$$

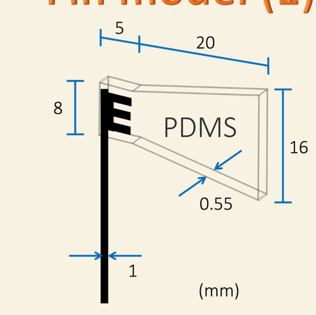
(algorithm by J. O. Dabiri *et al.*, 2014)



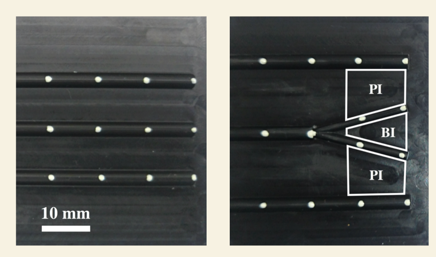
3D vectorial velocity field

A relaxation method is used for the particle tracking (probability based matching). The randomly spaced vector field is interpolated on a regular grid (top images: vertical and horizontal planes from the 3D field).

Fin model (1)



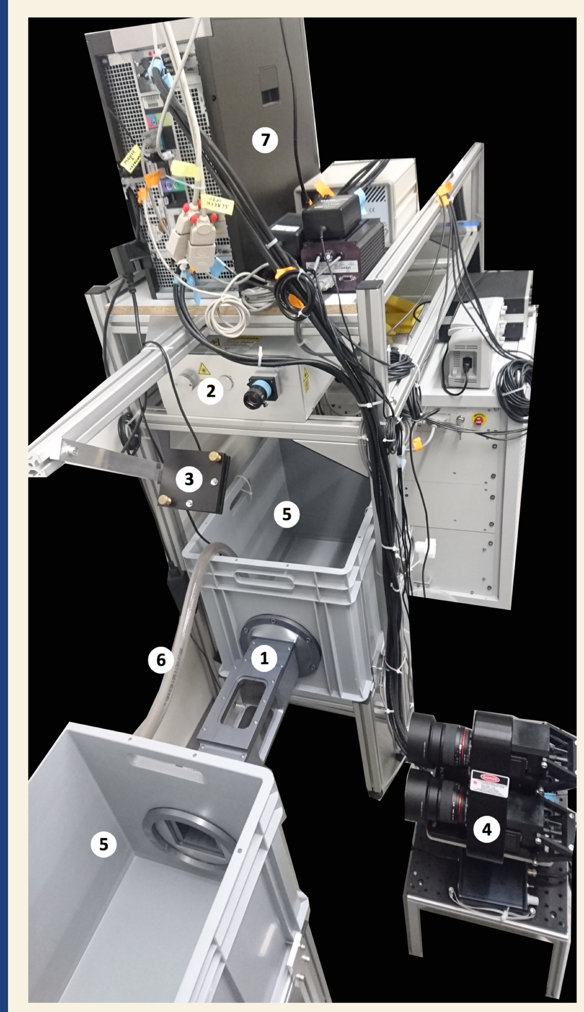
	Exp. 1	Exp.2
f (Hz)	3	3
θ_0(°)	10	25
U_∞(cm/s)	0	1.7



Fin model (2)

f=0.5 Hz / θ_0=11°/ U_∞=5 cm/s

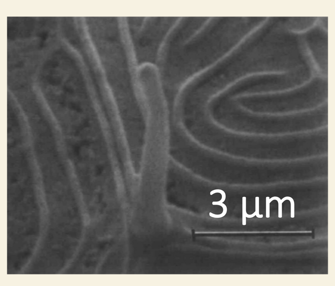
Rigid plate and rods model to mimick the primary (PI) and the bifurcation interray (BI) zones.



Experimental Set up

1. Flow chamber, encloses fin model and tracer particles (~40 µm) advected by the fluid
2. Double-pulsed laser (532 nm, 120 mJ/pulse max.)
3. Mirror to deflect the laser beam and illuminate the measurement volume
4. Camera triplet (4 MP, 180 Hz)
5. Water tanks connected with hose 6. and pump
7. V3V software for system synchronization and image post-processing

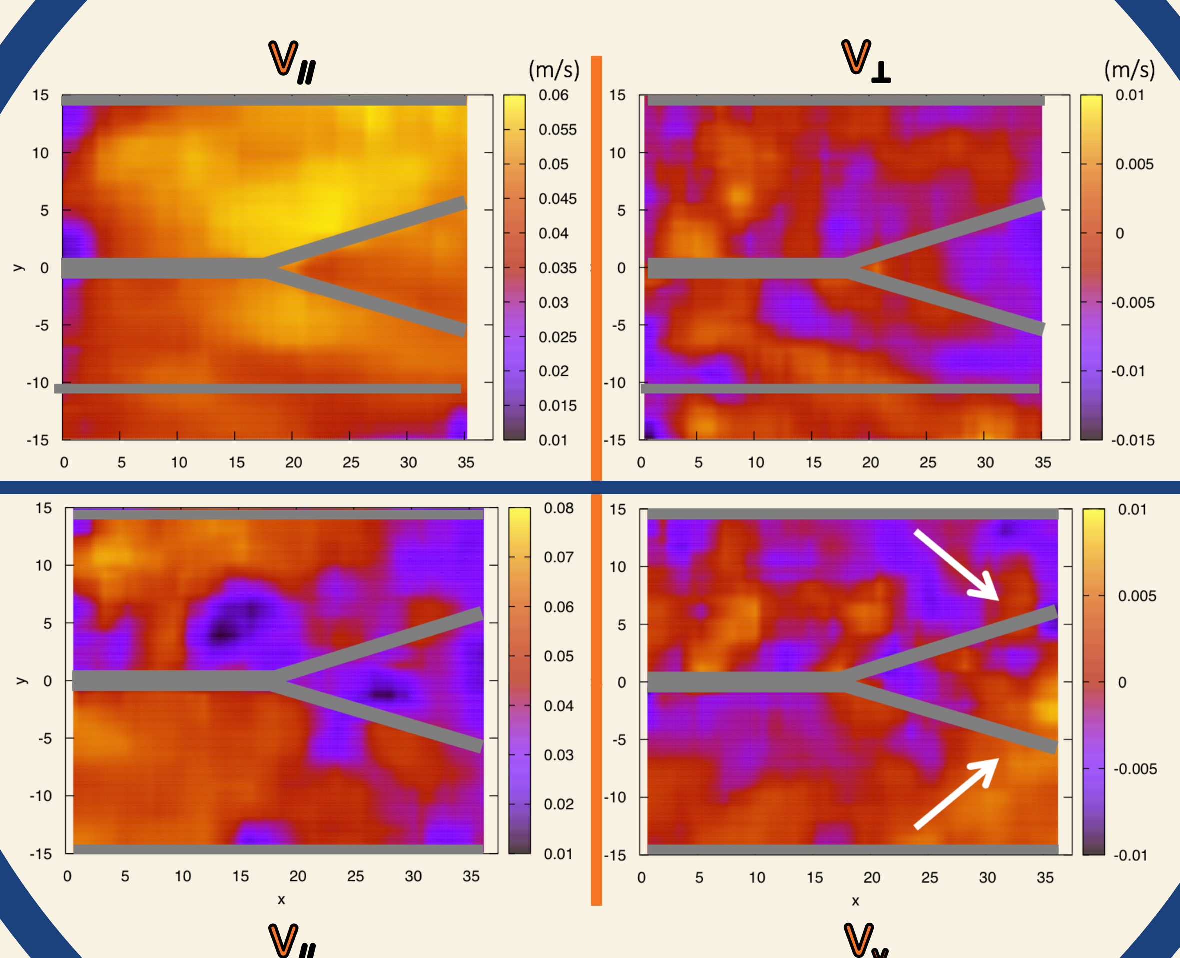
RESULTS – flow in the bifurcation region



Water flow around the SCC apices is crucial for sensory function, via the reduction of boundary layer thickness and/or turbulent mixing.

Apex of a SCC in an adult zebrafish (K. Kotrschal *et al.*, 1997)

max. angle (front)



0° angle (travelling back)

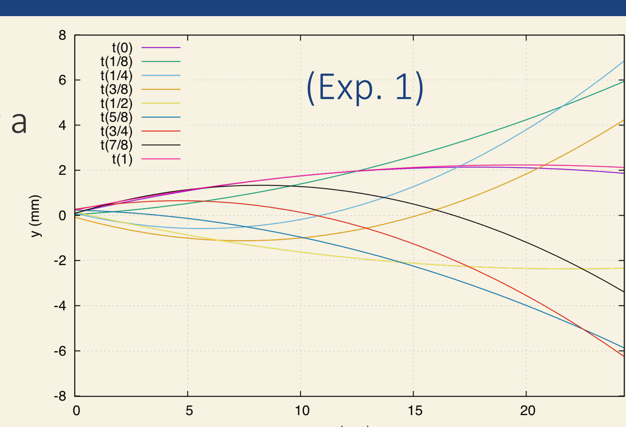
Enhanced flow towards the bifurcation interray, perpendicularly ($\mathbf{V_\perp}$) or vertically ($\mathbf{V_y}$), combined with a deceleration of the fluid parallel to the surface ($\mathbf{V_{/\!/}}$) in the V-shaped region

➘

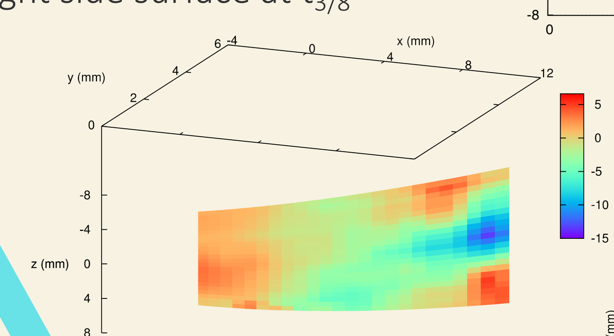
Increased access to chemical signals coming from outside the boundary layer while allowing a better local mixing through turbulence

RESULTS – hydrodynamic stress on the fin

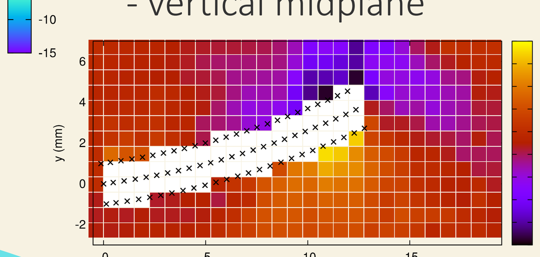
(a) Fin midline dynamics over a full period.



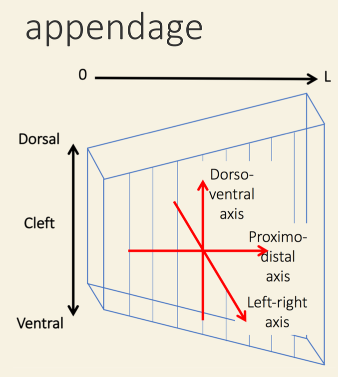
(b) Pressure (Pa) on the fin right side surface at $t_{3/8}$



(c) Pressure (Pa) at $t_{3/8}$ - vertical midplane



(d) Main axes on the propulsive appendage



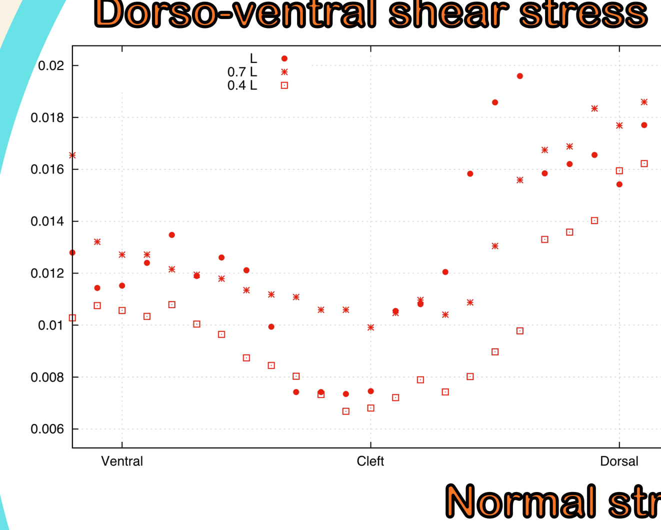
Hydrodynamic stress curves

(Exp. 2)

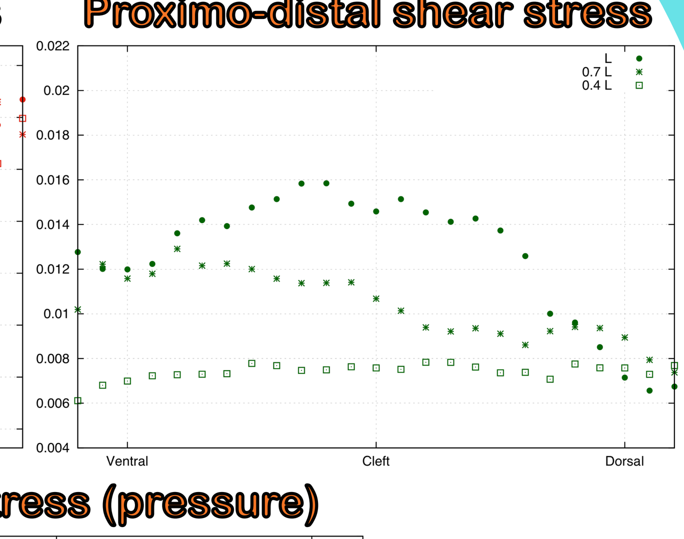
➞ Absolute values averaged on both sides and six oscillation periods

➞ Correlations with the fin morphology: bilobed edge, cleft depth, bifurcation plane

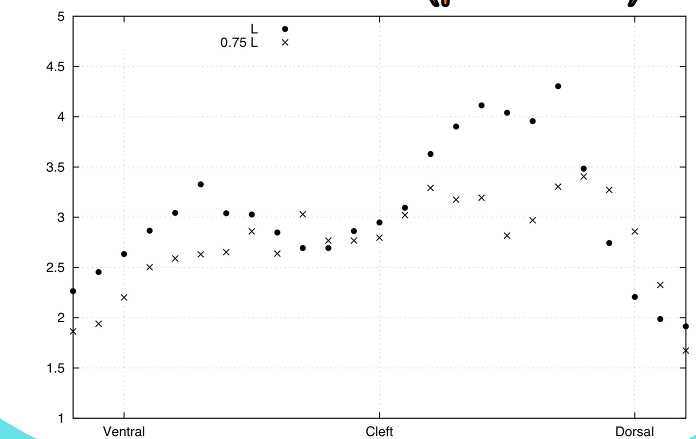
Dorso-ventral shear stress



Proximo-distal shear stress

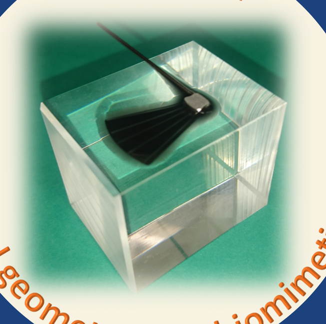


Normal stress (pressure)



***all in Pa**

OUTLOOK



refined geometries for biomimetic fins

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