Hydrodynamic stress and bone growth regulation in the zebrafish caudal fin

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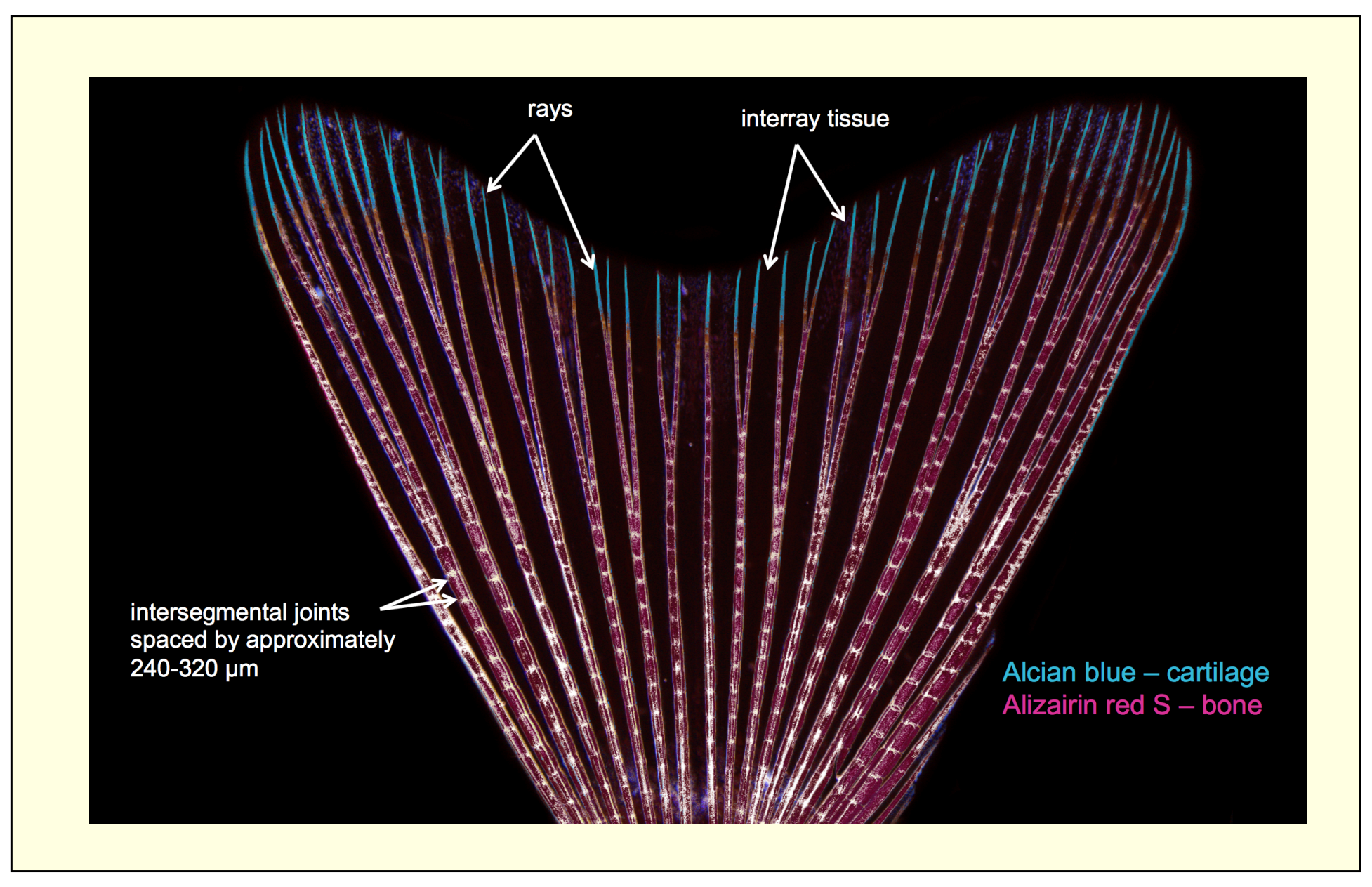
INTRODUCTION

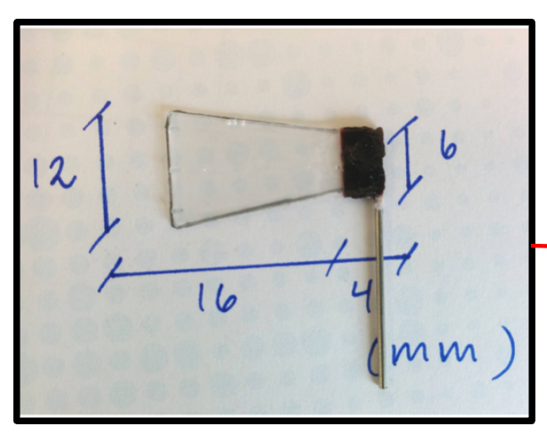
Patterning mechanisms, as the differentiation of bones, are influenced by environmental factors e.g. mechanical stress. A certain plasticity in the development of bones and organs allows the optimization of morphological structures to their functions. The zebrafish is a prototype organism for the study of feedbacks between environmental factors and growth regulation mechanisms. We focus on the caudal fin, a vertebrate organ capable of complete regeneration following amputation. Hydrodynamic pressure and viscous stress are measured on synthetic fins flapping in a flow chamber. The main goal is to pinpoint threshold forces acting on fin-like structures, and correlate those with morphologic patterning such as the distribution of bifurcation points in the caudal fin's bony rays.



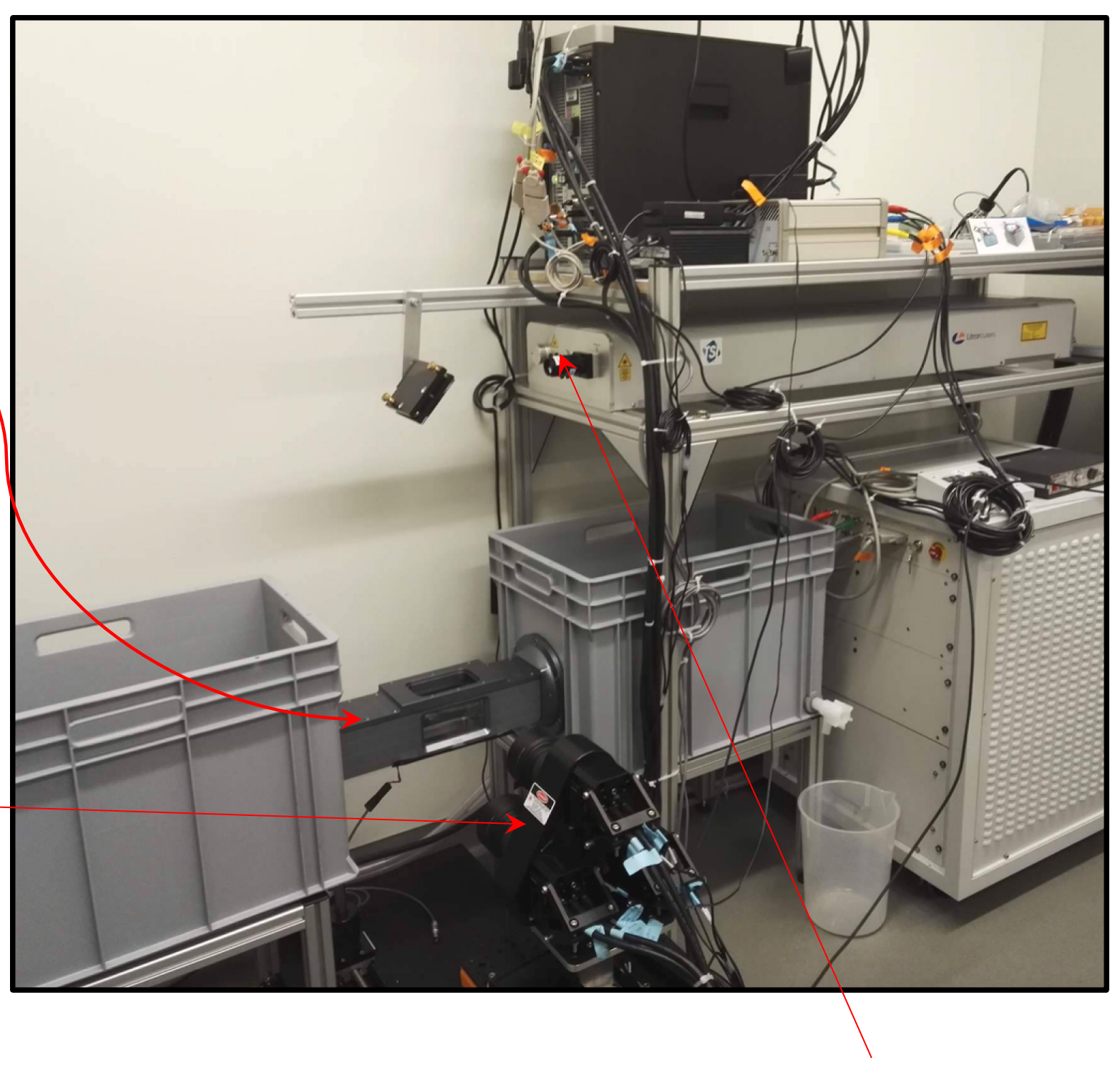
Zebrafish caudal fin. *Bony rays display plasticity in branching patterns.*
(C. Pfefferli, A. Jazwinska, 2015)

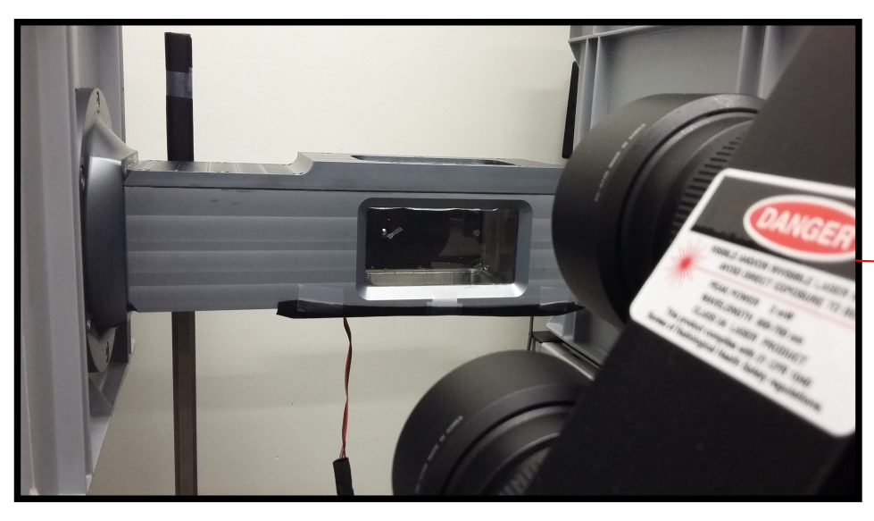
EXPERIMENTAL METHOD

3-D particle image velocimetry : Set up



Synthetic fin (PDMS) inserted in the flow chamber, activated by a servomotor



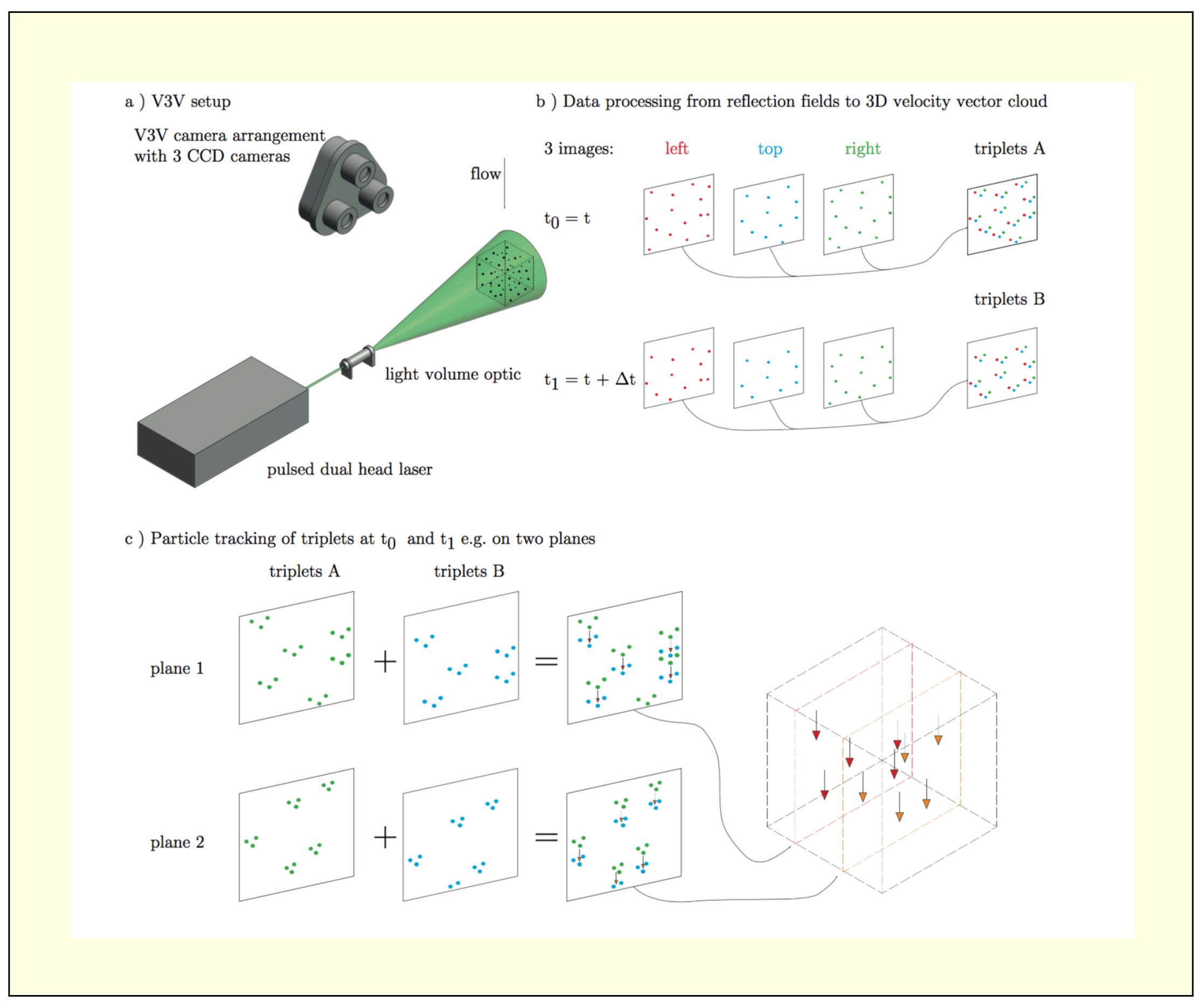


180 Hz, 4 MP camera triplet

Double-pulsed laser, 532 nm, 120 mJ/pulse

Principle

- Tracer particles (polyamides ~ 40 μm) advected by the flow and illuminated by the laser beam
- Image triplets captured by three cameras at a constant rate → 3D reconstruction of particles' positions
- Double-pulsed laser illuminating the flow chamber → pairs of position frames separated by a very small time interval (Δt ~ 4.75 μs)
- Tracking algorithm to compute particle displacements between subsequent position frames → flow velocity vector field



(A. Kalmbach, M. Breuer, 2012)

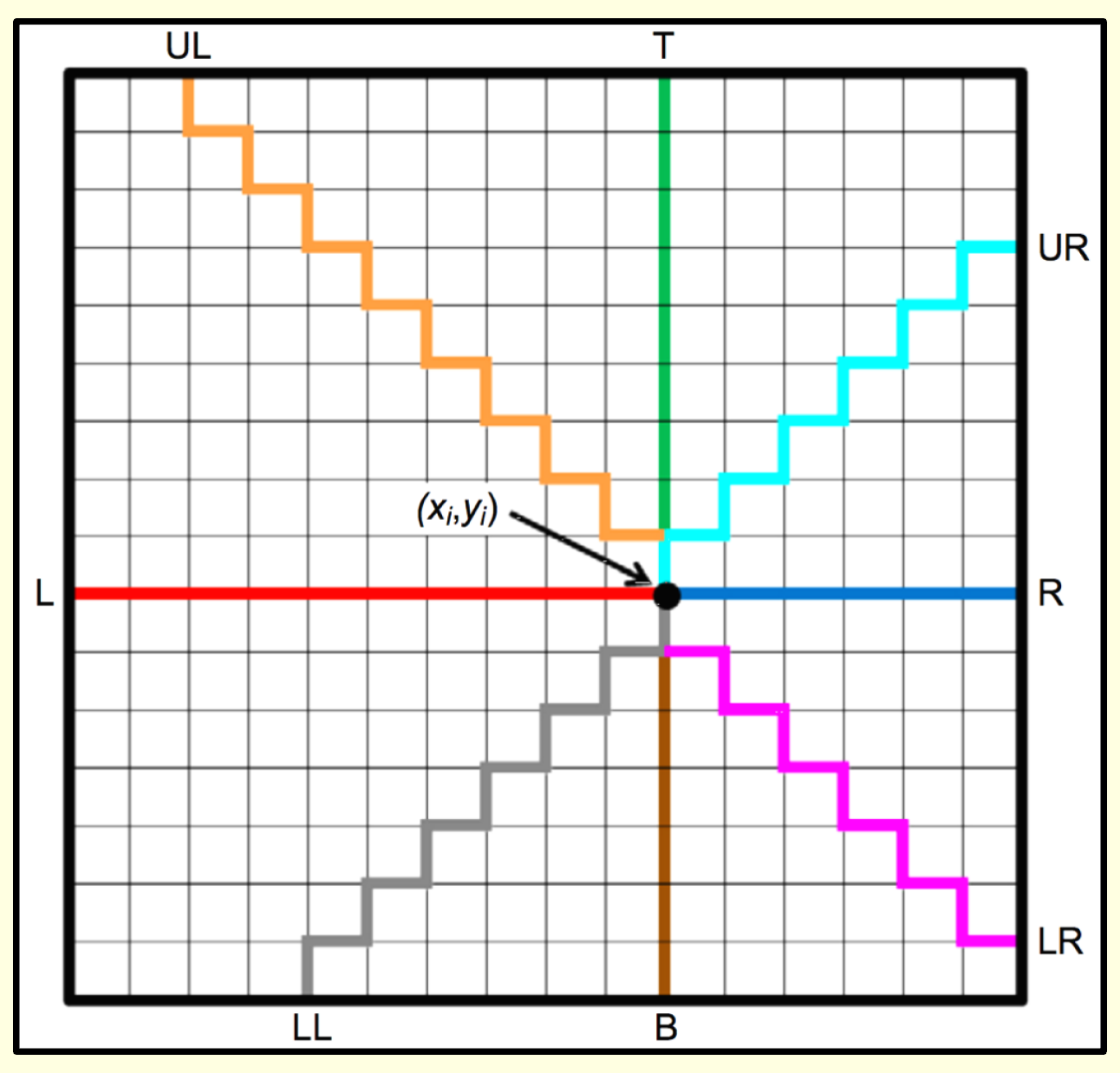
CALCULATIONS

Based on the fluid velocity vector fields, and the Navier-Stokes equation of motion for fluids, hydrodynamic stress components are calculated on the fin's surfaces. The pressure is obtained by integrating along eight different paths through the measurement volume, and by selecting the median among the eight values.

$$\tau_{ij} = -p\delta_{ij} + \mu\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$$

$$p_2 - p_1 = \int_{\mathbf{x}_1}^{\mathbf{x}_2} \nabla p \, d\mathbf{x}$$

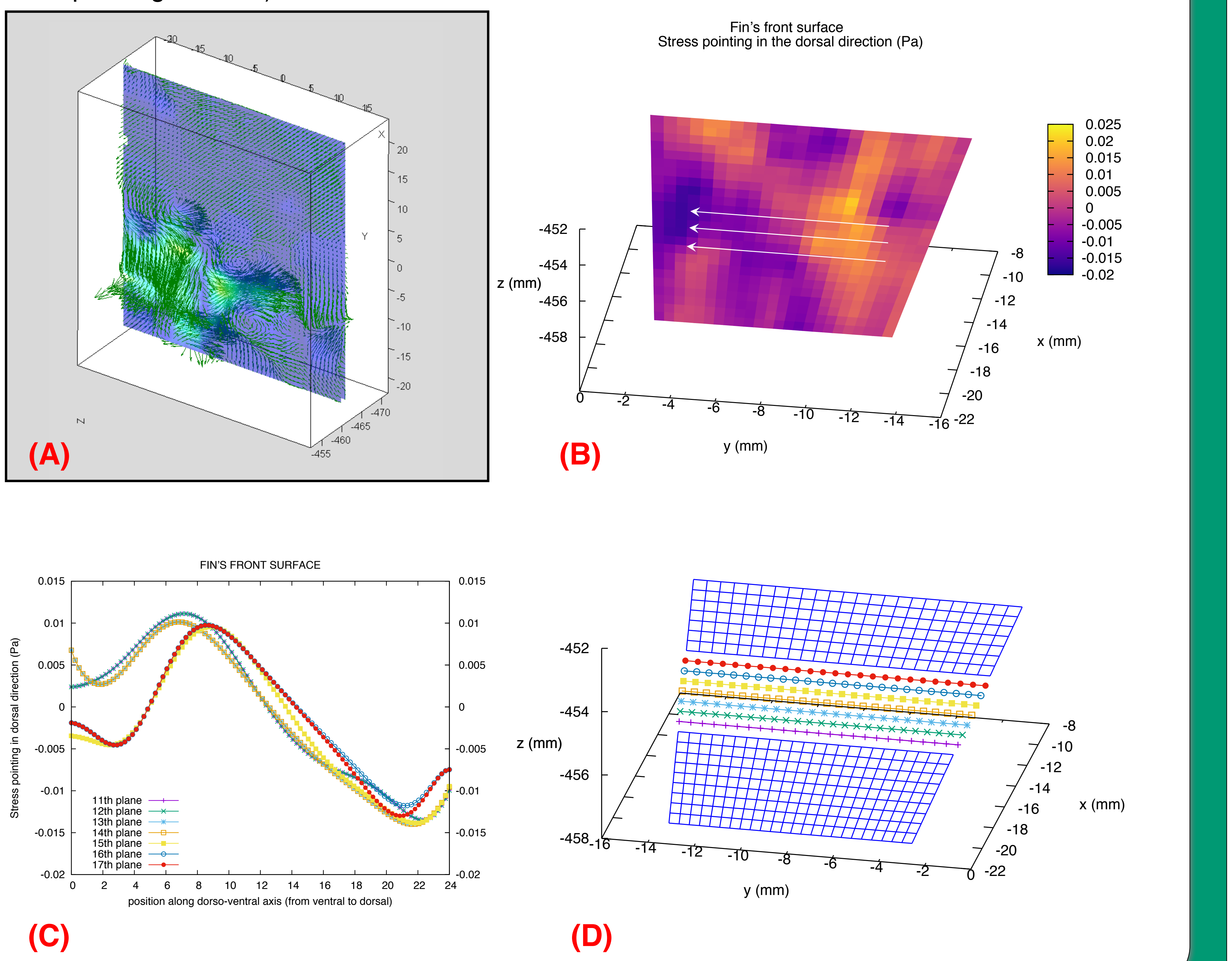
$$\nabla p = -\rho\left(\frac{D\mathbf{u}}{Dt} - \nu\nabla^2\mathbf{u}\right)$$



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

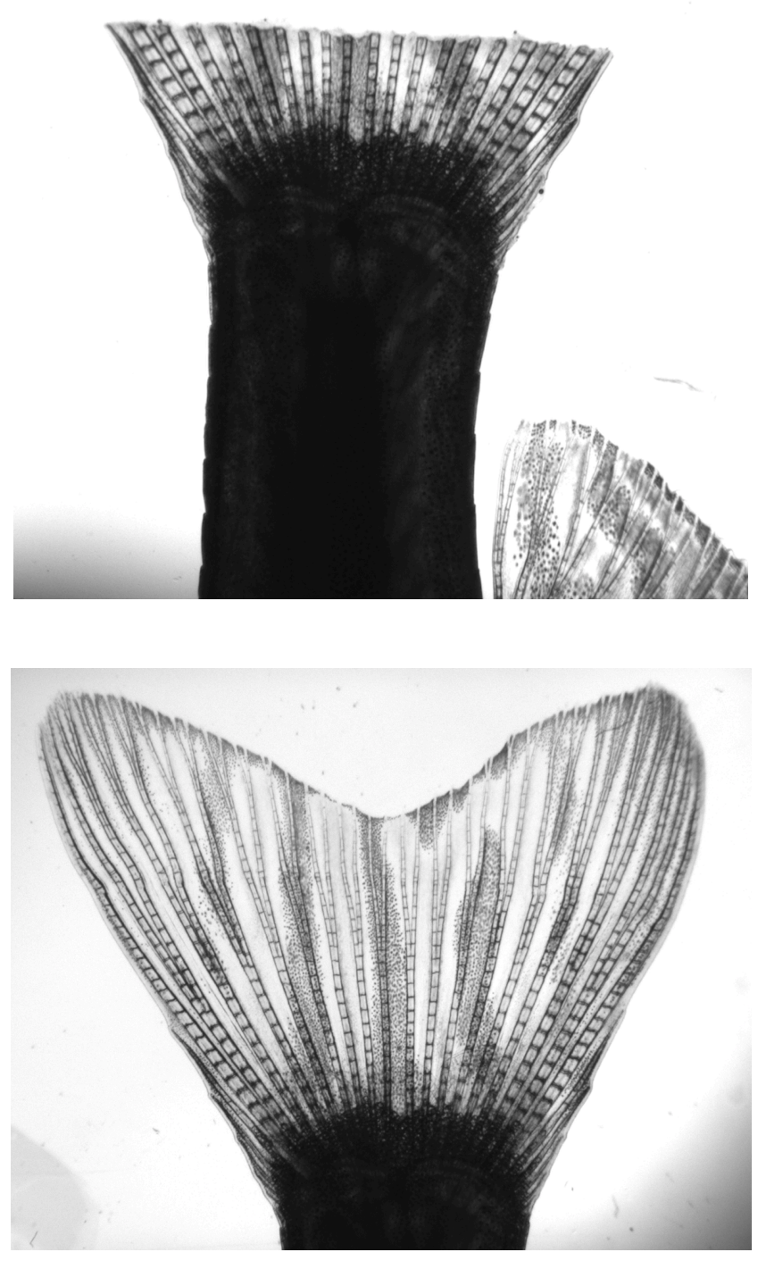
RESULTS

(A) Velocity vectors colored with velocity magnitude. (B) Viscous stress, component parallel to the dorso-ventral axes (arrows). (C) Viscous stress, along dorso-ventral axes, for the middle portion of the fin / see axes indicated in (D). Note that this is the signature of a compression of the tissue (stress pointing inwards).



OUTLOOK

- Compare with numerical results (deformable fin interacting with fluid). Serves as a benchmark for the simulations & the experimental method.
- Draw conclusions regarding the **functional role of hydrodynamic stress in shaping the fin during regeneration** (position of bifurcation points, overall shape, final size – correlated to force thresholds)



Complete regeneration of the caudal fin following amputation (~ 20 days)