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Dr. Roberto Capanna, MAE Department, GWU

Molecular Tagging Velocimetry (MTV) to Measure Wall Shear Stress in Model Cardiovascular Flows

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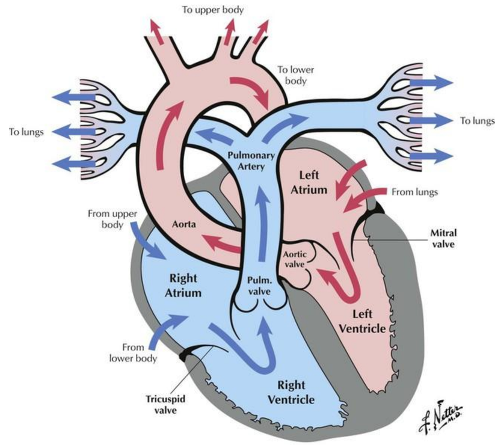

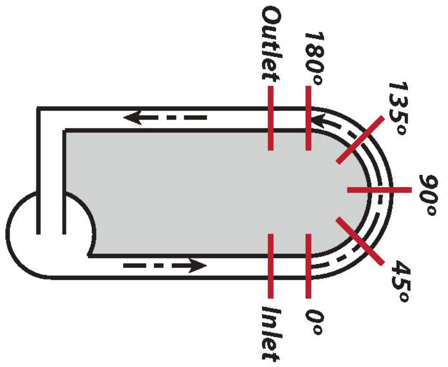

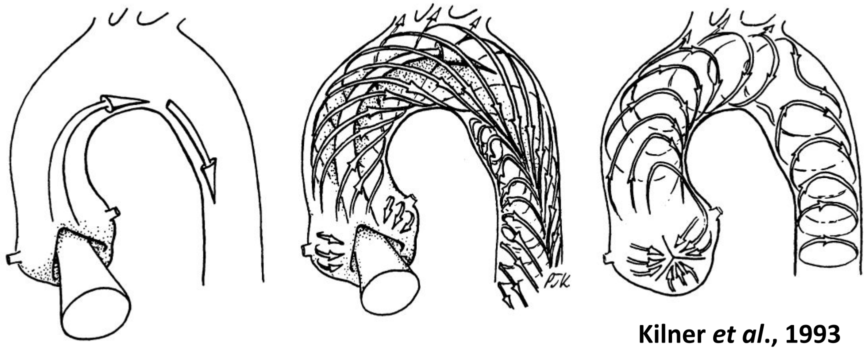

Kilner *et al.*, 1993

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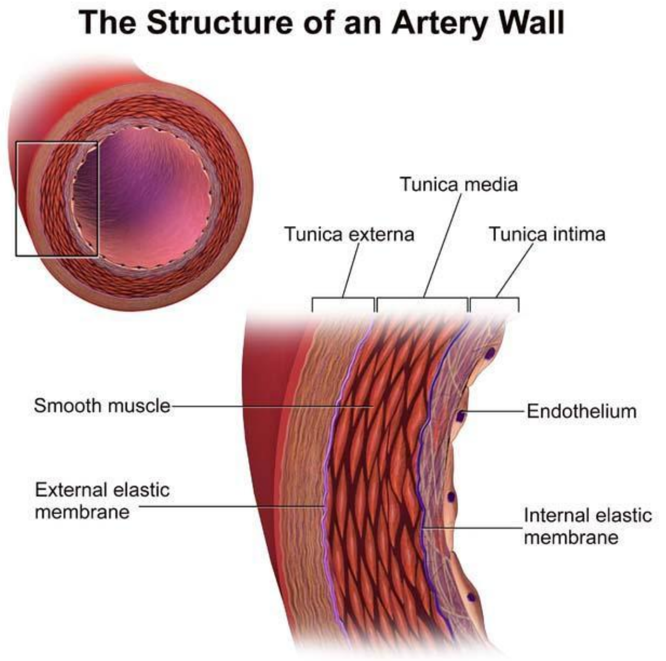
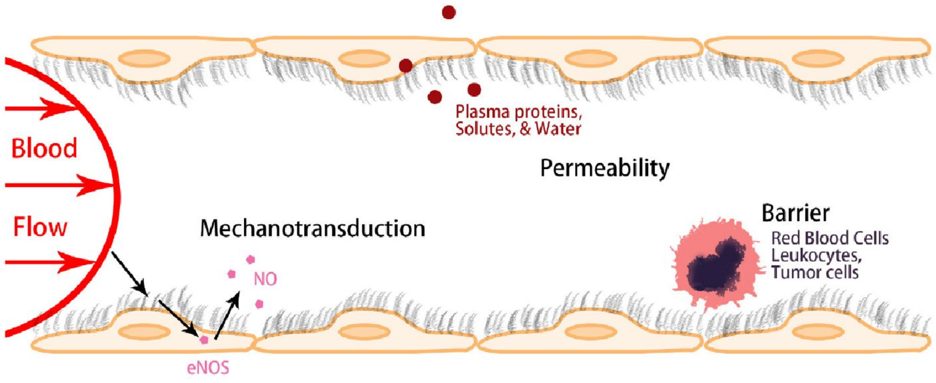
Biofluid Dynamics Laboratory

Introduction



https://teachmeanatomy.info/the-basics/ultrastructure/blood-vessels/



Xia, Y. and Fu, B. M., *Yale journal of biology and medicine* 91 (2018), pp.257-266.

How can we improve our understanding of the role of shear stress at the arterial lumen under complex arterial blood flow conditions ?

- **Design laboratory-scale experiment for large vessels** such as the aorta or the carotid artery
- **Estimate pulsatile flow stress on the lumen by experiments**

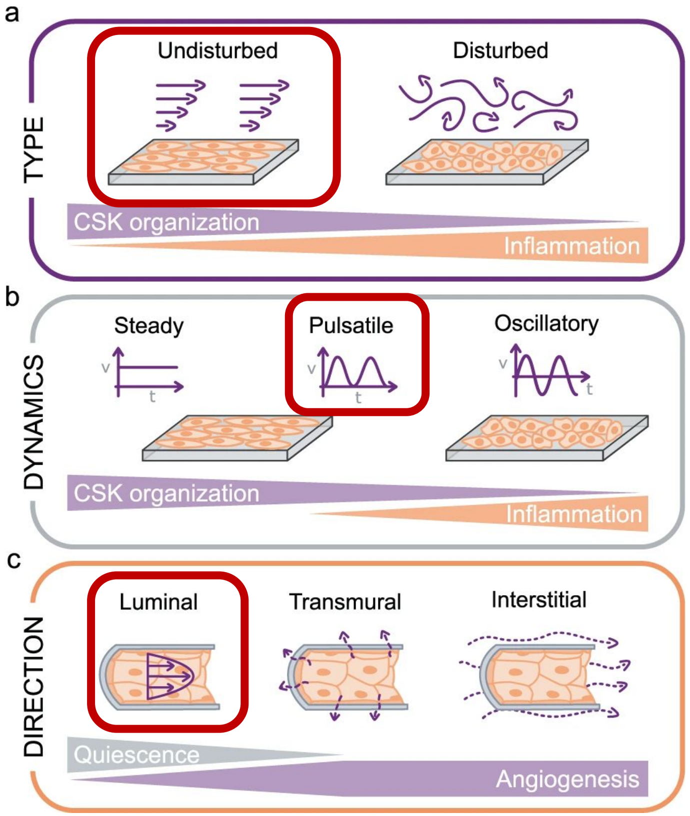


Image reference: Dessalles, C.A., Leclech, C., Castagnino, A. *et al.* Integration of substrate- and flow-derived stresses in endothelial cell mechanobiology. *Commun Biol* **4,** 764 (2021). https://doi.org/10.1038/s42003-021-02285-w

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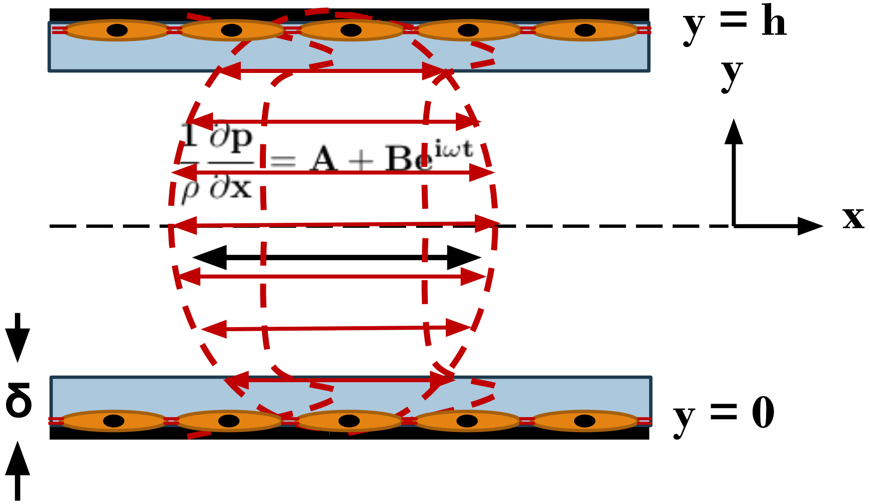
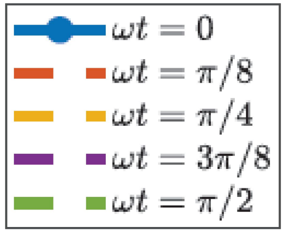
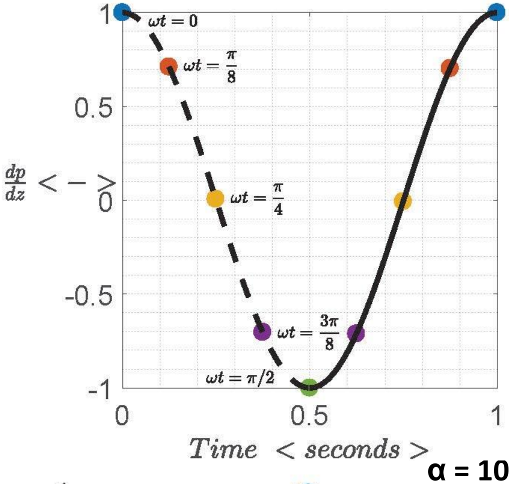
Physical interpretation of the Womersley number (α) - Pressure drop 1Hz cosine function



$$\alpha^2 = \left(\frac{L}{\sqrt{\nu/\omega}}\right)^2$$

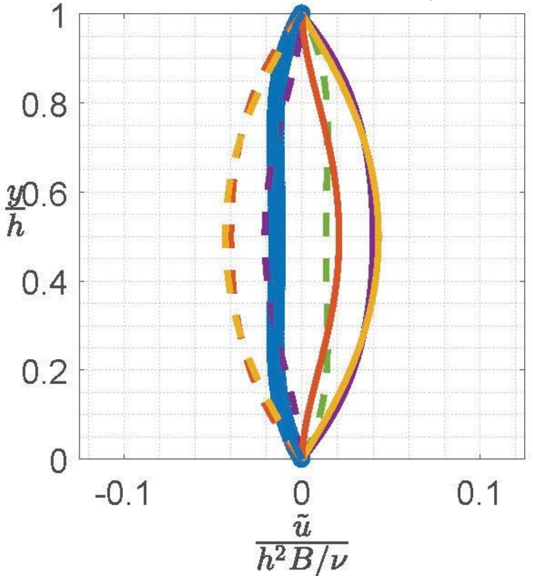
$$\delta = \left(\frac{\nu}{\omega}\right)^{1/2}$$

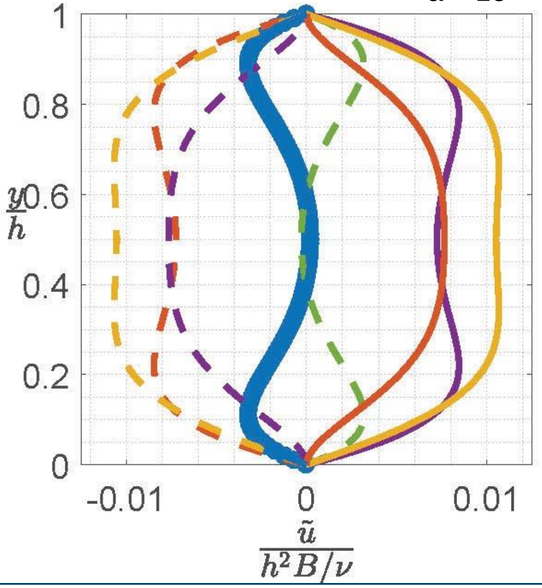




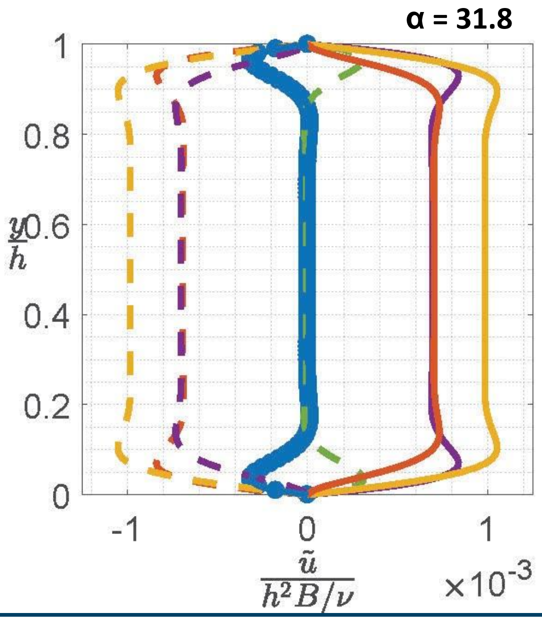
$$\alpha^2 = \frac{\rho\omega L^2}{\mu} = \frac{\omega L^2}{\nu}$$

Low frequencies of oscillations (ω ⟶ 0)





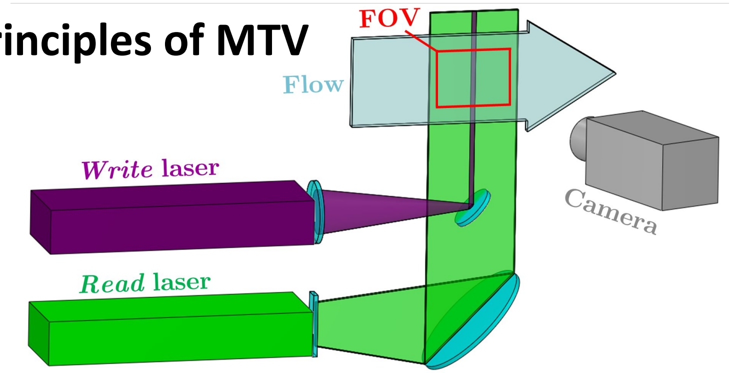
High frequencies of oscillations (ω ⟶ ∞)

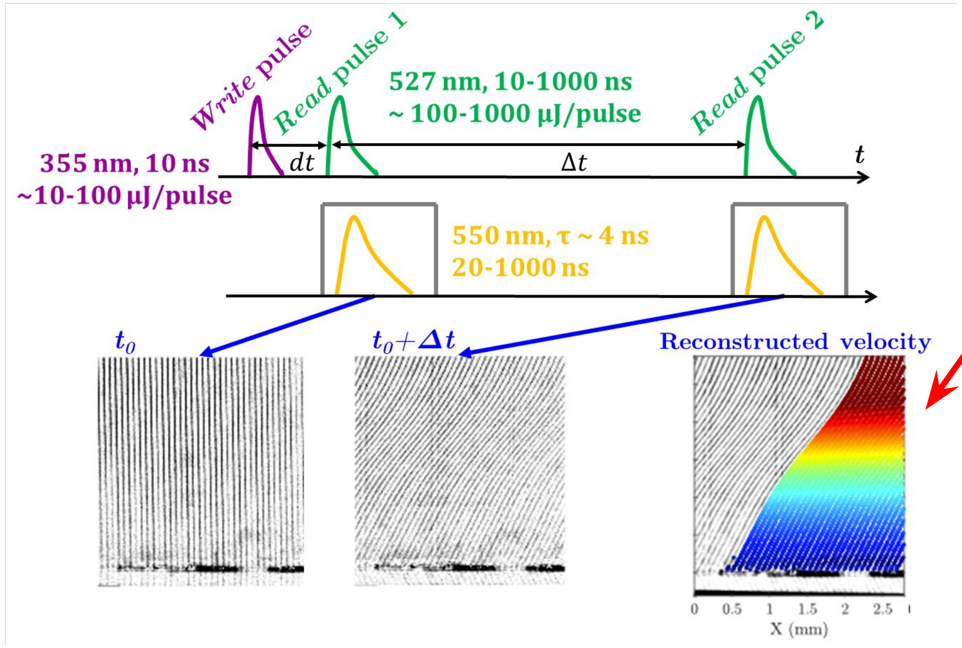


MTV techniques – A novel photobleaching approach with Talbot-effect structured illumination

Fort & Bardet, Wall shear stress measurements in water by molecular tagging velocimetry at high spatio-temporal resolution, *Exp Fluids* (submitted)

Operating Principles of MTV





- **Molecular** tracers added or already present
- Tracers activation (tagging) with a first laser (***write***)
- **Lagrangian tracking** of tagged pattern with a 2nd laser (***read***)

Spatially continuous
→ velocity gradients directly resolved at the wall

But historically, MTV in water:

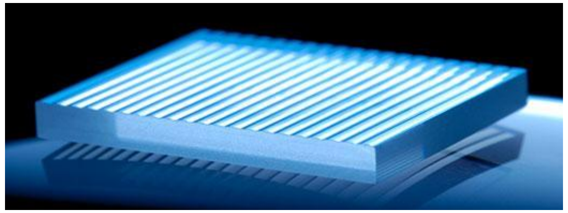
- Limited spatial resolution
- Limited temporal resolution
- Limited laser options

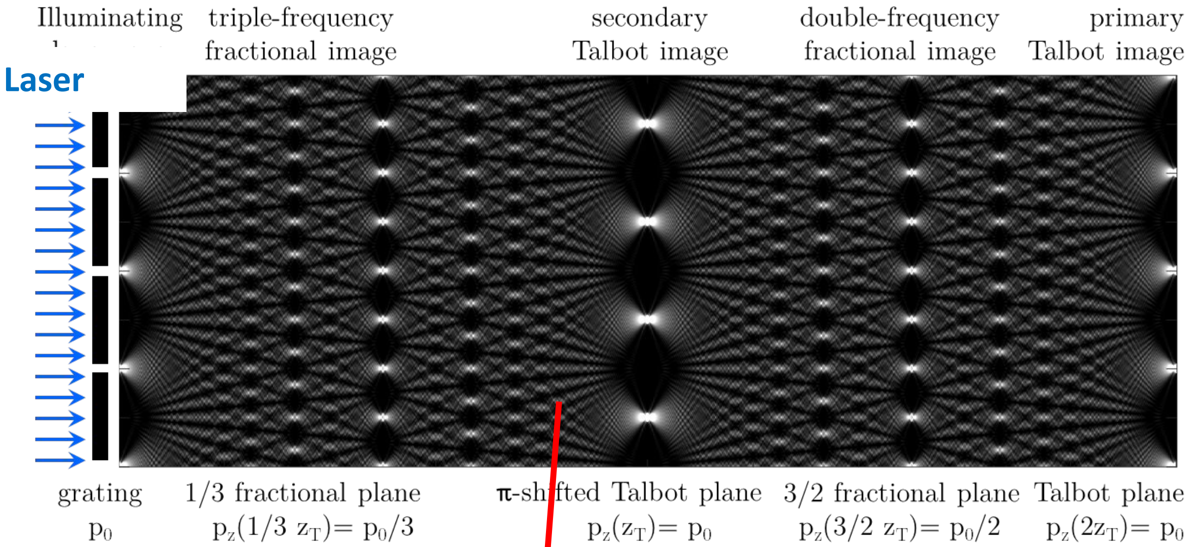
patterns

Fort, André, Pazhand & Bardet, Talbot-effect structured illumination: pattern generation and application to long-distance µ-MTV, *Exp Fluids* (2020)

Talbot carpet (fractal)

Microlens array (MLA)



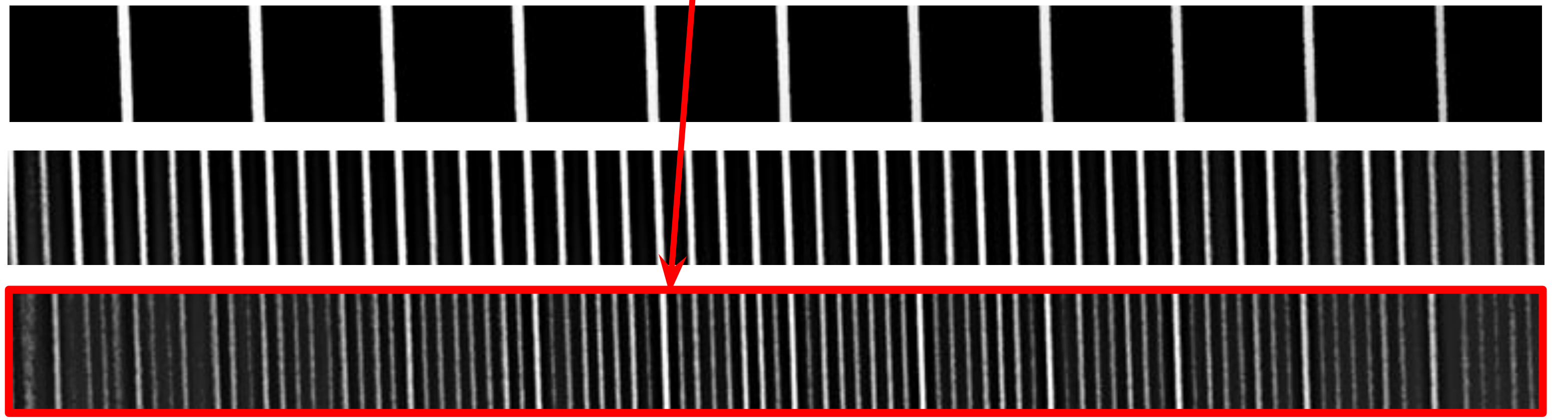


Talbot distance: $z_T = \frac{p_0^2}{\lambda}$

Pattern periodicity varies along **z**

$$p\left(z = \frac{M}{N} z_T\right) = \frac{p_0}{N}$$

$z_T = 254$ mm



$p = 300$ µm, w $= 33$ µm

$\frac{3}{4} z_T$

$p = 75$ µm

$\frac{5}{8} z_T$

$p = 38$ µm, w $= 17$ µm

Rhodamine 6G (R6G) is a broadly used fluorescent dye

Fort & Bardet, Efficient photobleaching of rhodamine 6G by a single UV pulse, *Appl Opt* (2021)

→ 95%-pure rhodamine 6G dye costs **$0.7/g** (< $1000 for whole 1.4 million gallon LCC)

1st peak of absorption

frequency-
based on N
(**Nd:YAG, N**

Rhodamine 6G is very robust in the green (fluorescence = *read*)

Peak of emissivity

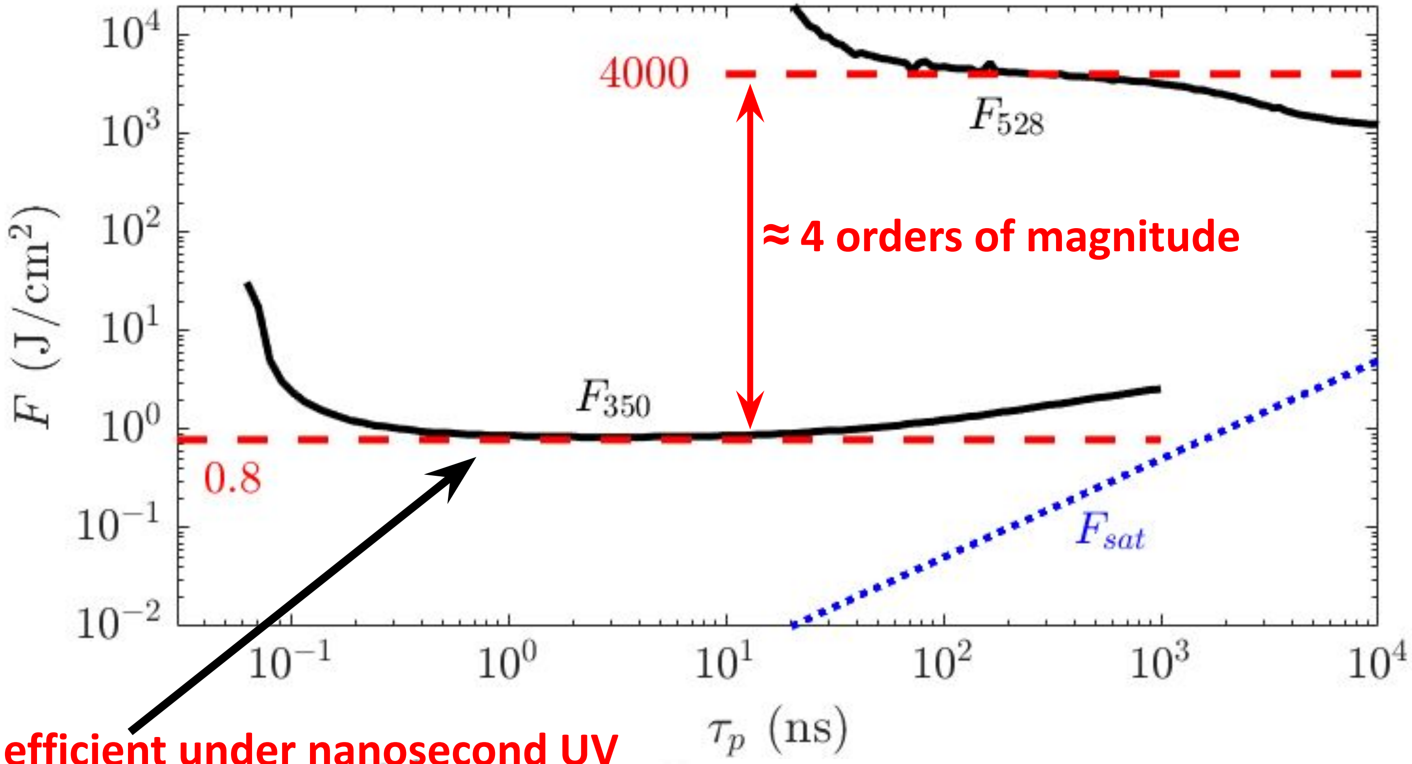
b)

σ_{01} / 10^{-16} cr

2nd peak of absorption

third harmonics of the same lasers

347 nn



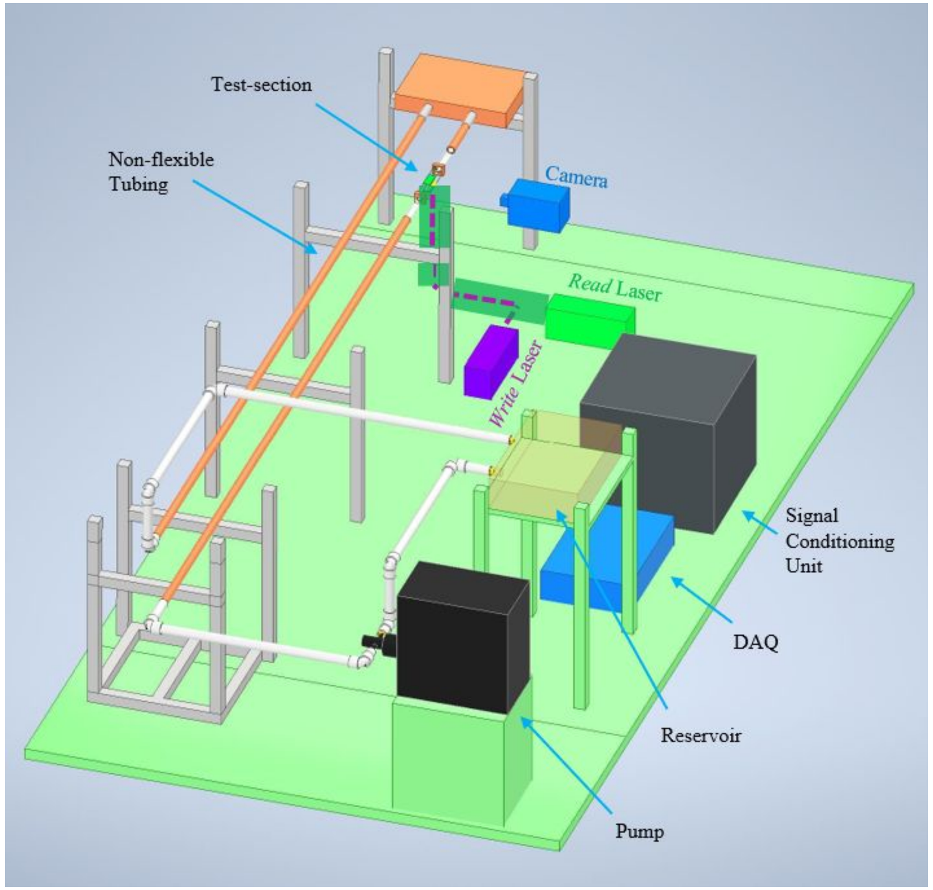
Photobleaching (*write*) is very efficient under nanosecond UV

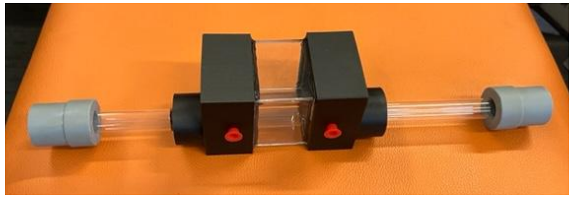
λ / nm

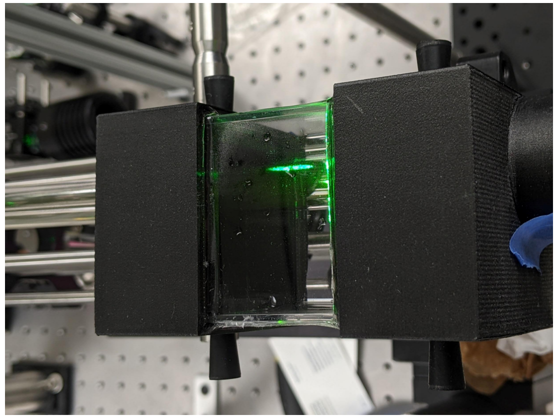
F_{350} = 0.8 J/cm^2 → 2.5 µJ for a 20-µm-wide beamlet

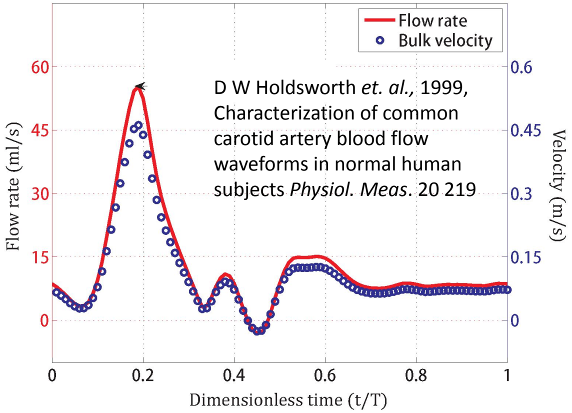
+ Many **spectral filters** and **dichroic mirrors** are commercially available at these wavelengths

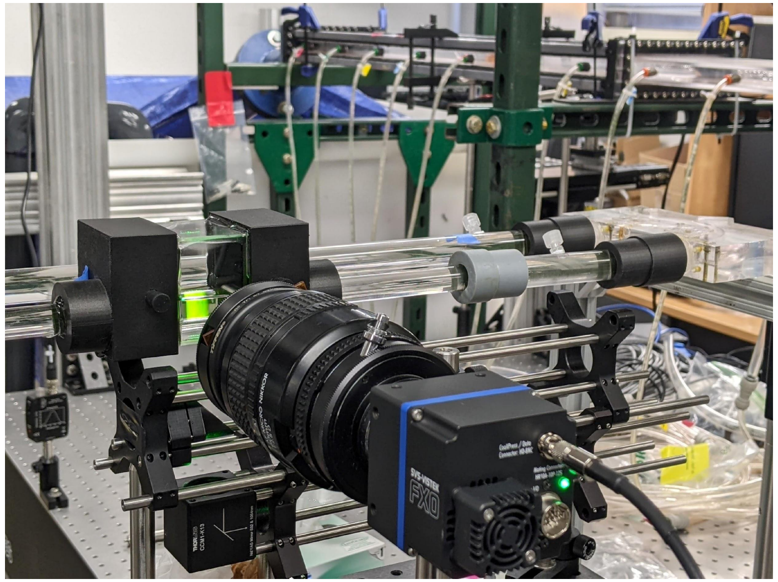
Experimental setup





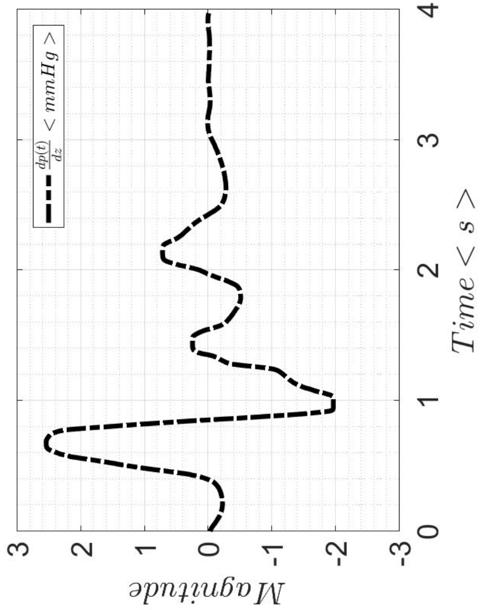


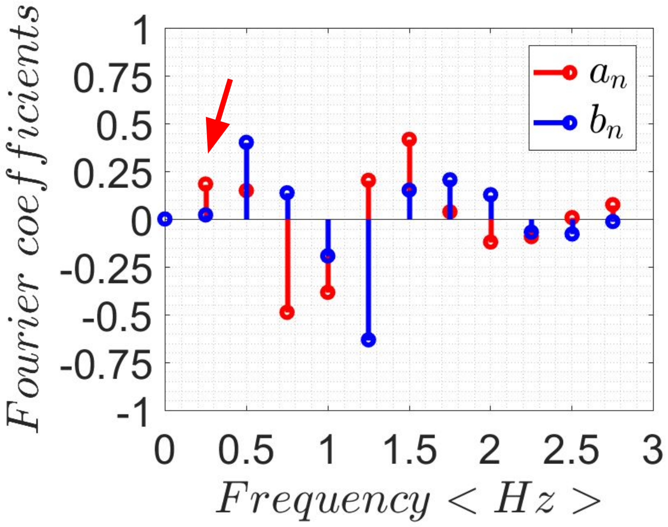


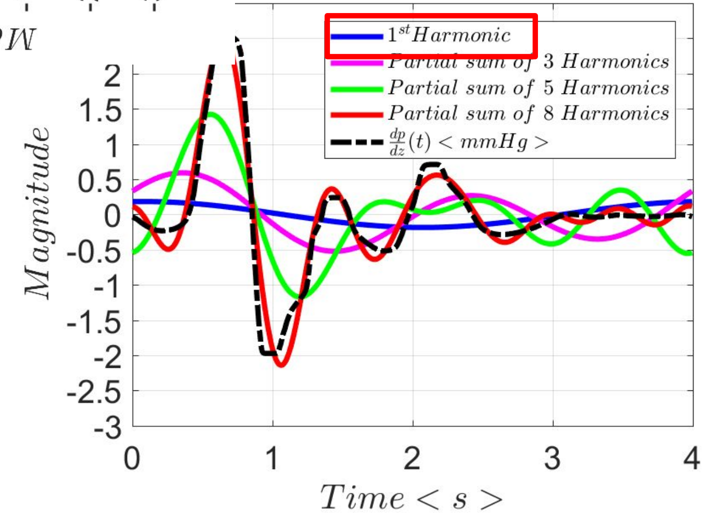


Harmonics of the pulsatile pressure drop

- Digitized carotid artery-based flow rate





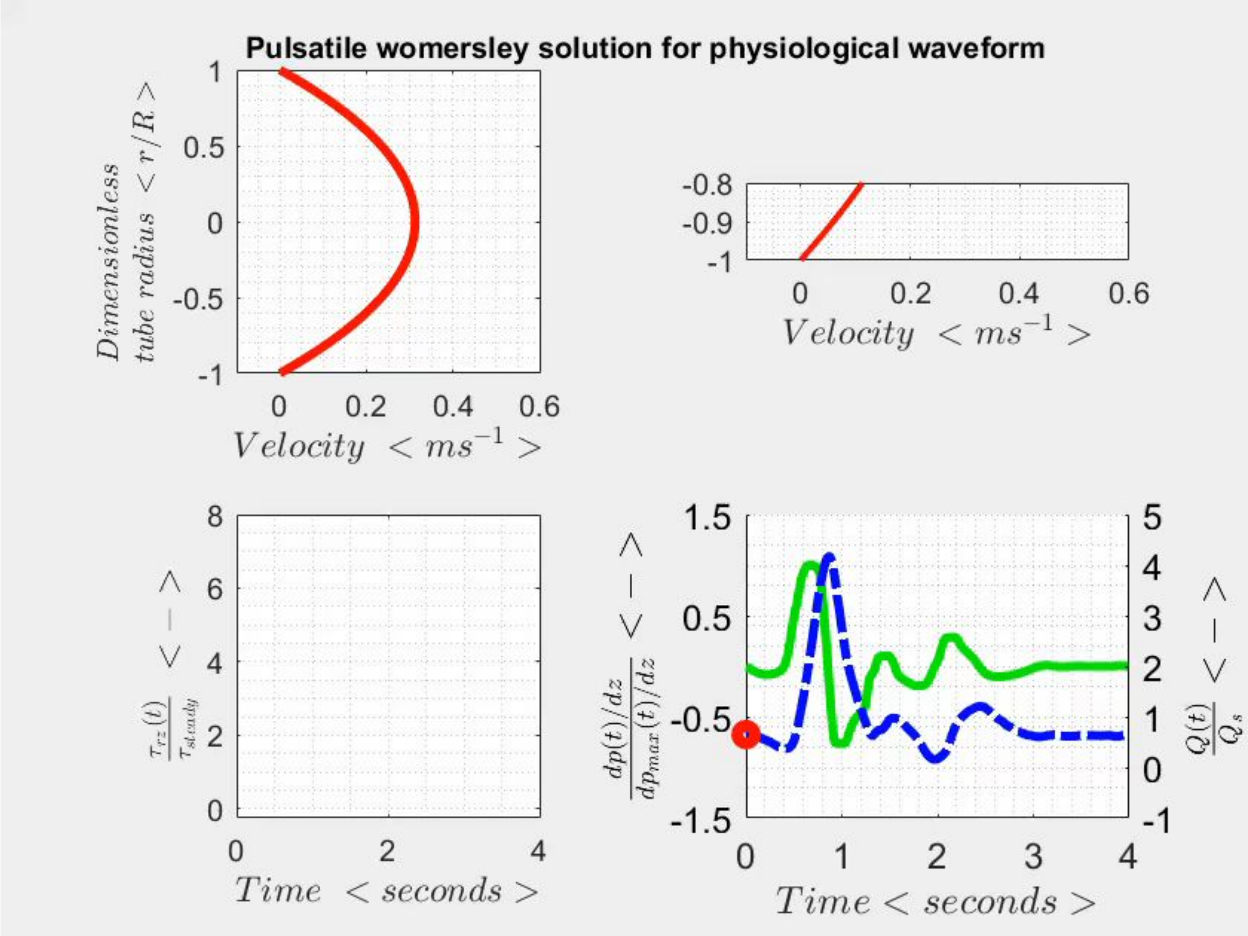


$$\alpha^2 = \frac{\rho\omega \mathbf{R}^2}{\mu} = \frac{\omega \mathbf{R}^2}{\nu}$$

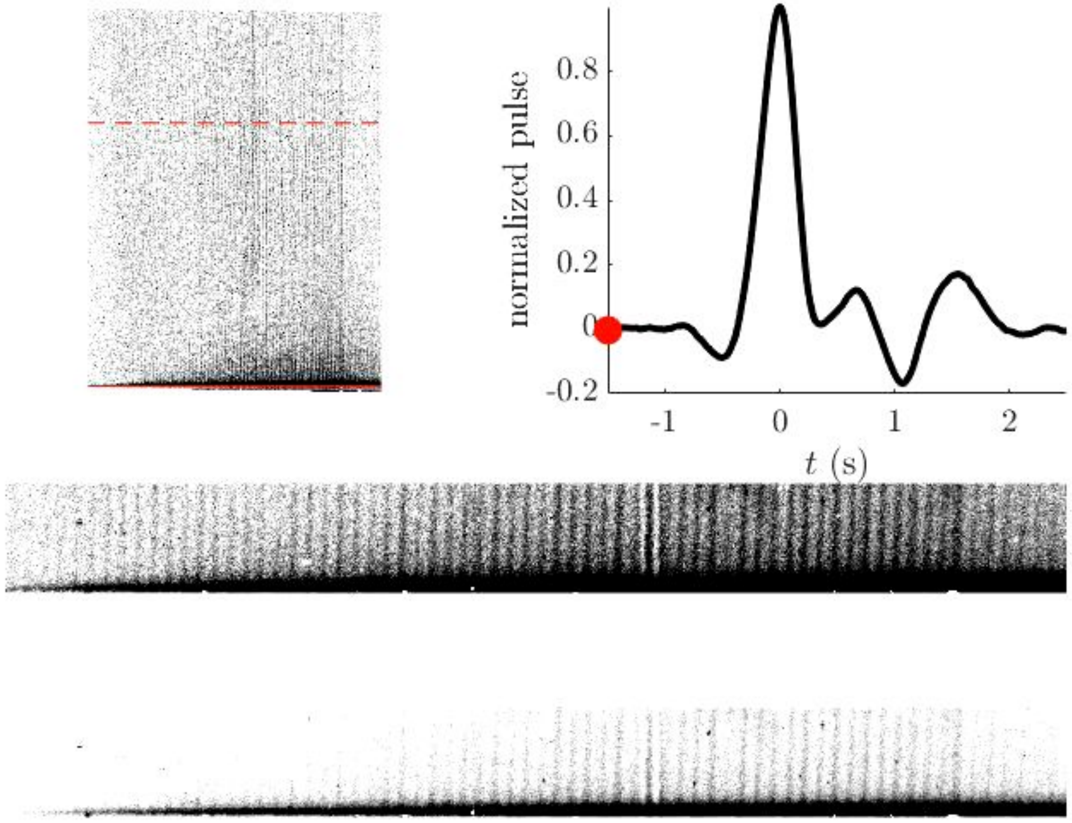
	3.98	5.86	8.43
	5.63	8.28	11.92
	6.89	10.15	14.60
	7.96	11.72	16.86
	8.90	13.10	18.85
	9.75	14.35	20.65
	10.53	15.50	22.30
	11.26	16.57	23.84

Summary of results

Analytical solution



MTV-based flow visualization

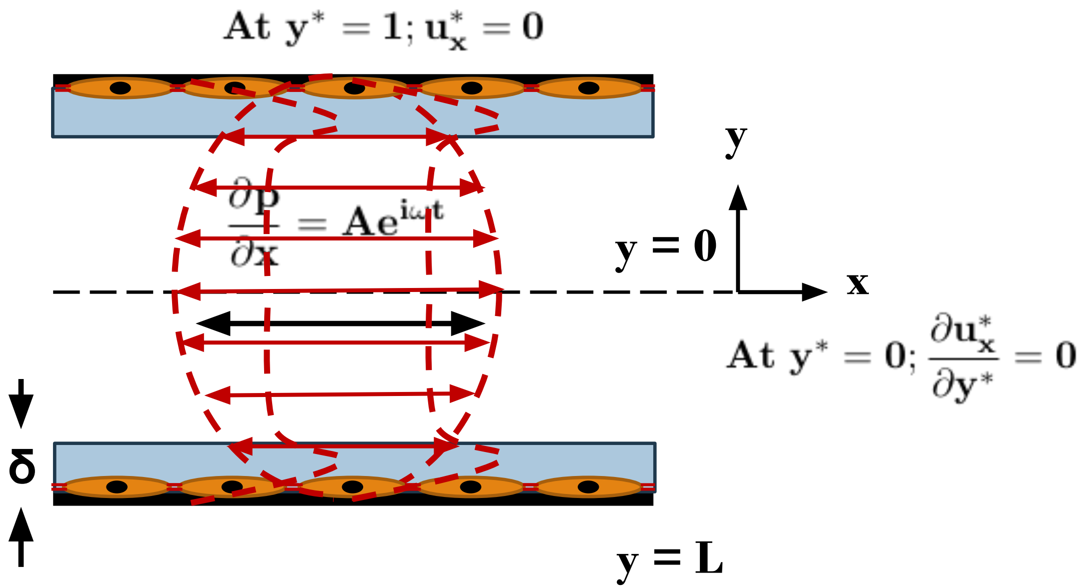


Physical interpretation of the Womersley number (α)

References: Schlichting, Landau-Lifshitz
Lectures of Prof. V. Kumaran

$$\mathbf{y}^* = \frac{\mathbf{y}}{\mathbf{L}} \qquad \mathbf{t}^* = \omega \mathbf{t}$$

$$\mathbf{u_x^*} = \frac{\mathbf{u_x}\mu}{\mathbf{L^2 A}}$$



$$\alpha^2 = \frac{\rho \omega \mathbf{L^2}}{\mu} = \frac{\omega \mathbf{L^2}}{\nu}$$

$$\alpha^2 = \left(\frac{\mathbf{L}}{\sqrt{\nu/\omega}}\right)^2$$

$$\alpha^2 \frac{\partial \mathbf{u_x^*}}{\partial \mathbf{t^*}} = \frac{\partial^2 \mathbf{u_x^*}}{\partial \mathbf{y^{*2}}} - \mathbf{e^{it^*}}$$

Low frequencies of oscillations (ω → 0)

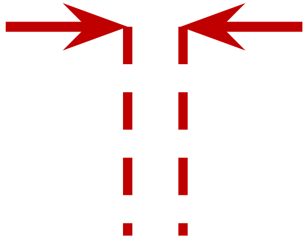
High frequencies of oscillations (ω → ∞)

$$\delta = \left(\frac{\nu}{\omega}\right)^{1/2}$$

Introduction

- A brief look at a result from Womersley (1955)

Relation of flow (Q) to the pressure gradient (P) in the femoral artery of a dog.



$$\frac{\partial p}{\partial x} = A e^{i\omega t}$$

$$Q_s = \frac{p_1 - p_2}{8\mu\ell}\pi r^4$$

$$\hat{Q}(t) = \frac{\pi r^2}{\rho}\frac{A}{i\omega}\{1 - \frac{2\alpha i^{3/2}}{i^3\alpha^2}\frac{J_1(\alpha i^{3/2})}{J_0(\alpha i^{3/2})}\}e^{i\omega t}$$

$$\alpha = R\sqrt{\frac{\omega}{\nu}}$$

"Measurements of the pressure gradient showed a phase-lag between pressure gradient and flow."

Reference: Womersley, J. R., Method for the calculation of velocity, rate of flow and viscous drag in arteries when the pressure gradient is known, *J. Physiol.* (I955) 127, 553-563

Drag force at the wall can be estimated for multi-harmonic flow waveforms