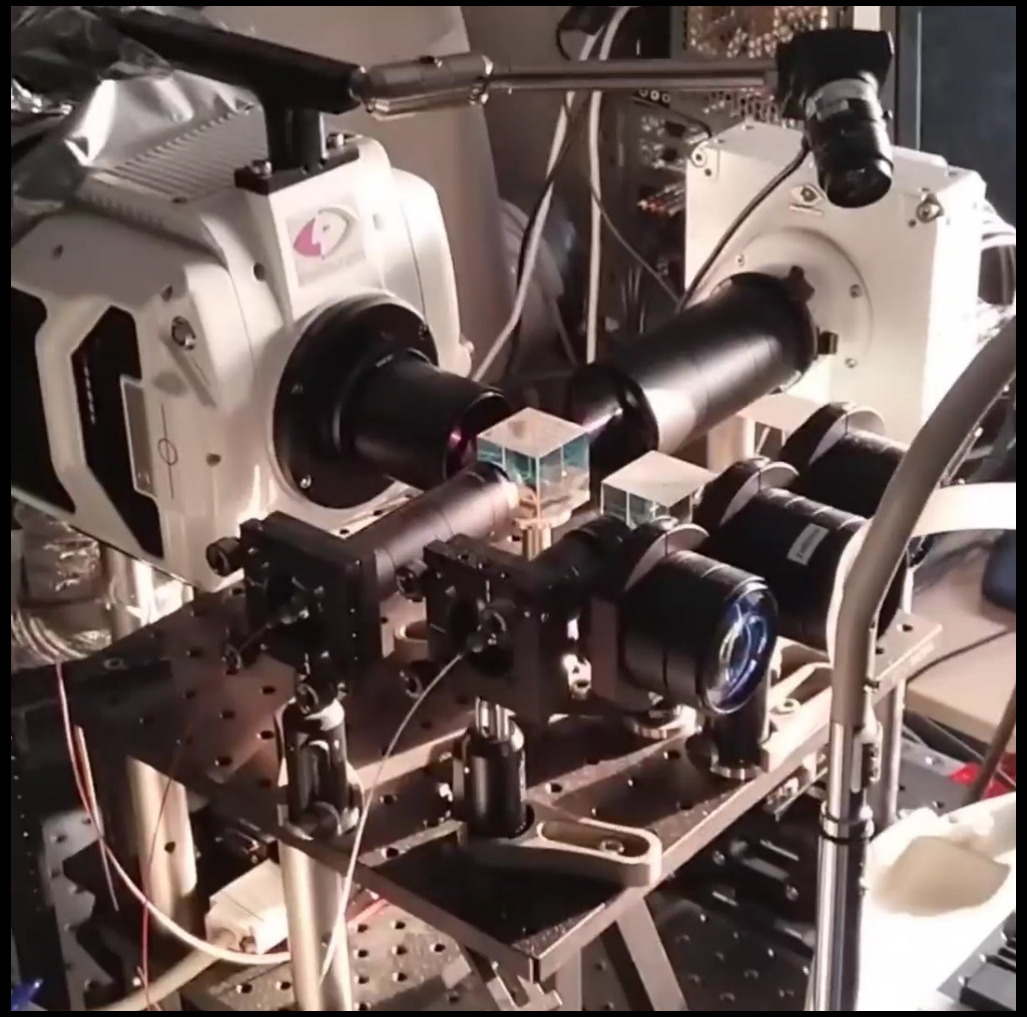
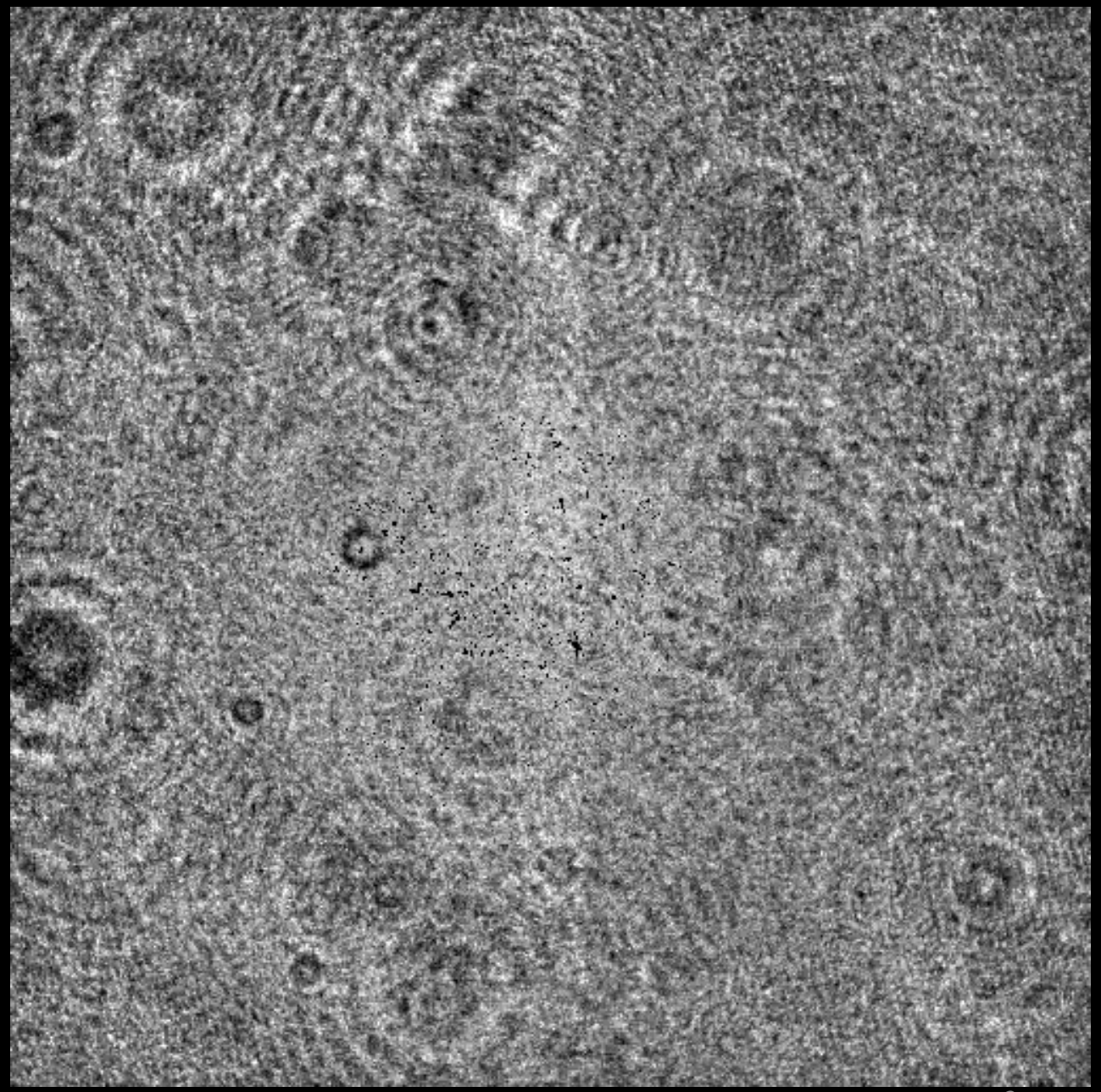
DIU Imagerie et pathologies rétiniennes
Hôpital des 15-20
amphithéâtre Bailliart
Michael Atlan
15 novembre 2023

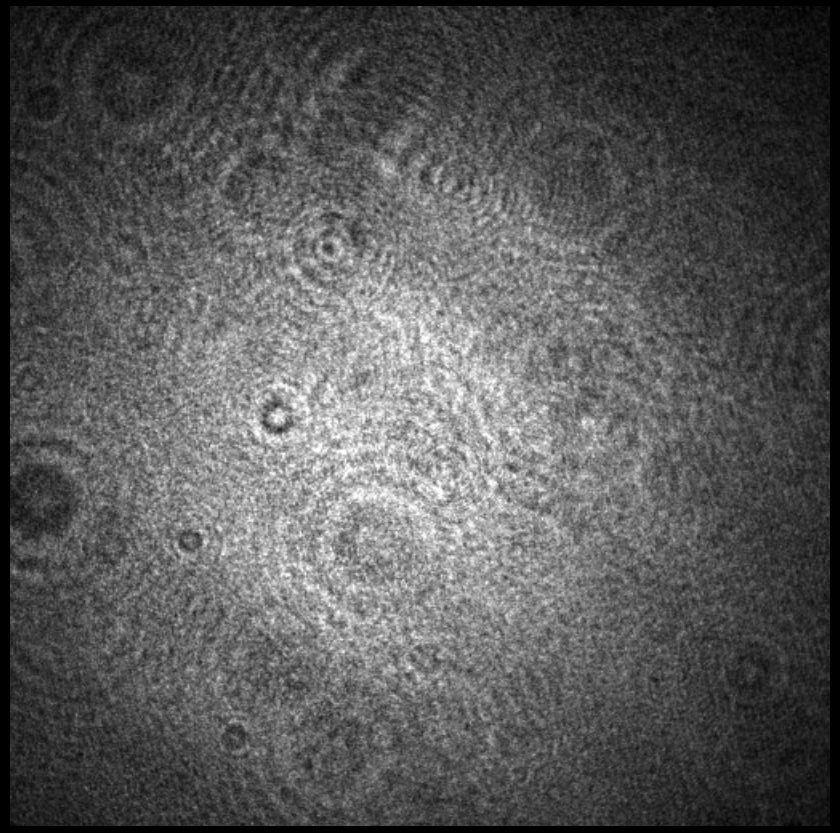
Mesure de la perfusion sanguine rétinienne par holographie Doppler et correction numérique d'aberrations

offline
camera
67 kHz

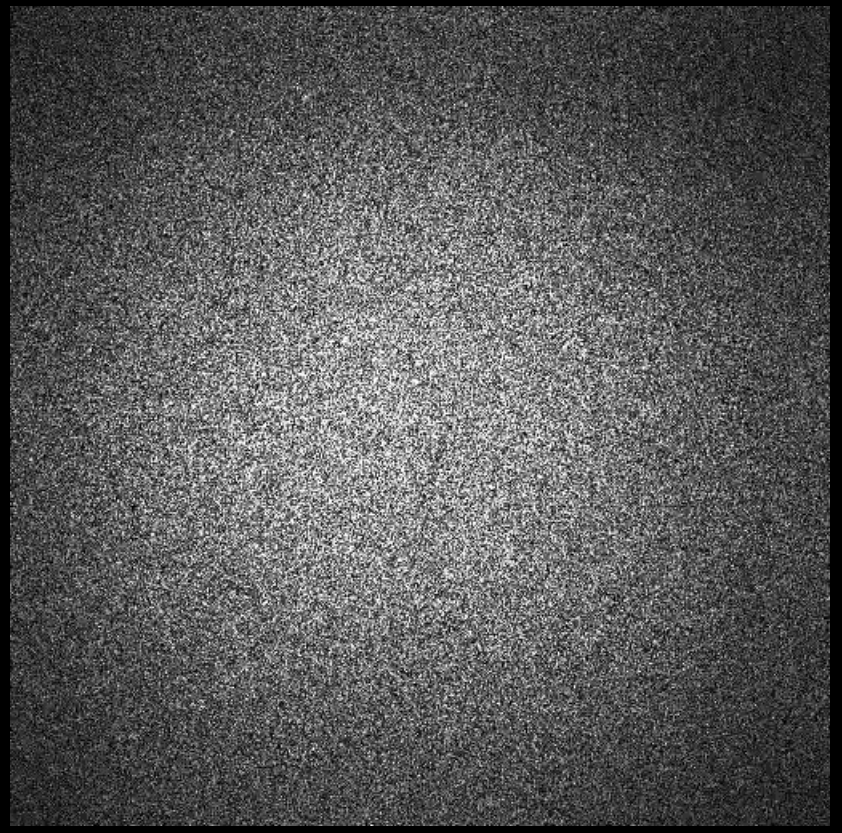
streaming
camera
4-30 kHz





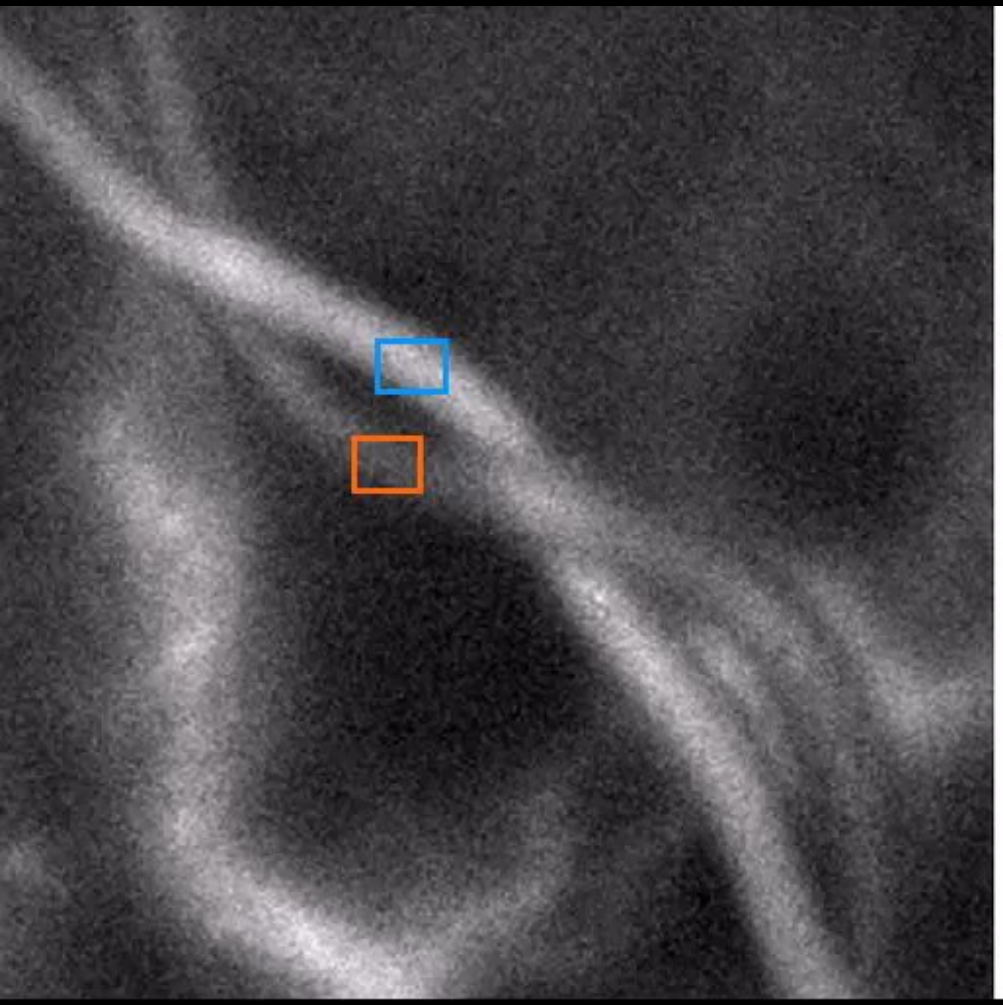


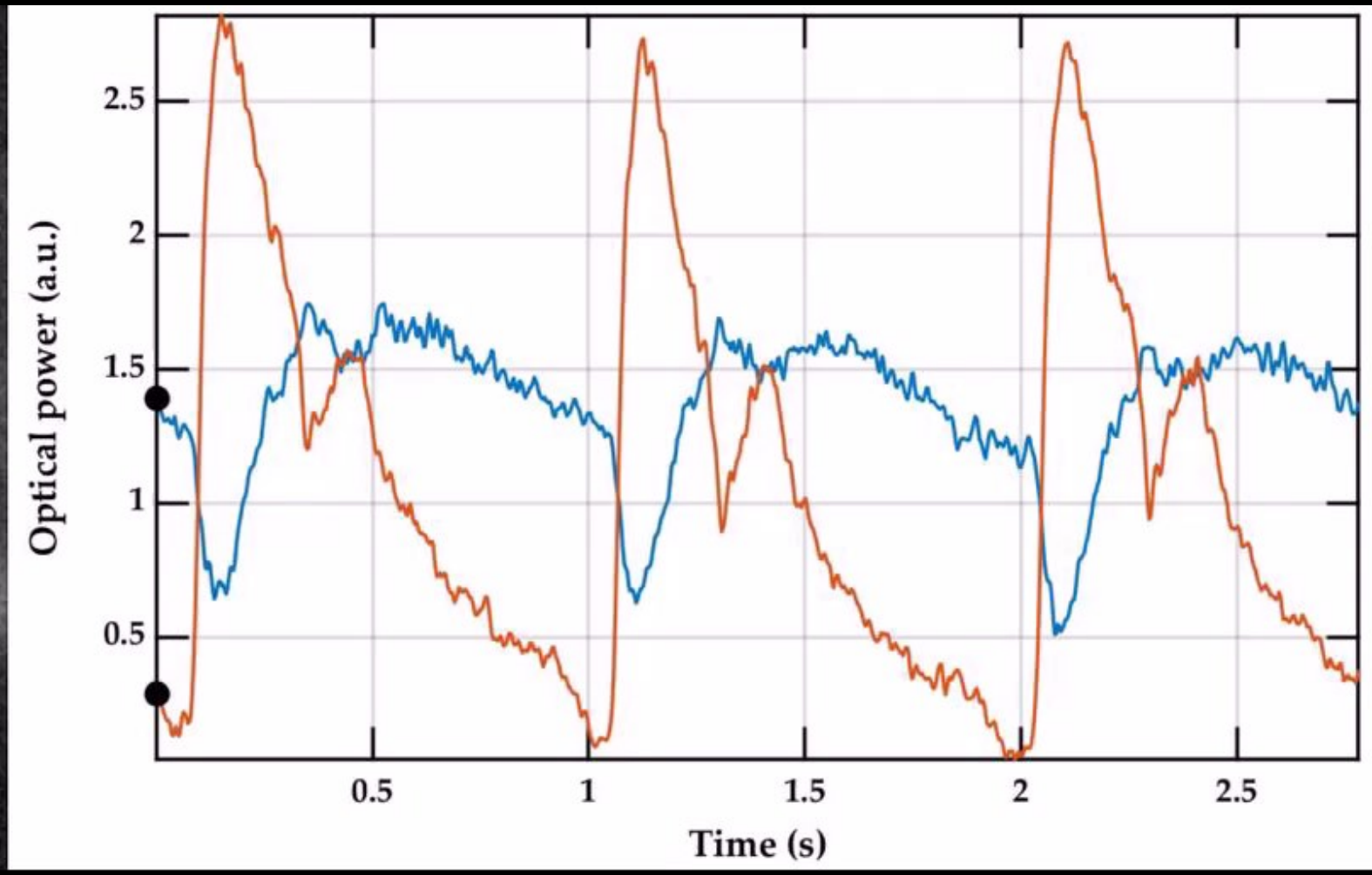
Raw camera footage @ 67 kHz



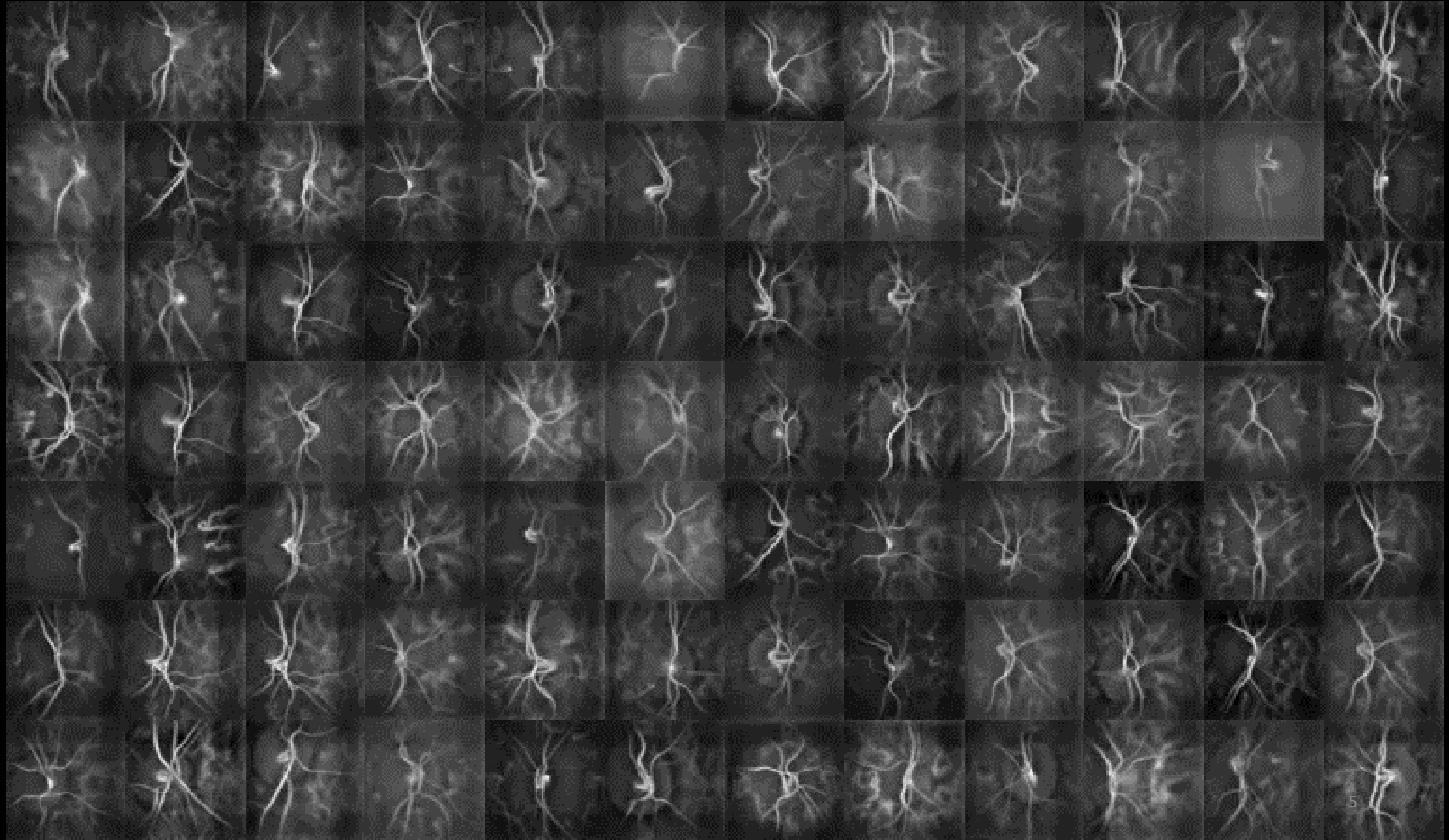
Reconstructed holograms
512 frames

Power Doppler image
7 ms

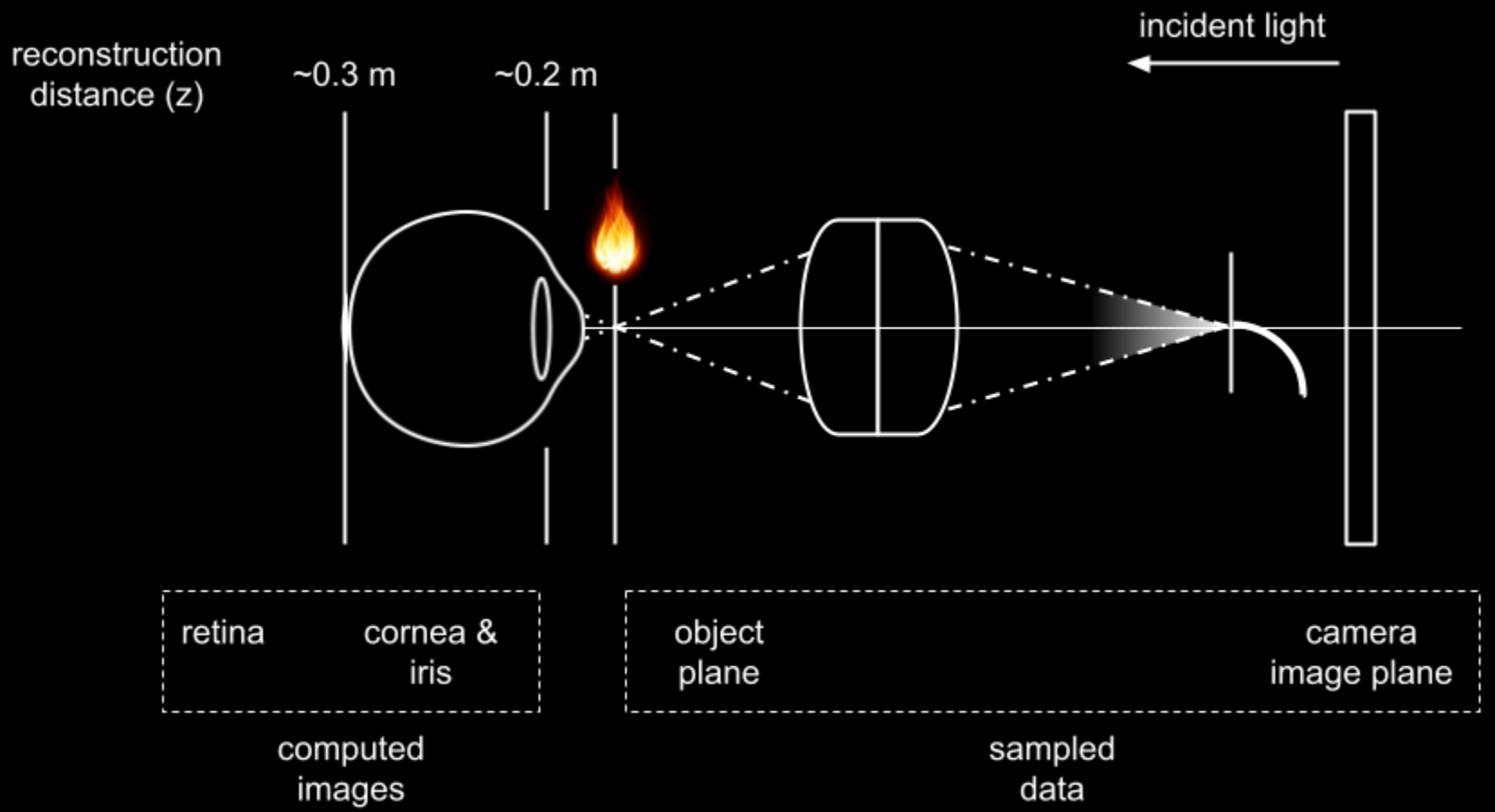


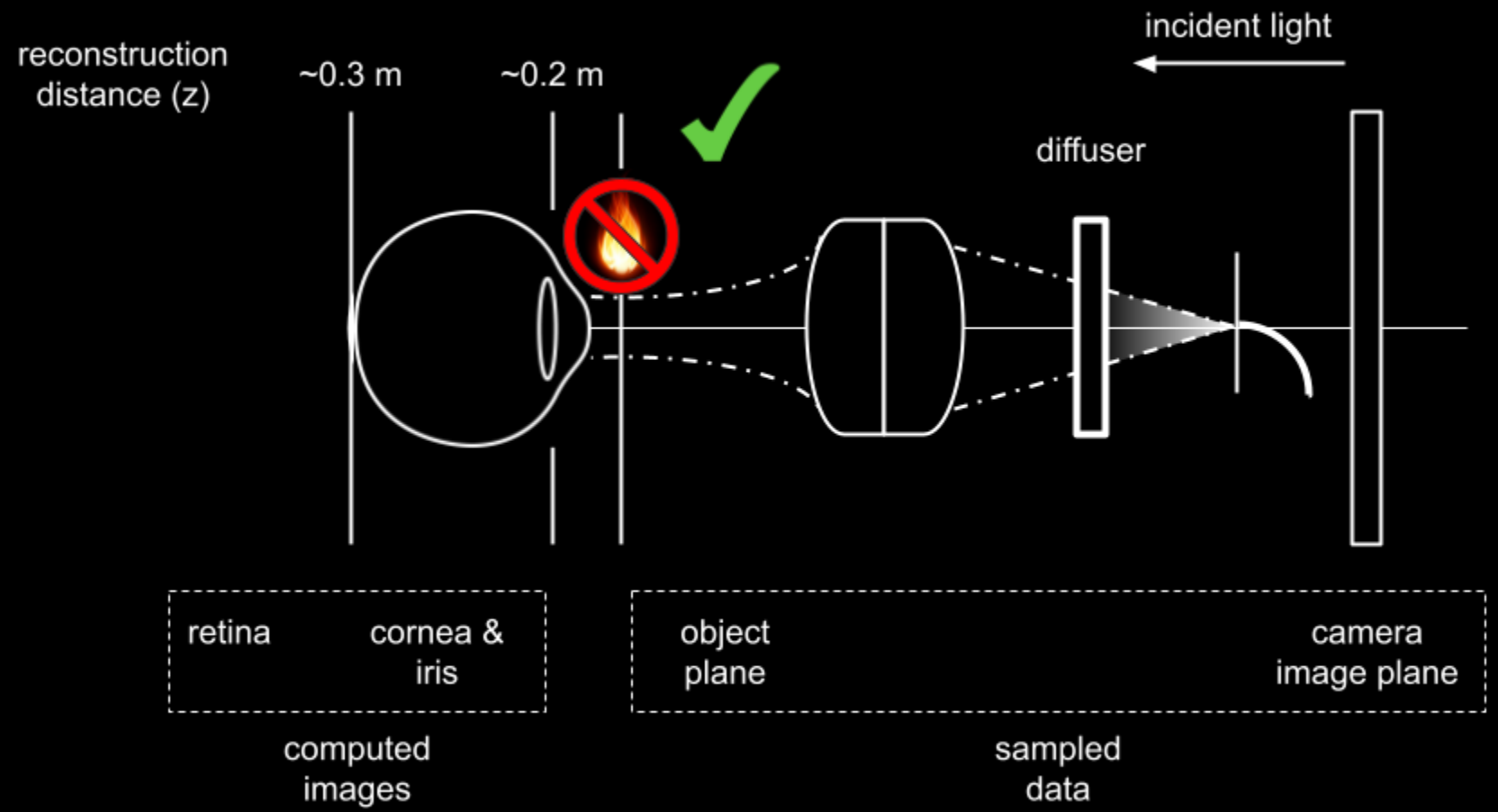


Puyo, L., Paques, M., Fink, M., Sahel, J. A., & Atlan, M. (2018). In vivo laser Doppler holography of the human retina. *Biomedical optics express*, *9*(9), 4113-4129.

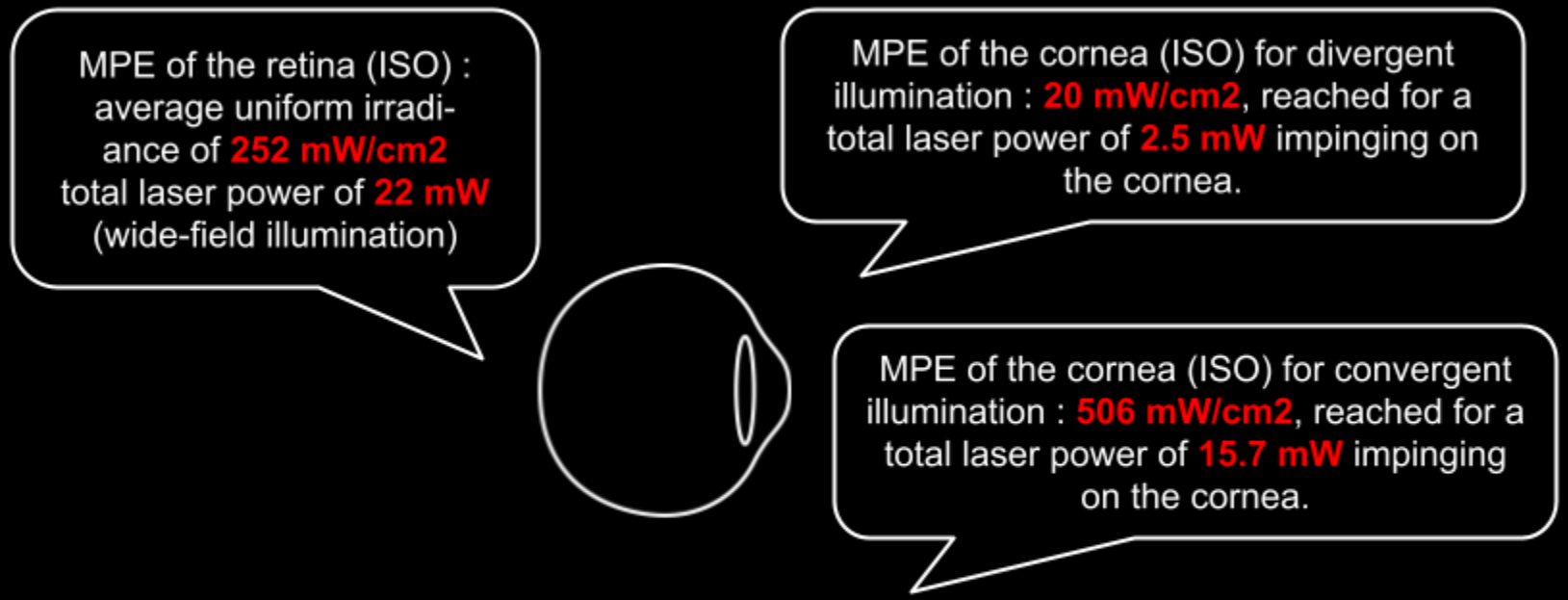


Sécurité de l'exposition oculaire : éclairage laser diffus


reconstruction
distance (z)
~0.3 m
~0.2 m
incident light
retina
cornea &
iris
object
plane
camera
image plane
computed
images
sampled
data

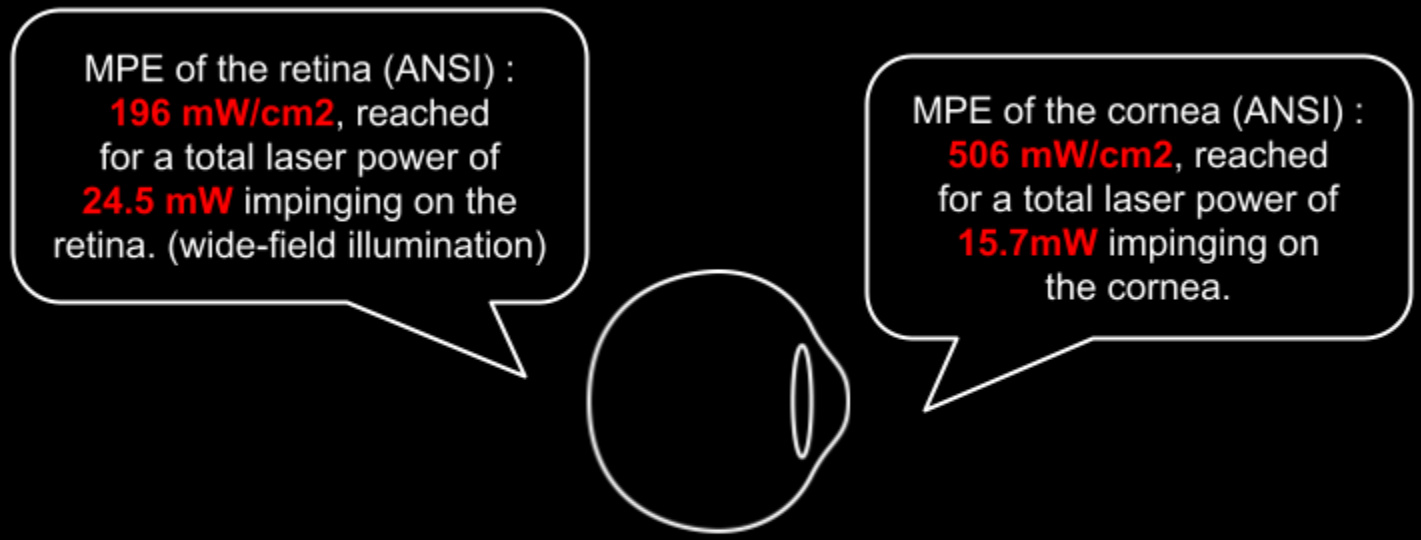


Bratasz, Zofia, Olivier Martinache, Yohan Blazy, Angèle Denis, Coline Auffret, Jean-Pierre Huignard, Ethan Rossi et al. "Diffuse laser illumination for Maxwellian view Doppler holography of the retina." *arXiv preprint arXiv:2212.13347* (2022).



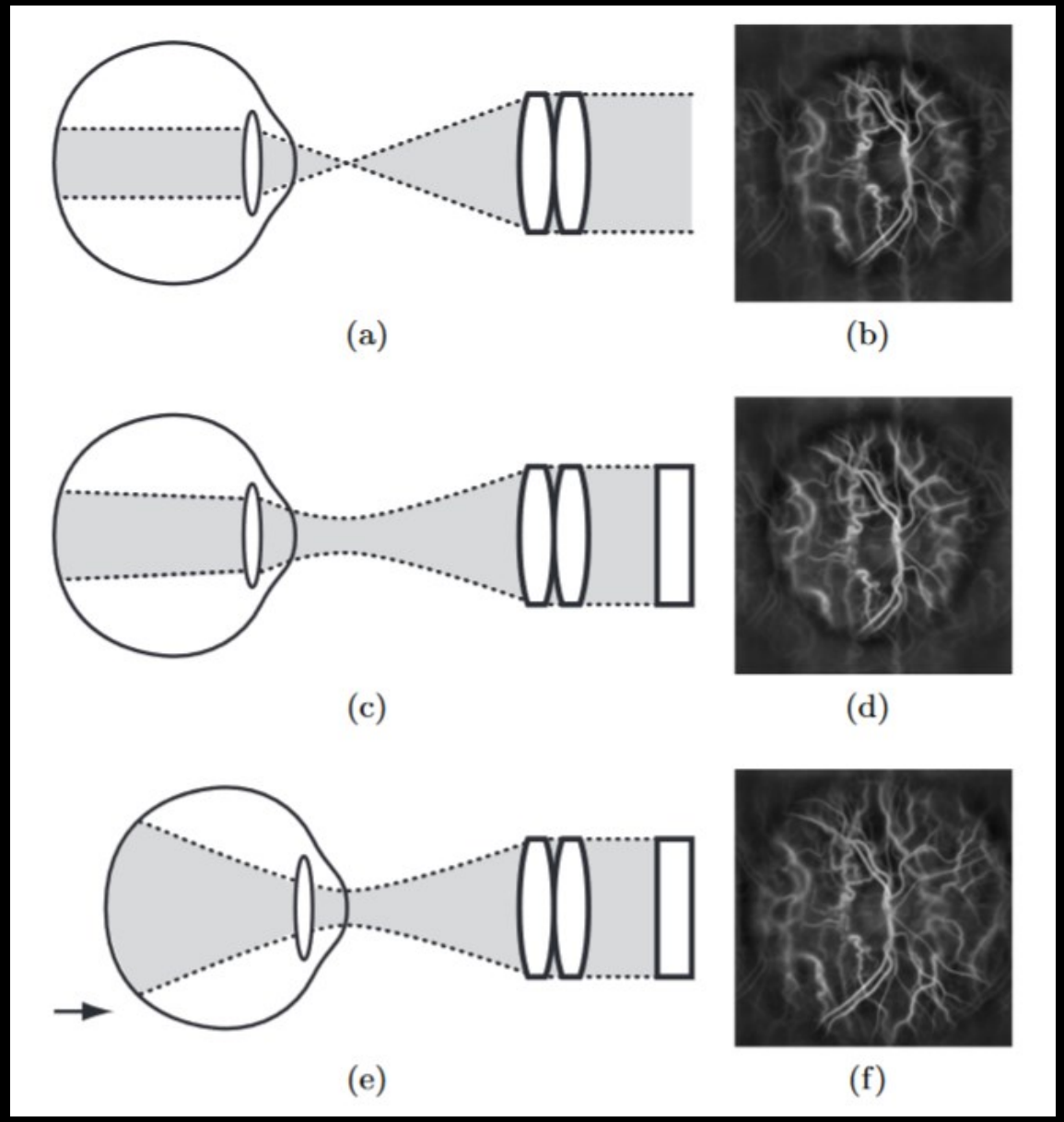
EUROPE
ISO 15004-1 : 2007
ISO 15004-2 : 2007
maximum permissible exposure, wavelength λ > 770 nm

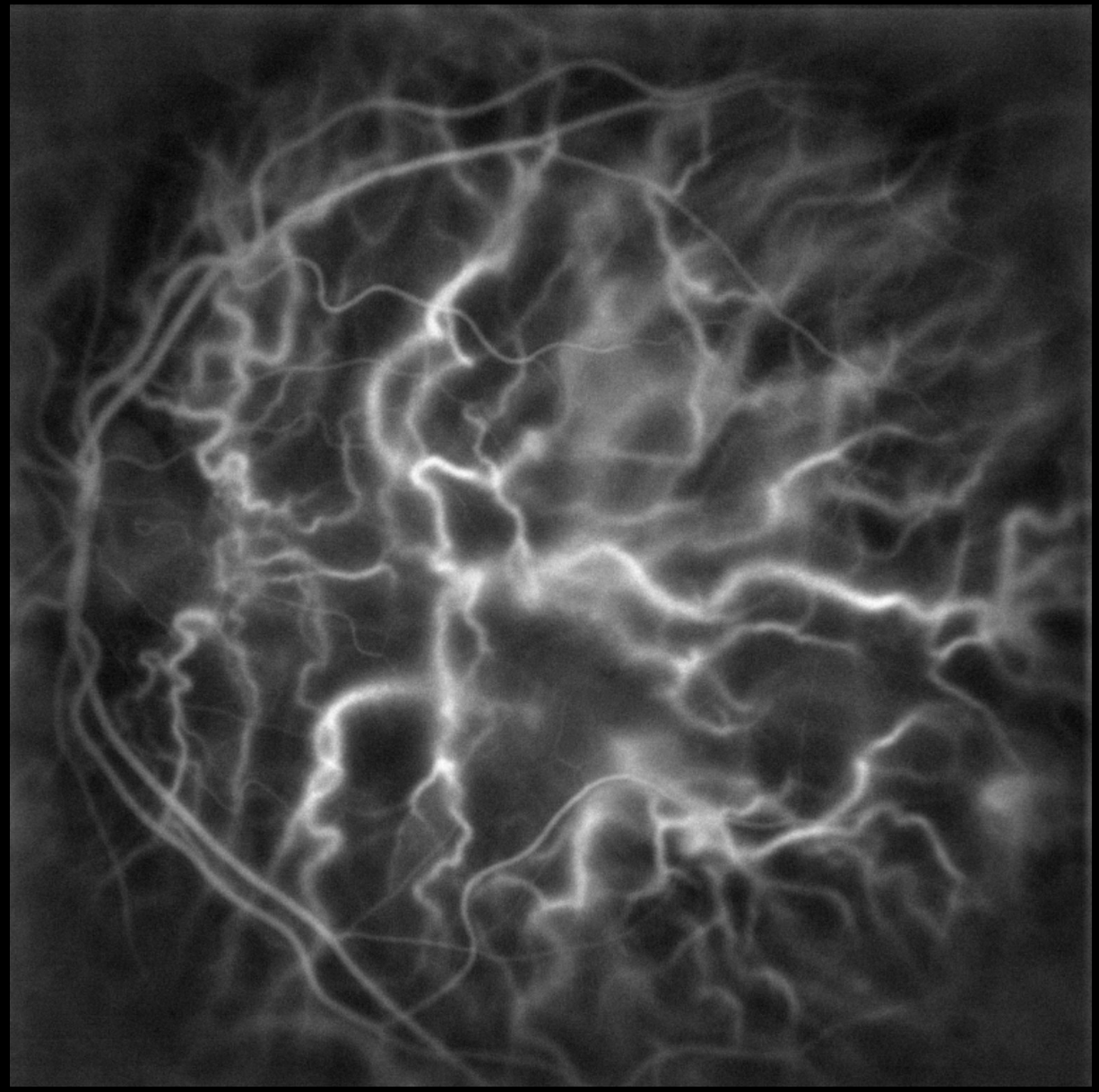
Bratasz, Zofia, Olivier Martinache, Yohan Blazy, Angèle Denis, Coline Auffret, Jean-Pierre Huignard, Ethan Rossi et al. "Diffuse laser illumination for Maxwellian view Doppler holography of the retina." *arXiv preprint arXiv:2212.13347* (2022).



USA
American National Standard for Safe Use of Lasers
ANSI Z136.1-200
maximum permissible exposure, wavelength λ > 770 nm

Bratasz, Zofia, Olivier Martinache, Yohan Blazy, Angèle Denis, Coline Auffret, Jean-Pierre Huignard, Ethan Rossi et al. "Diffuse laser illumination for Maxwellian view Doppler holography of the retina." *arXiv preprint arXiv:2212.13347* (2022).

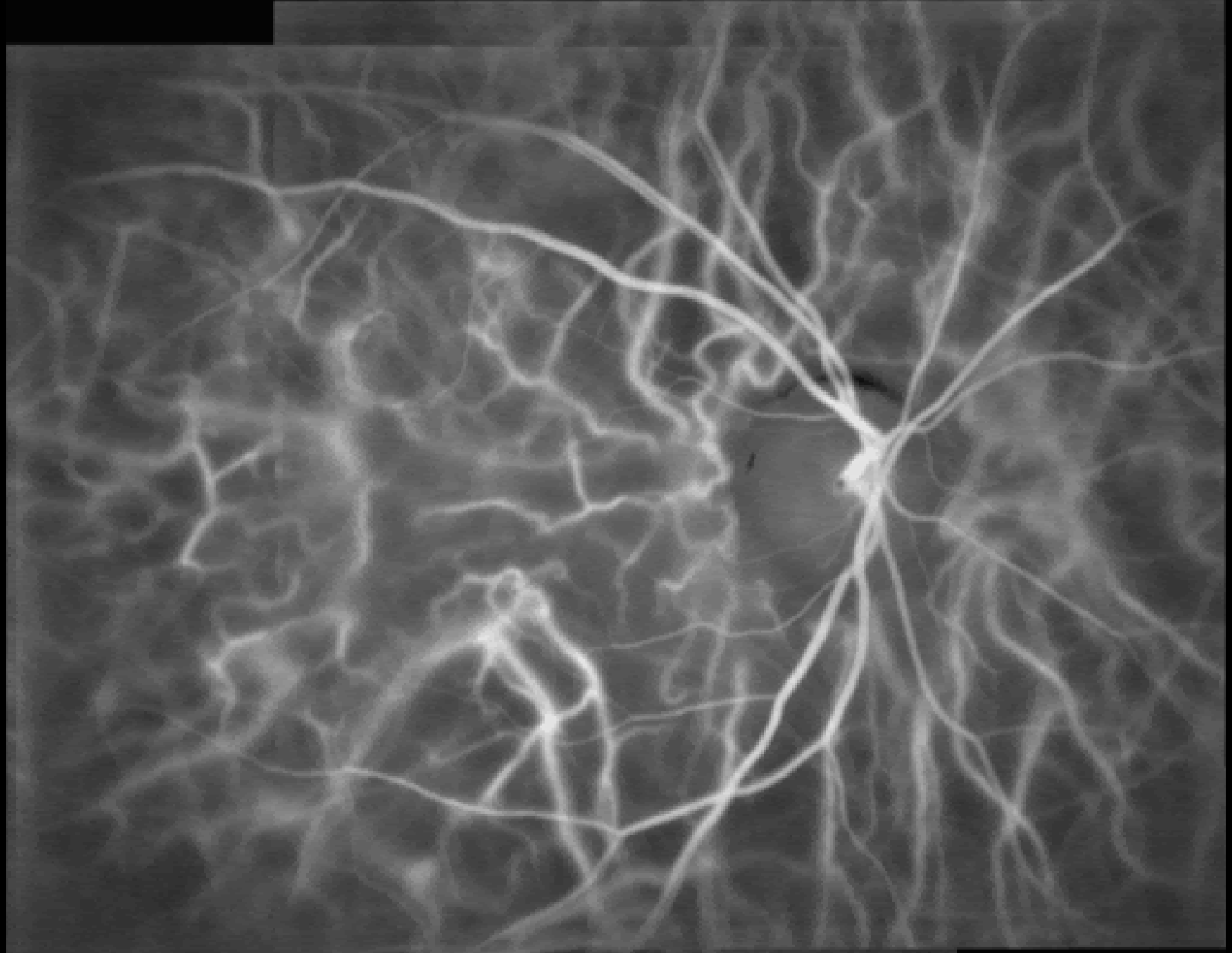


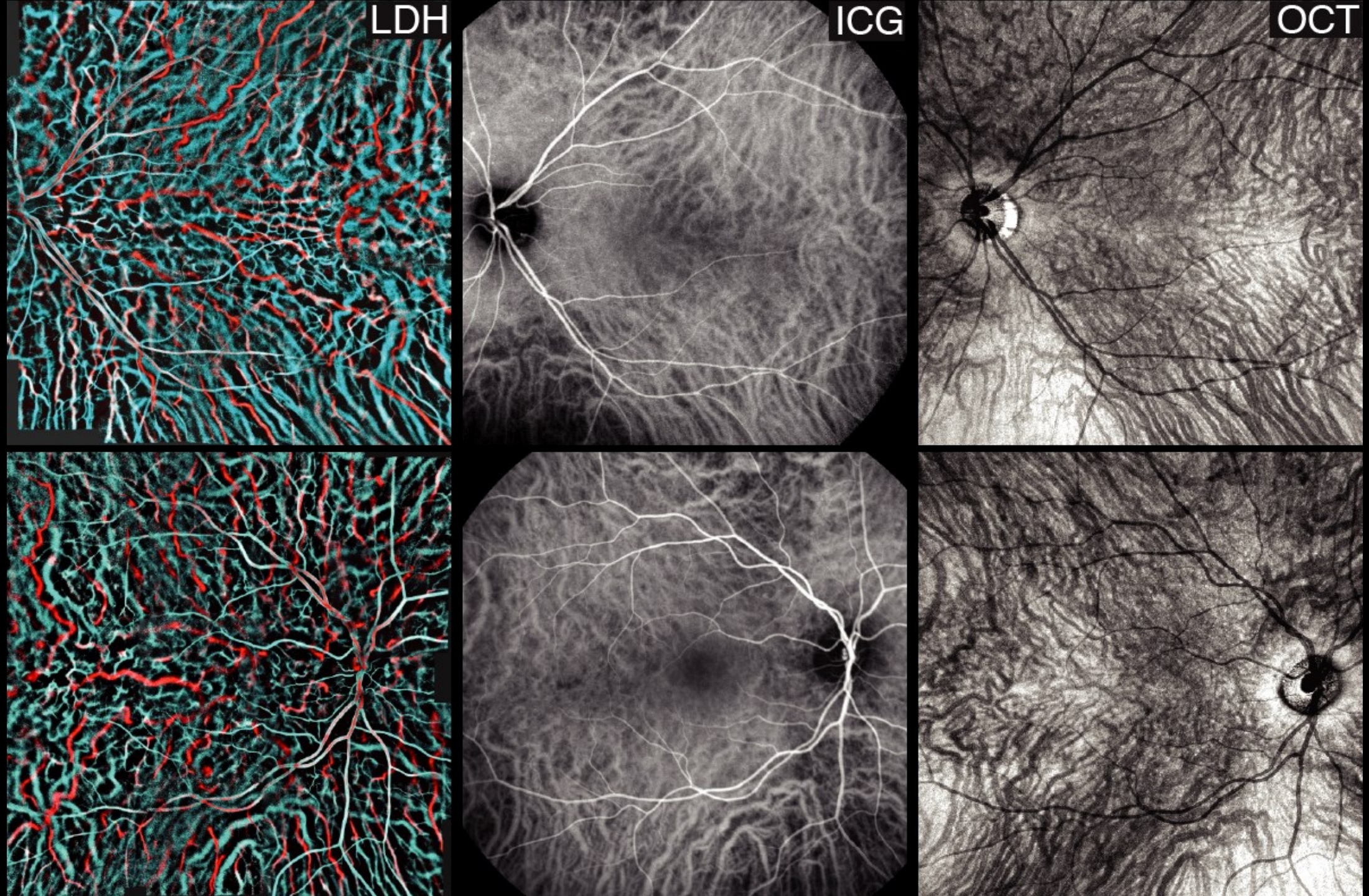


Bratasz, Zofia, Olivier Martinache, Yohan Blazy, Angèle Denis, Coline Auffret, Jean-Pierre Huignard, Ethan Rossi et al. "Diffuse laser illumination for Maxwellian view Doppler holography of the retina." *arXiv preprint arXiv:2212.13347* (2022).

Imagerie fonctionnelle grand champ des vaisseaux choroïdiens et rétiniens

~ 512x512 px frame, 12-bit, 67 kHz

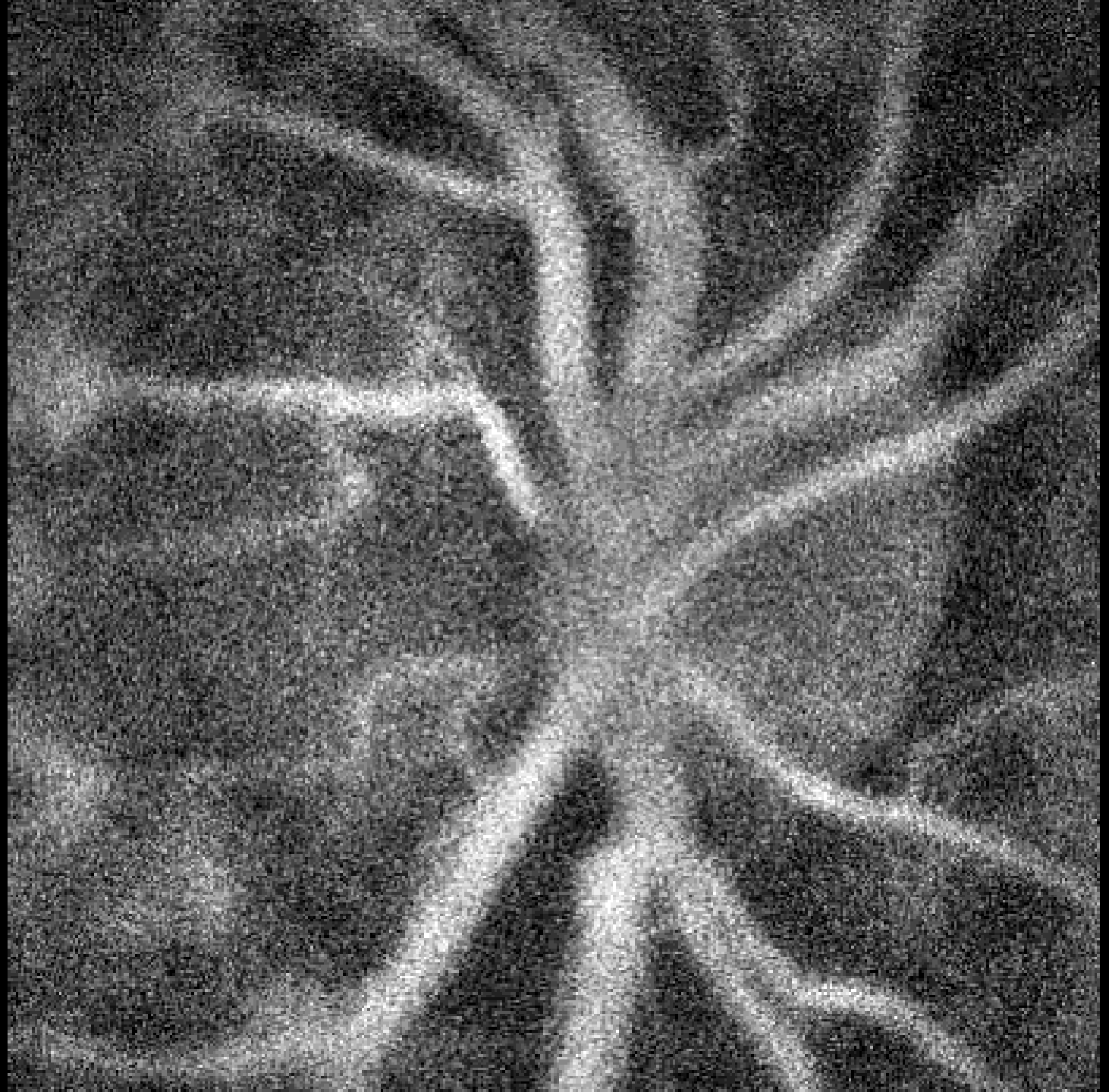


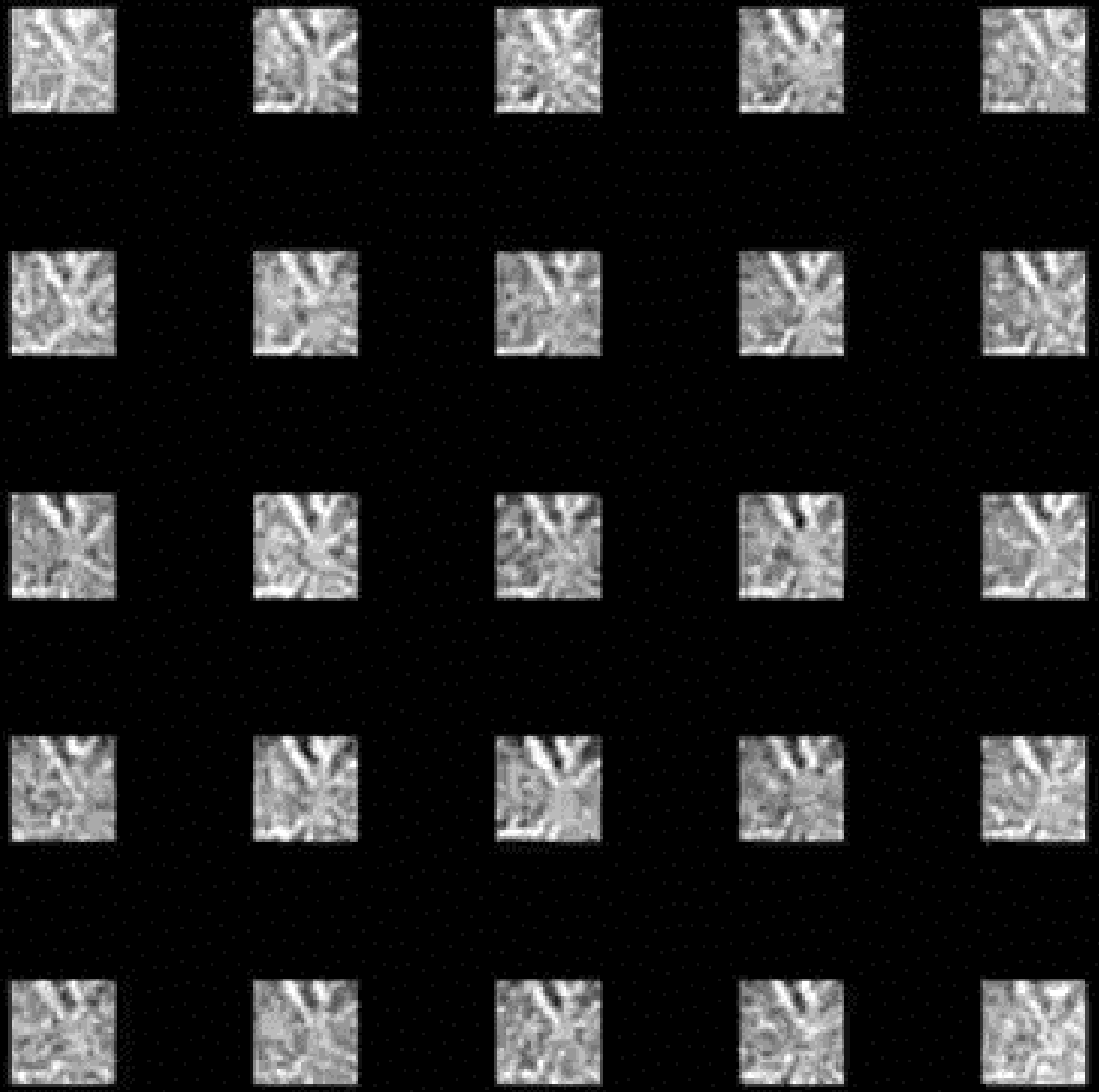

LDH
ICG
OCT

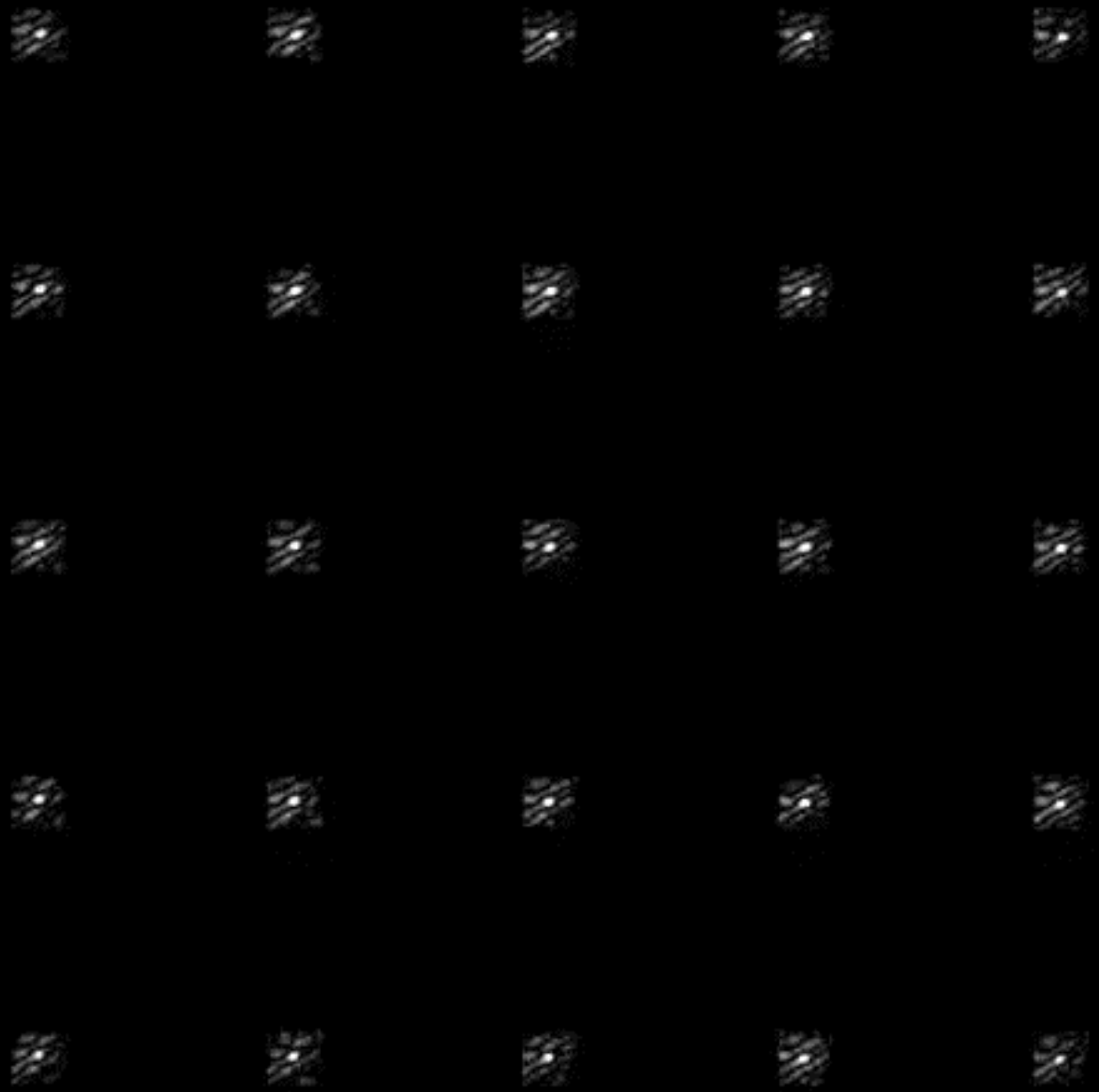
Correction numérique des aberrations

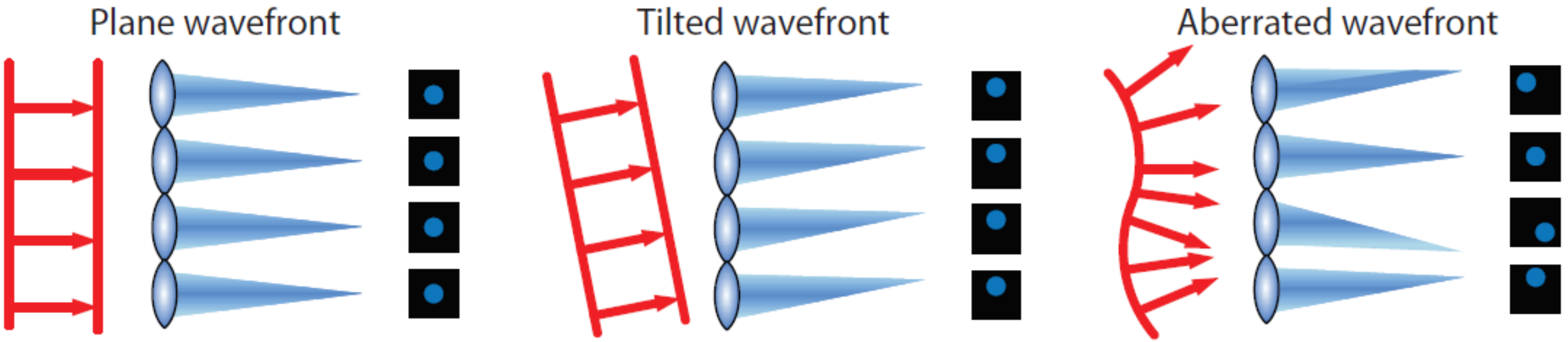
Abhishek Kumar, Wolfgang Drexler, and Rainer A Leitgeb. Subaperture correlation based digital adaptive optics for full field optical coherence tomography. Optics express, 21(9):10850-10866, 2013.

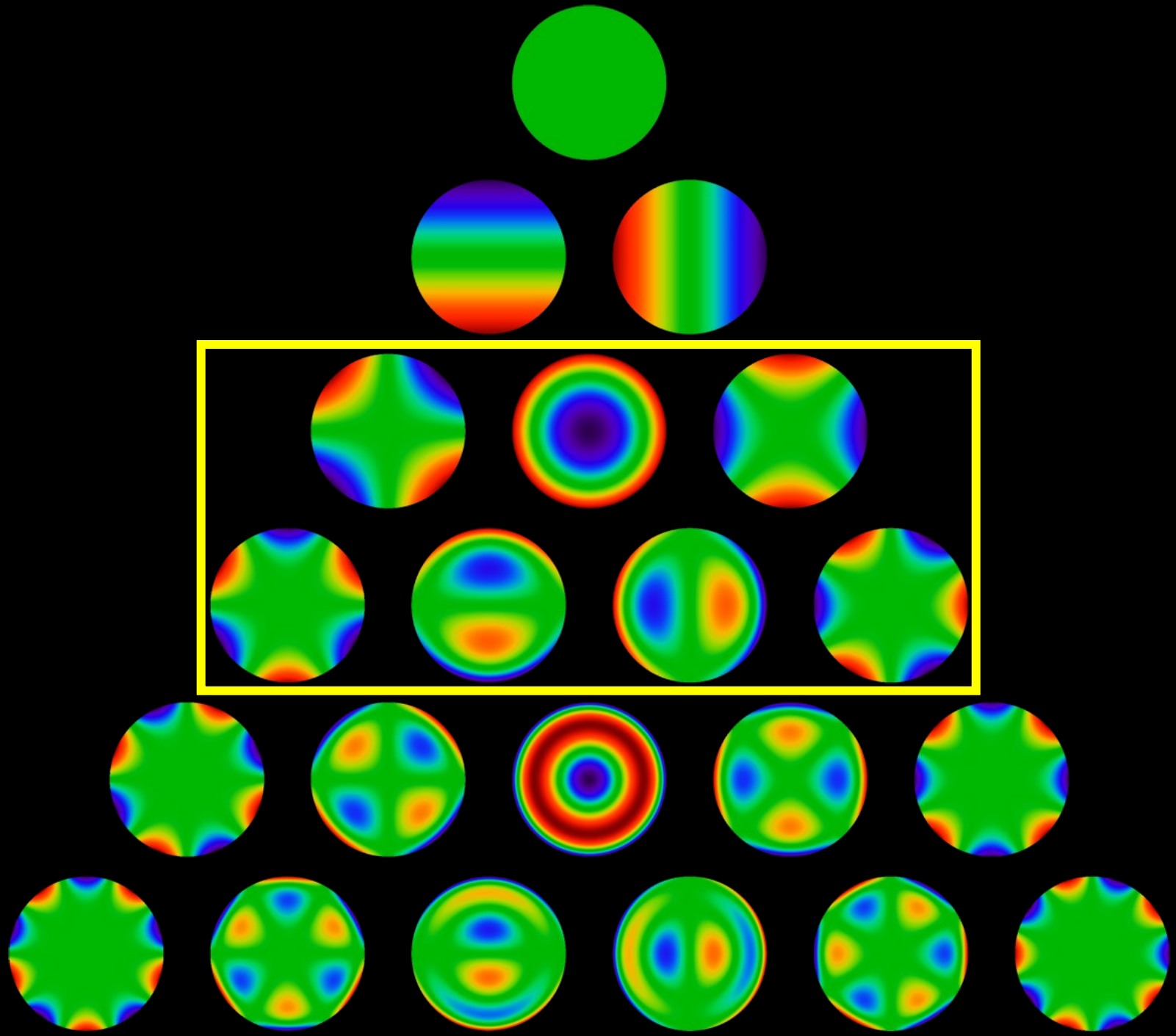
Laurin Ginner, Abhishek Kumar, Daniel Fechtig, Lara M Wurster, Matthias Salas, Michael Pircher, and Rainer A Leitgeb. Noniterative digital aberration correction for cellular resolution retinal optical coherence tomography in vivo. Optica, 4(8):924{931, 2017.

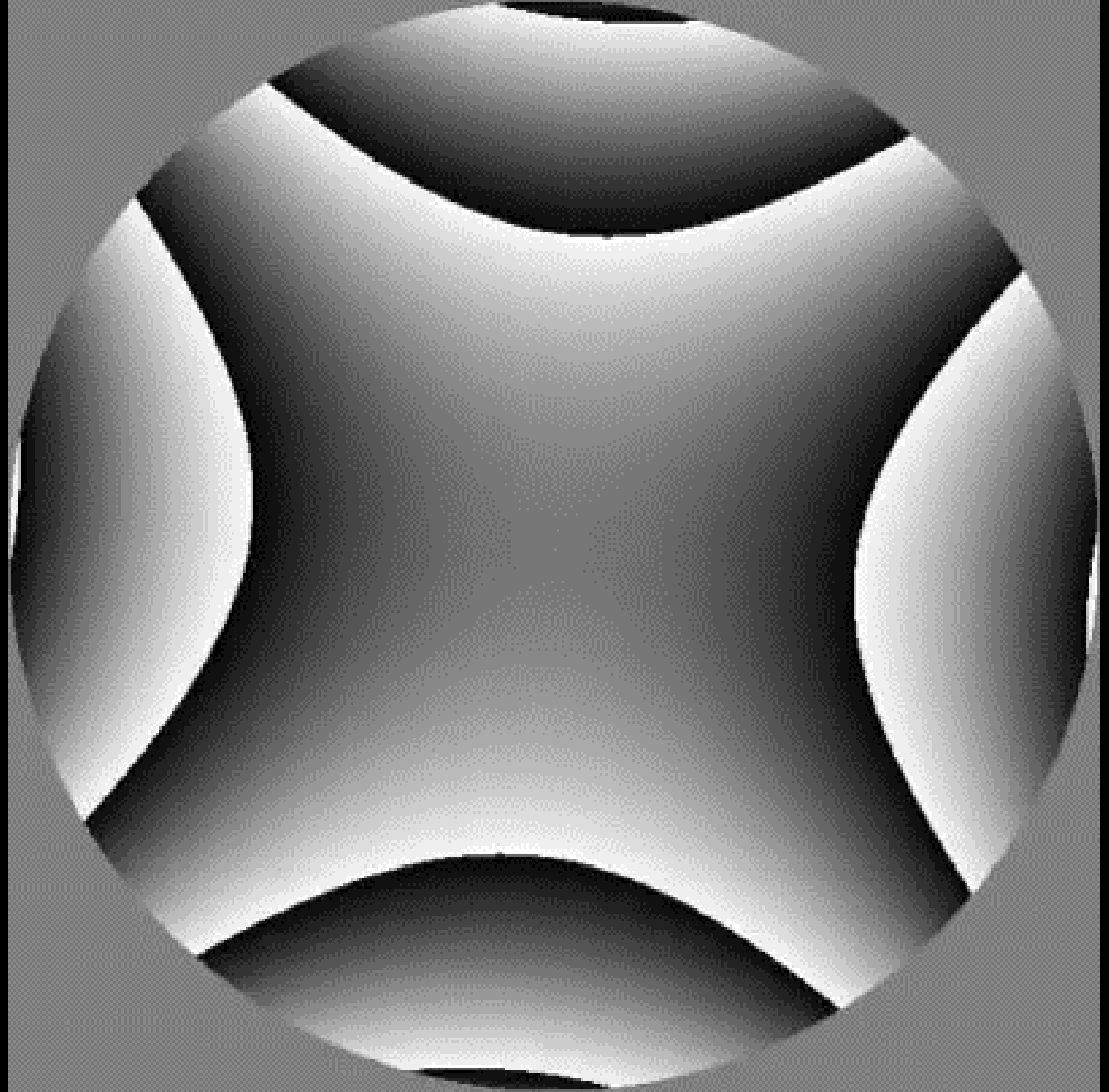


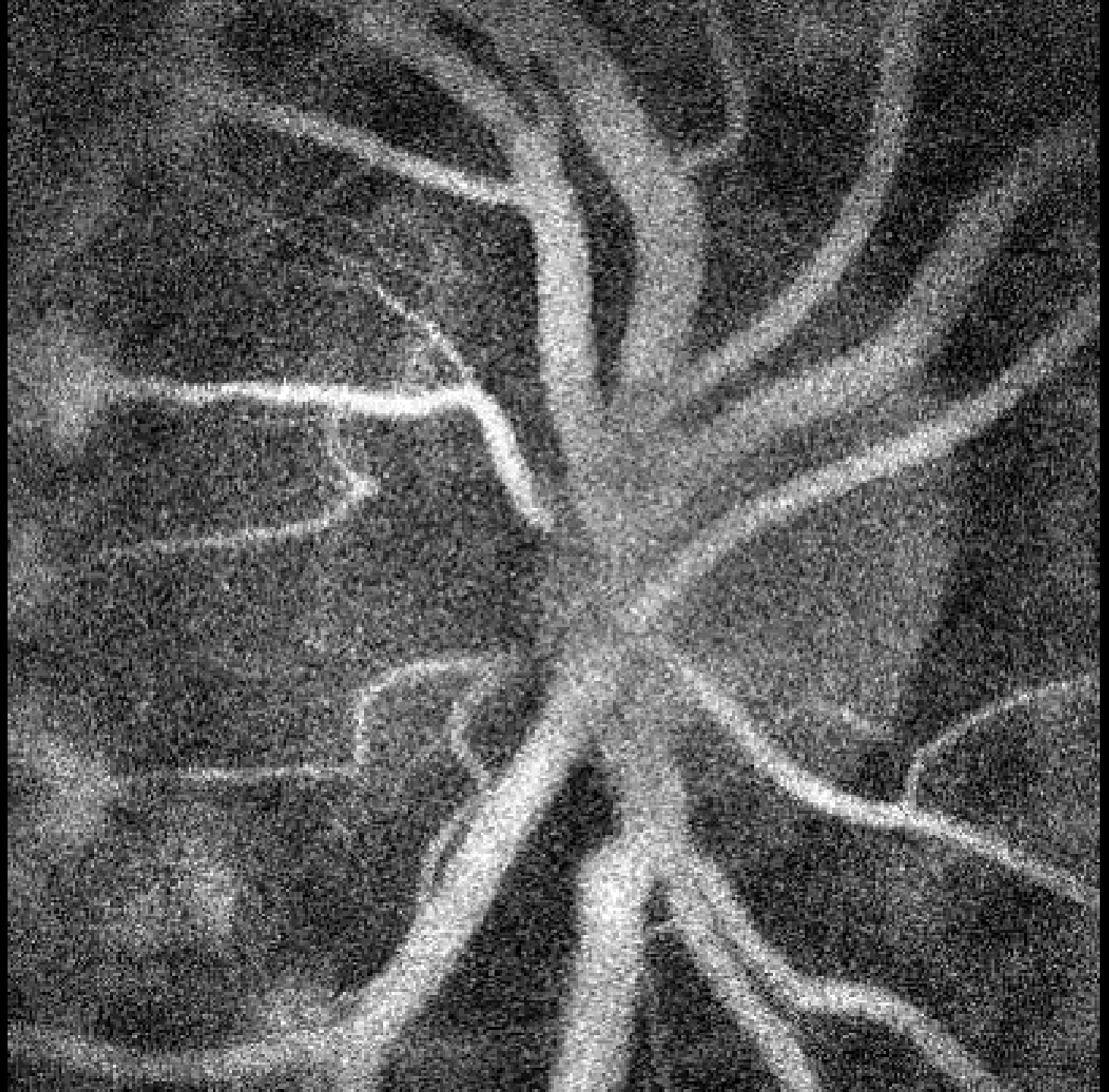


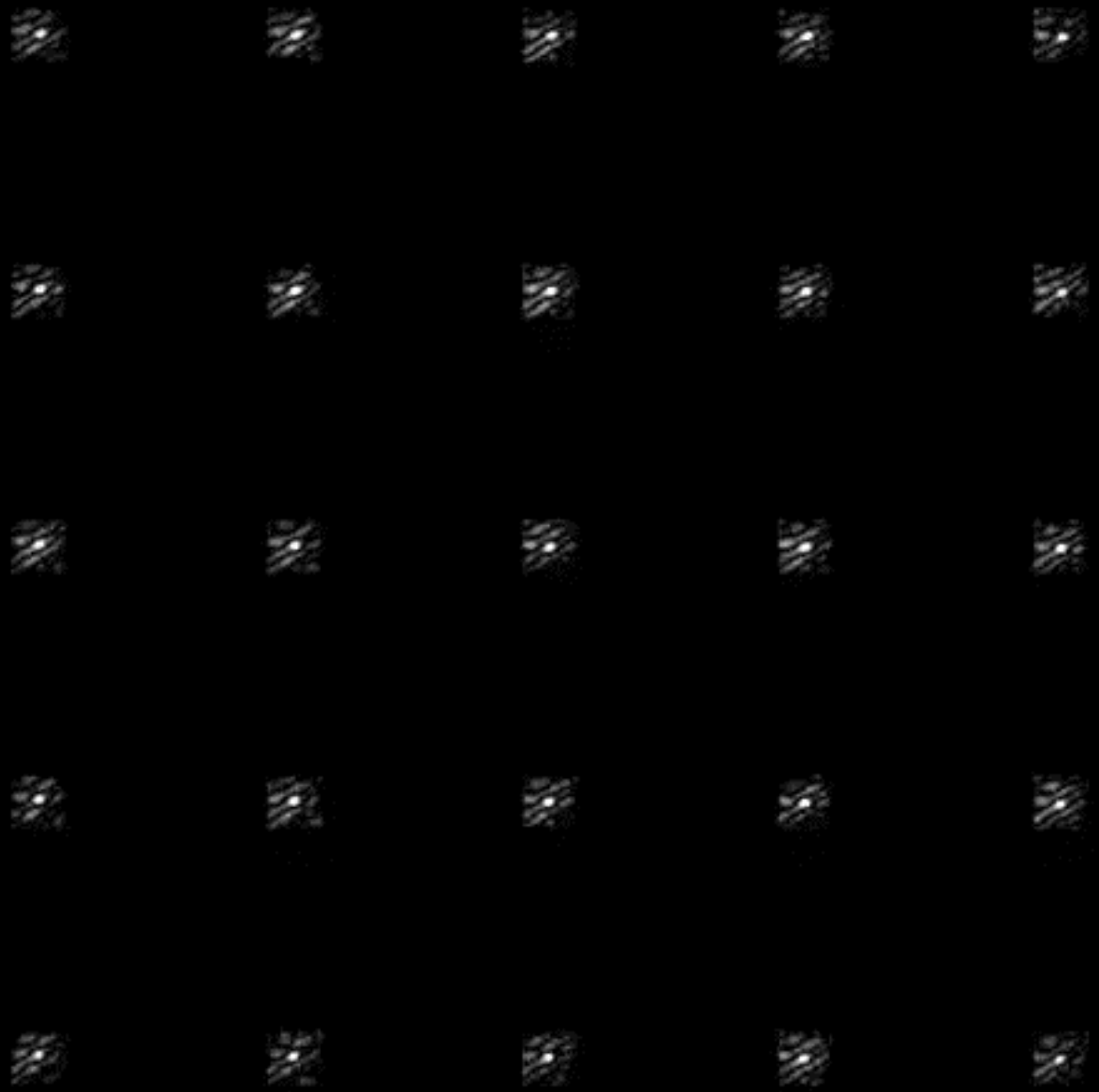


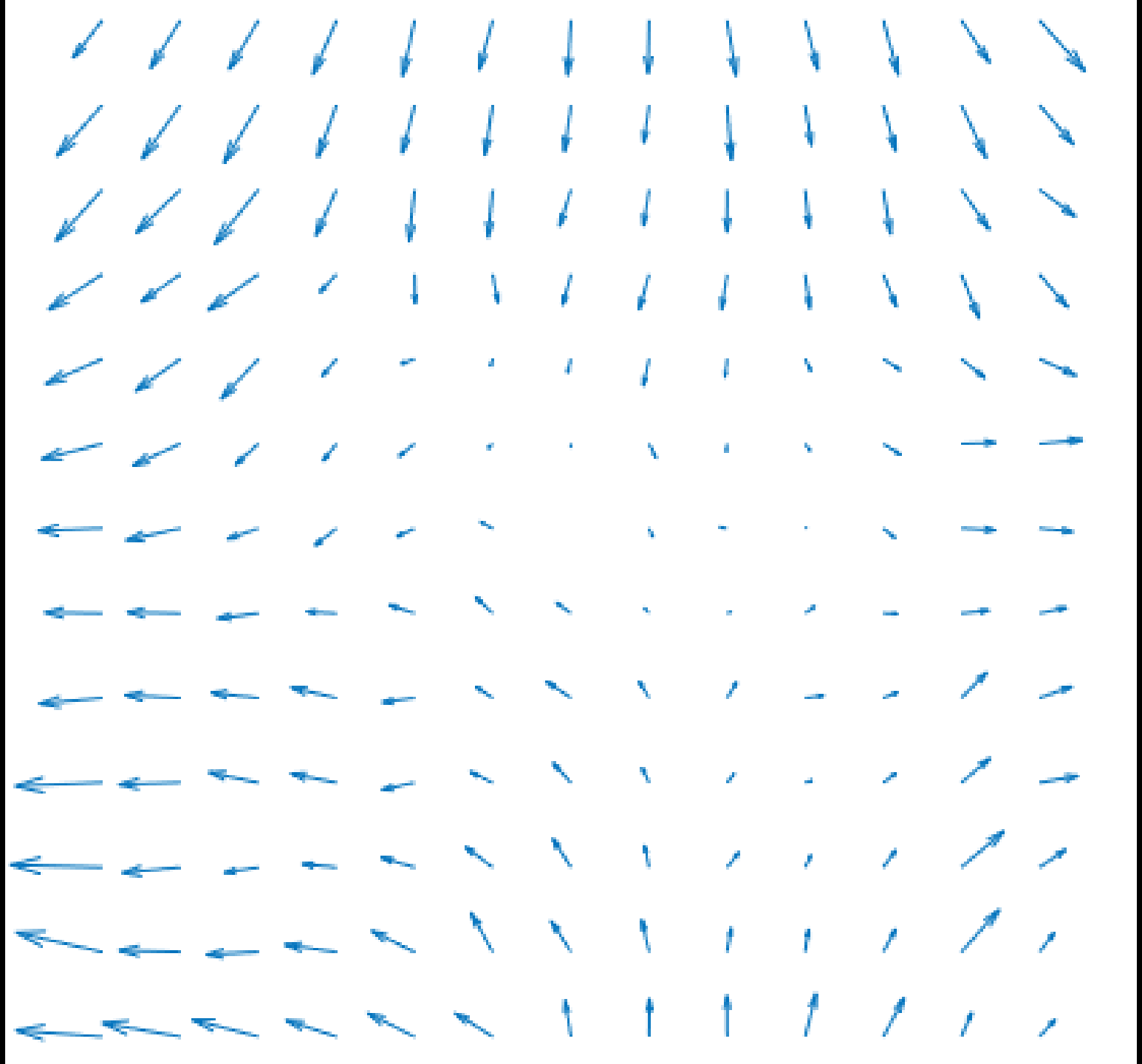

Plane wavefront
Tilted wavefront
Aberrated wavefront

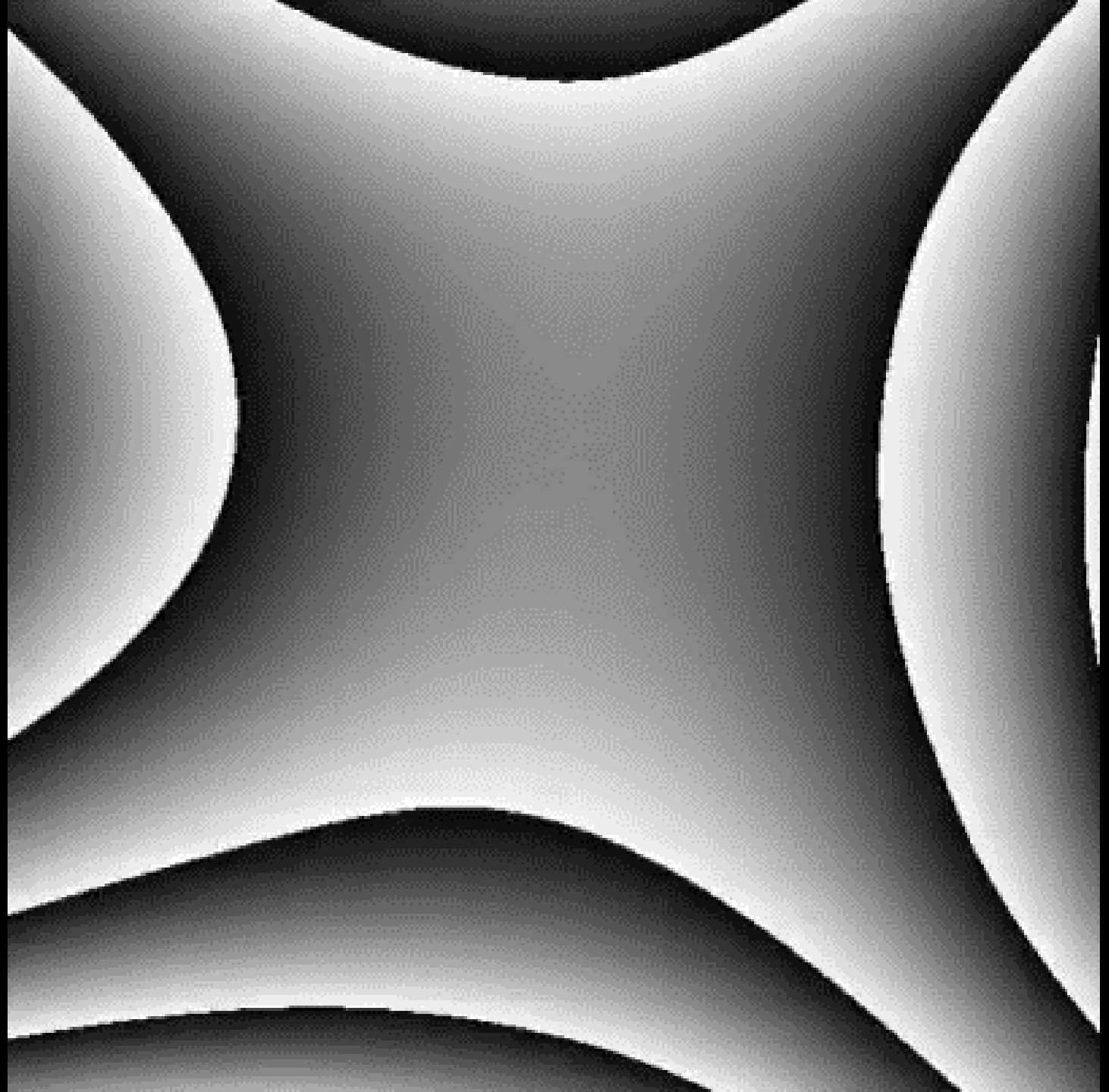


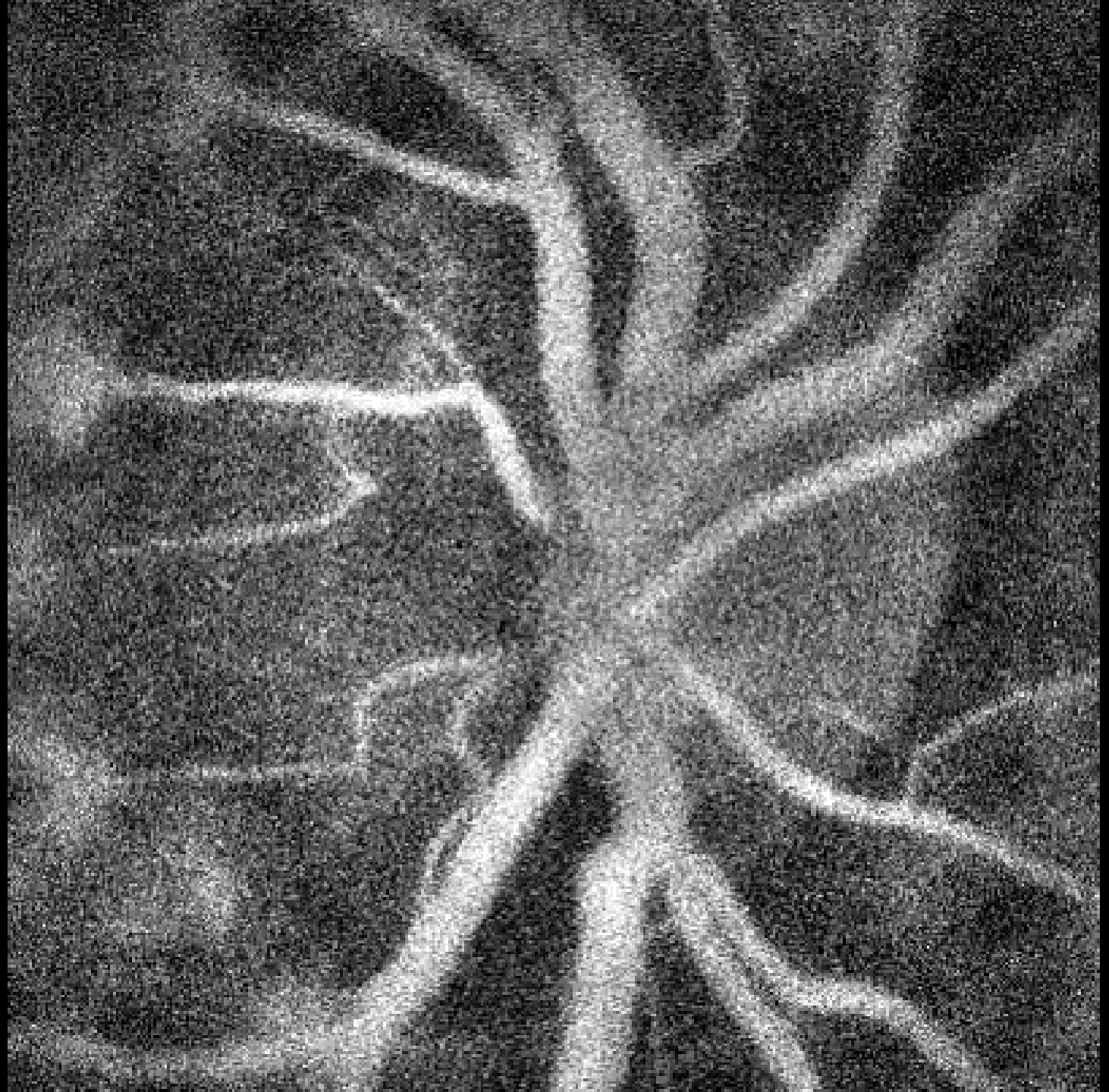


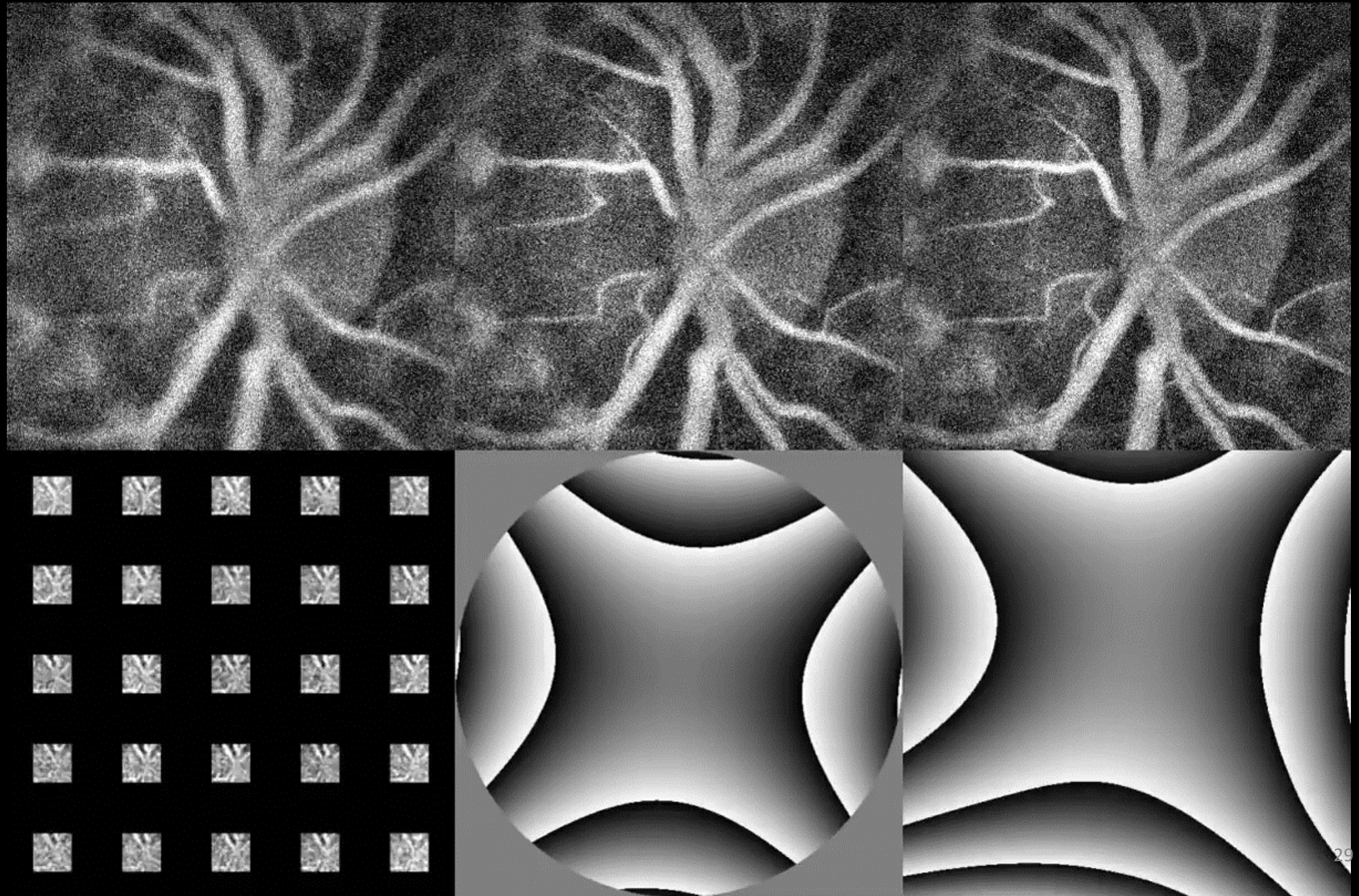


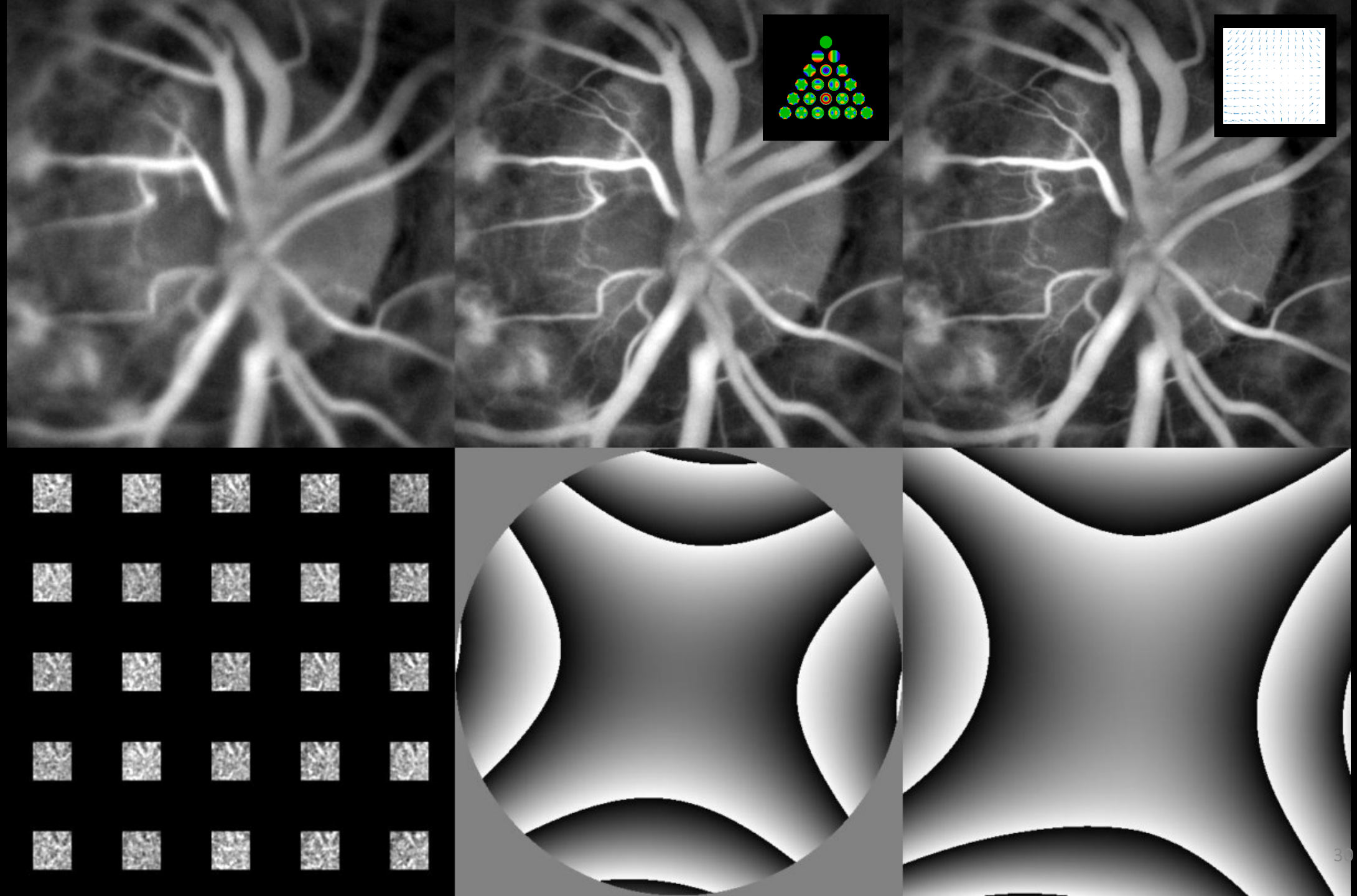


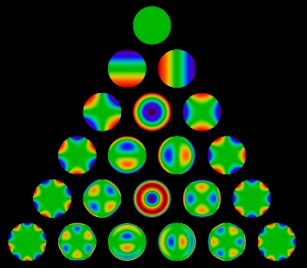


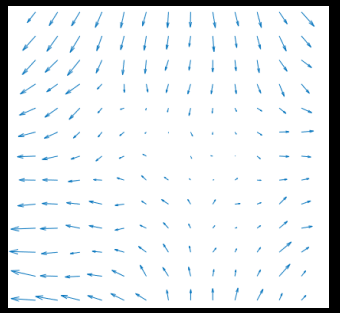




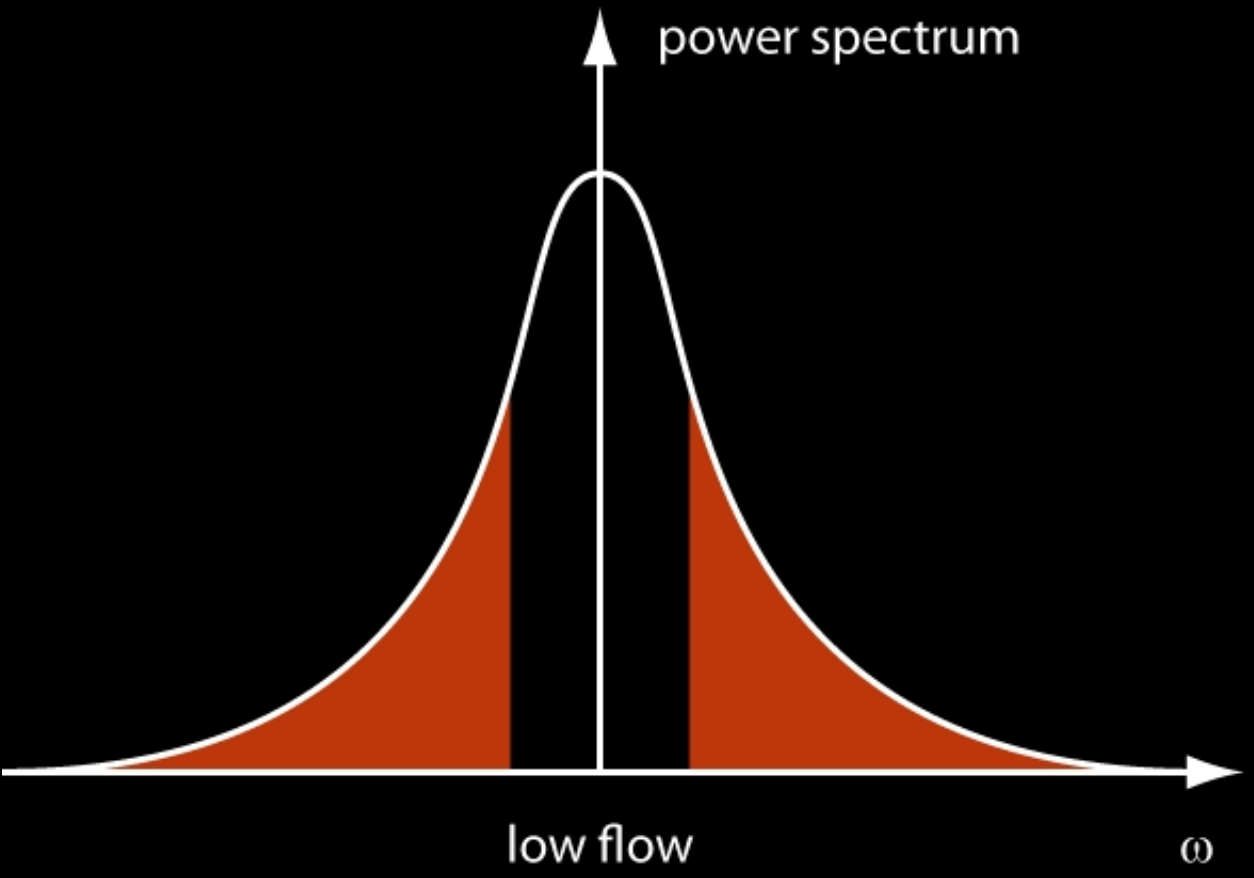


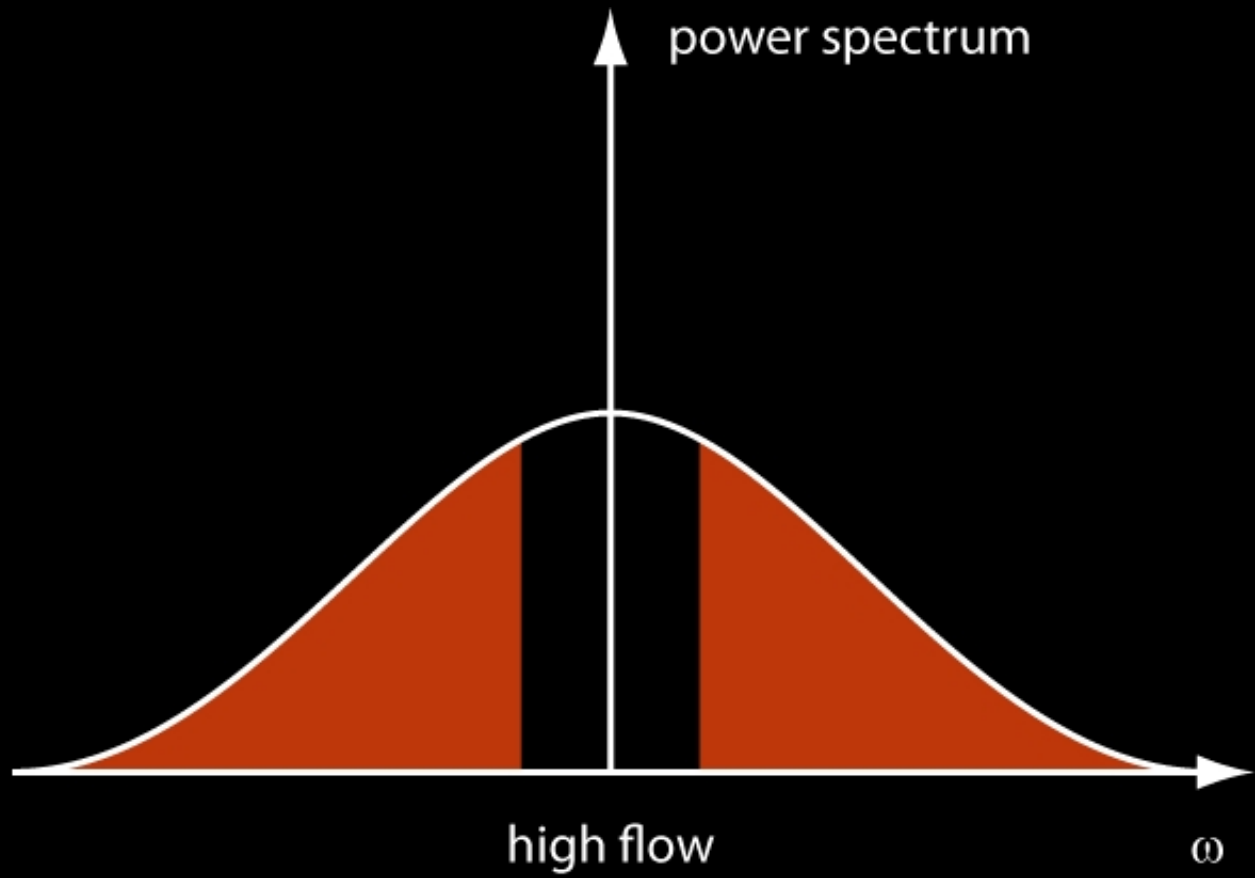


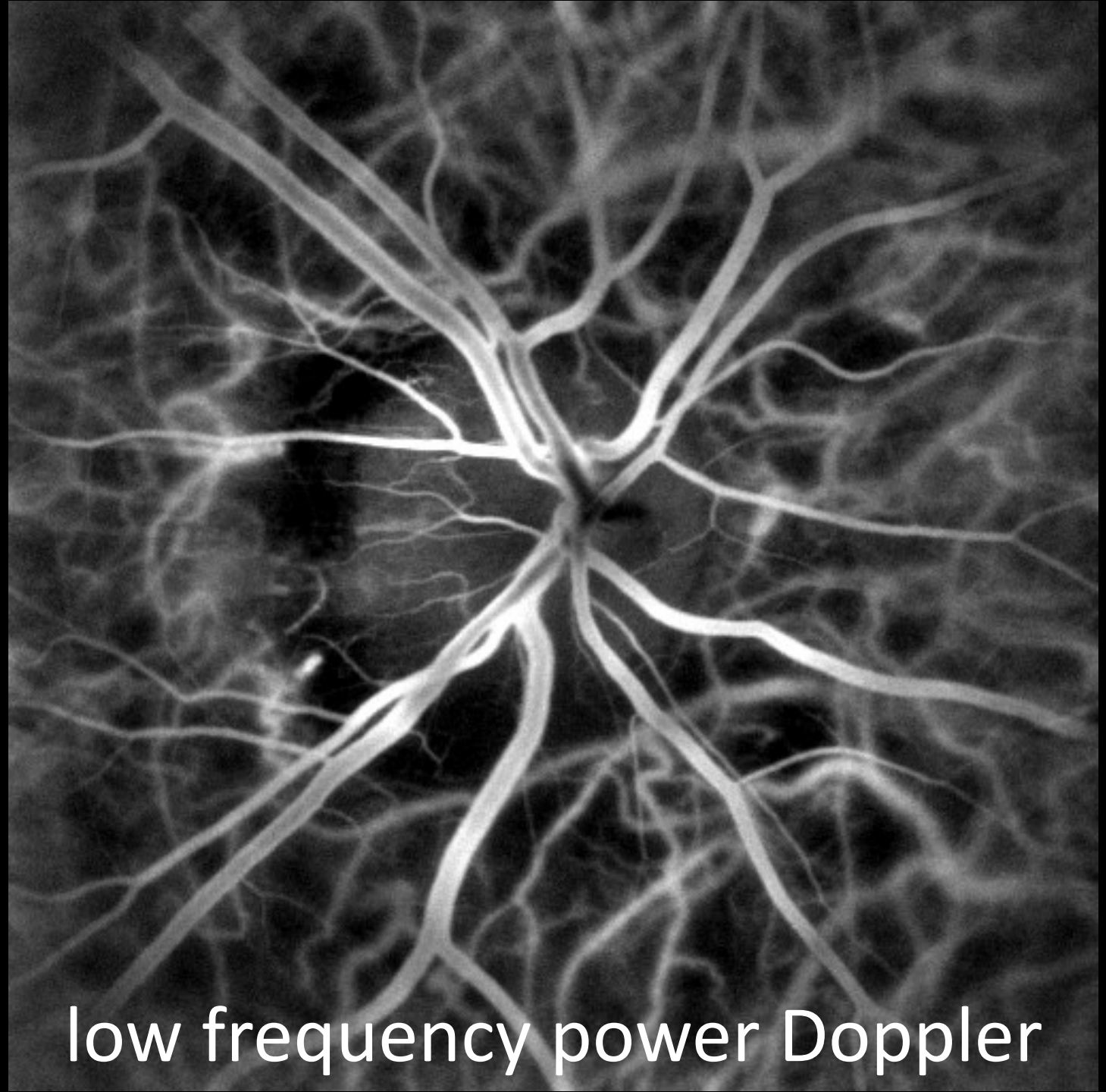




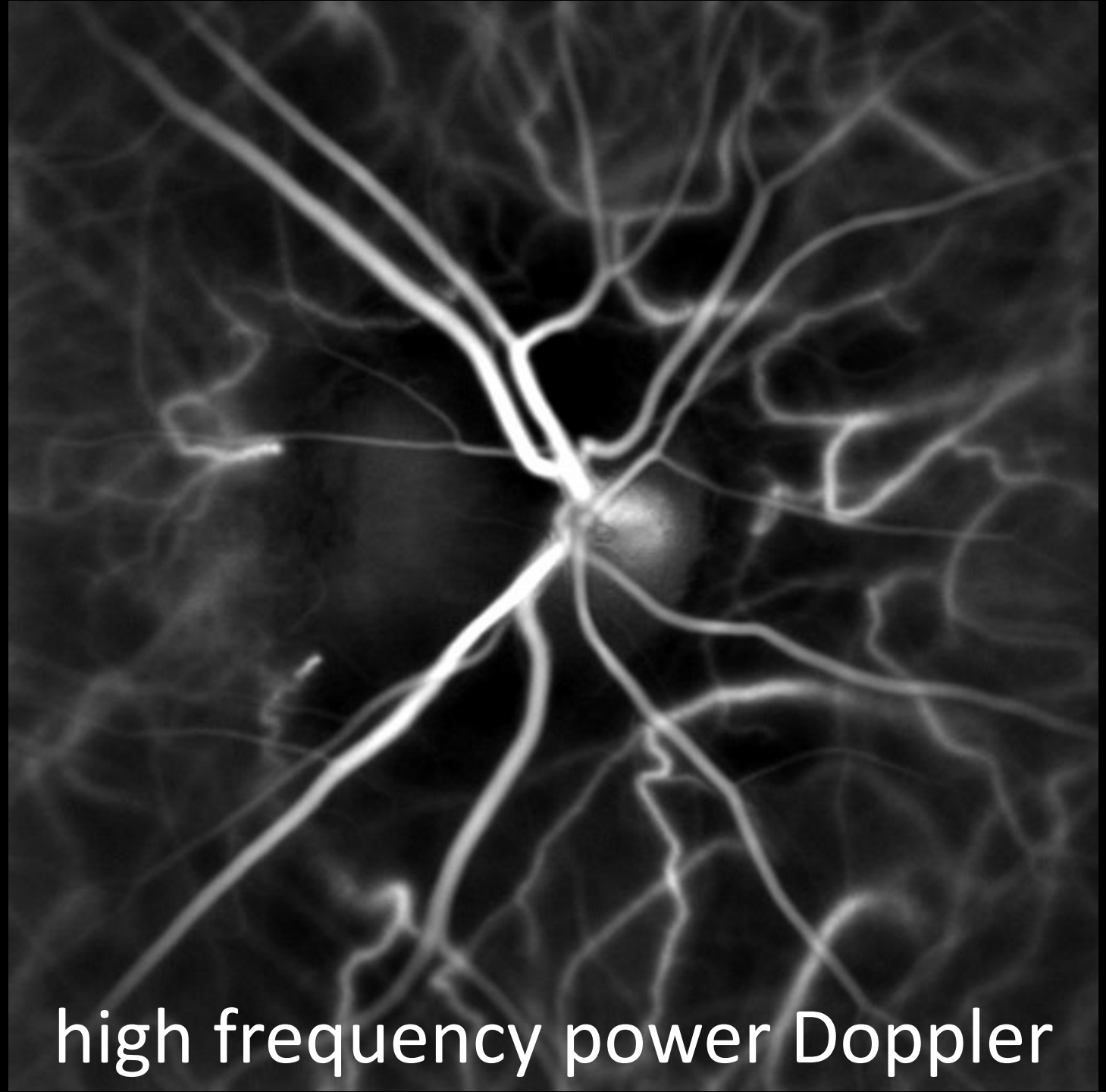
Composite color images of blood flow


power spectrum
low flow
ω

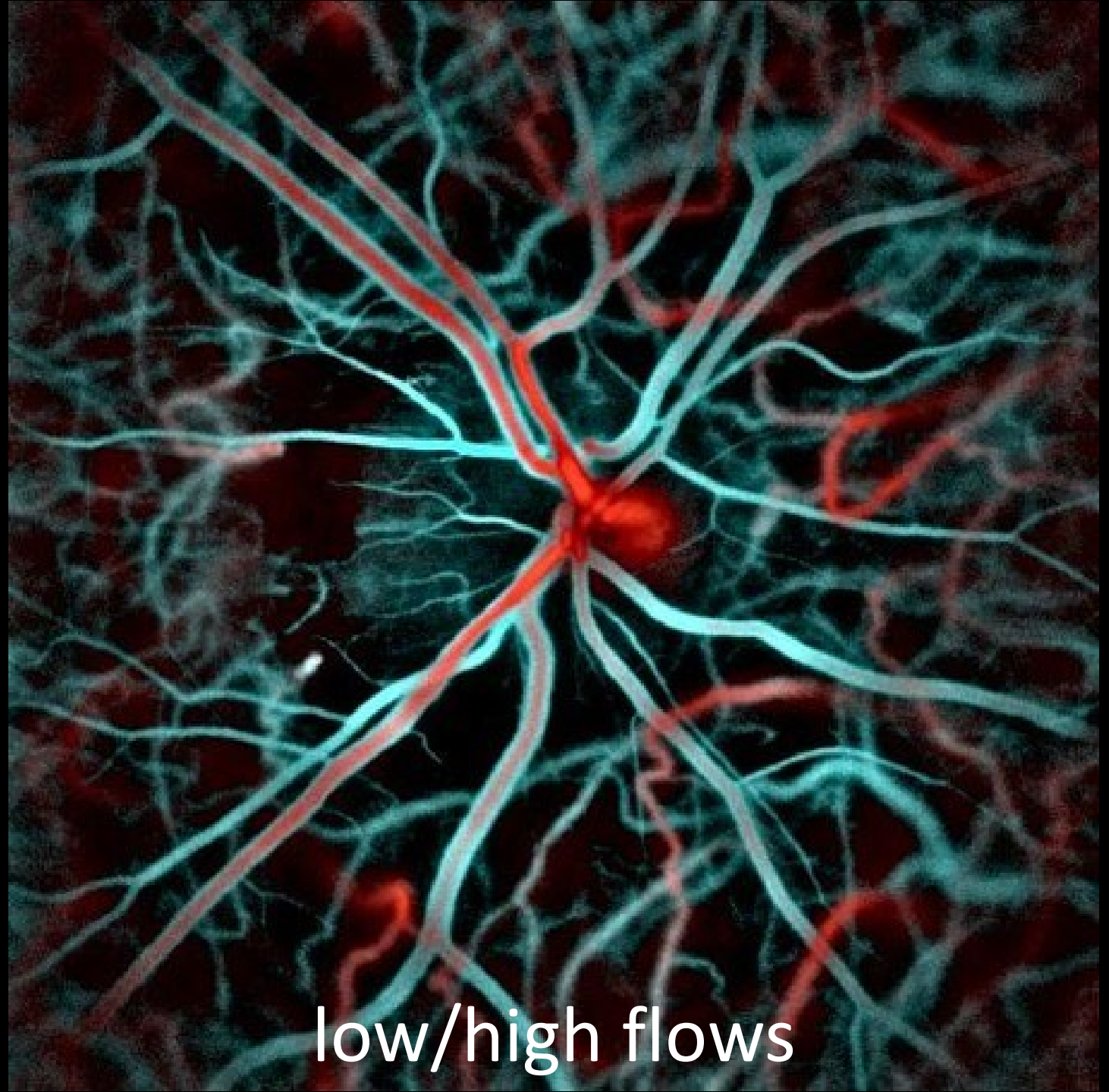

power spectrum
high flow
ω



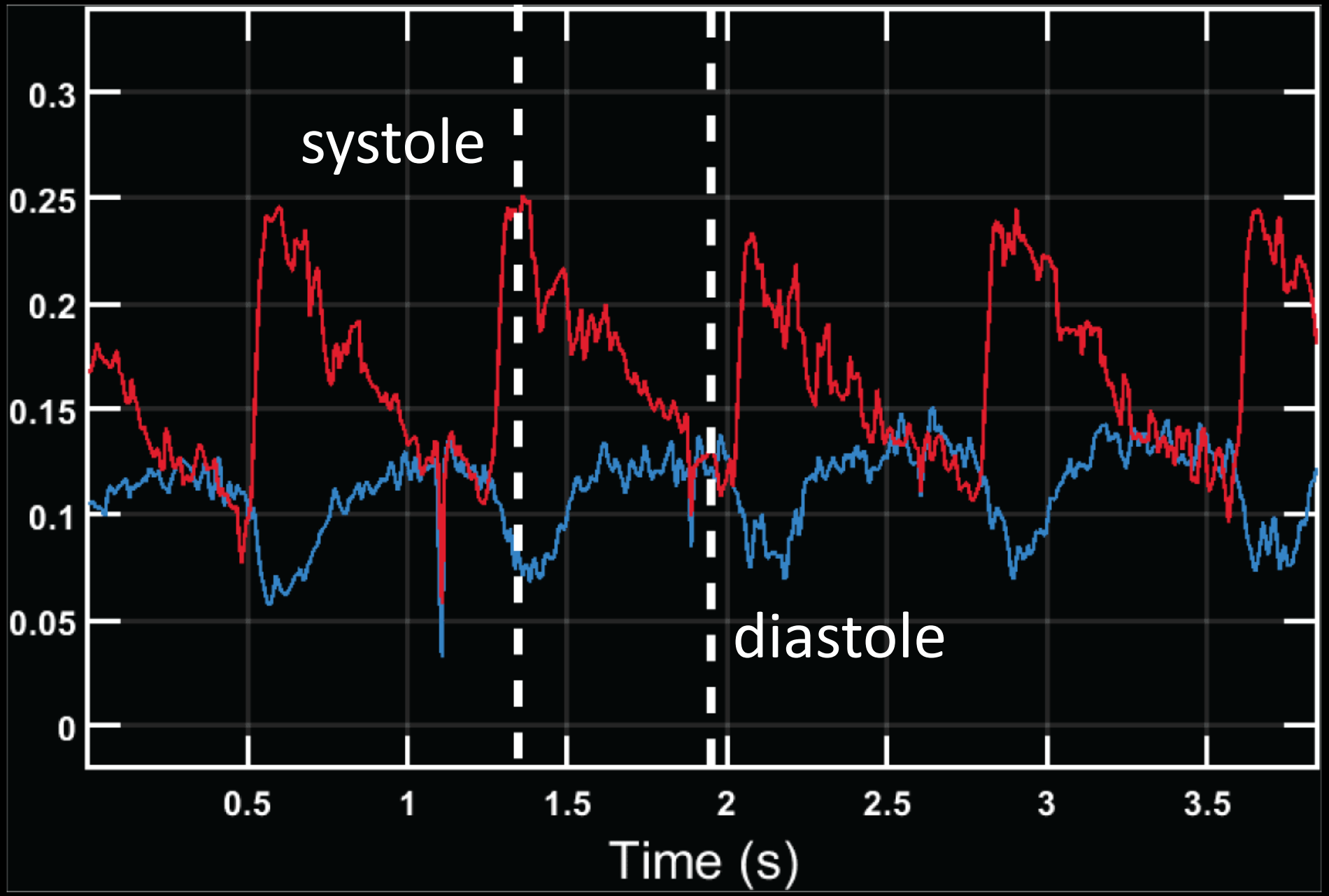
low frequency power Doppler

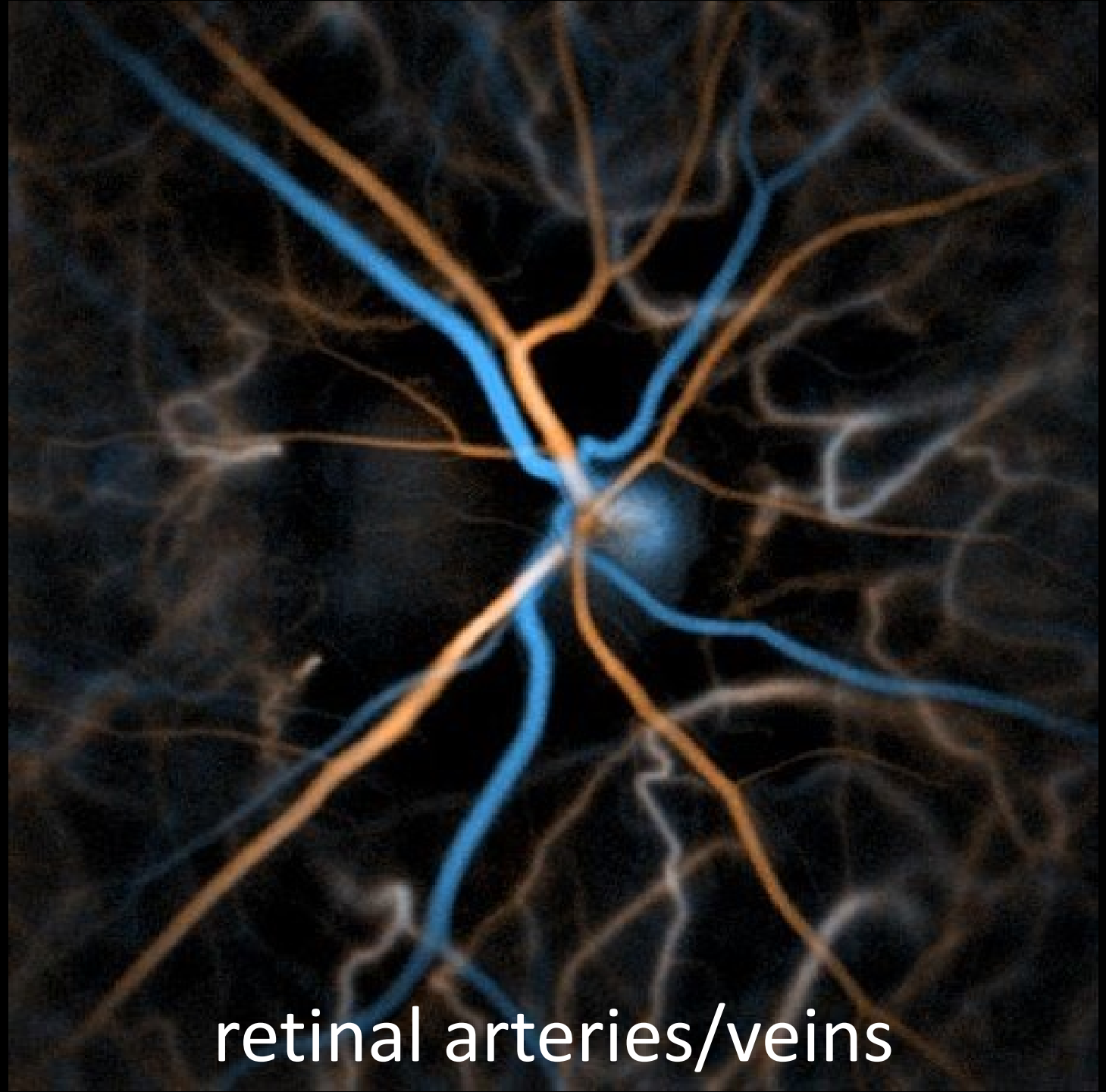


high frequency power Doppler

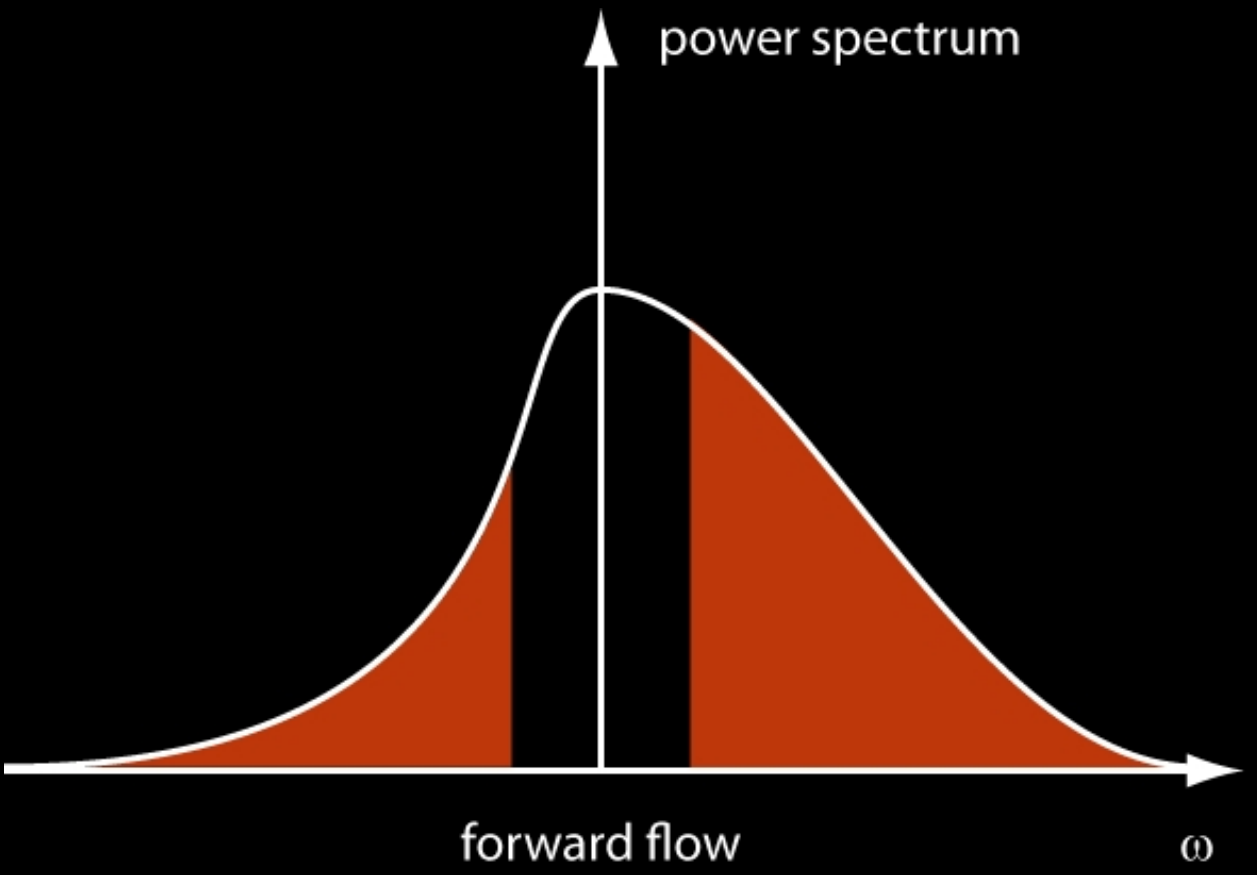


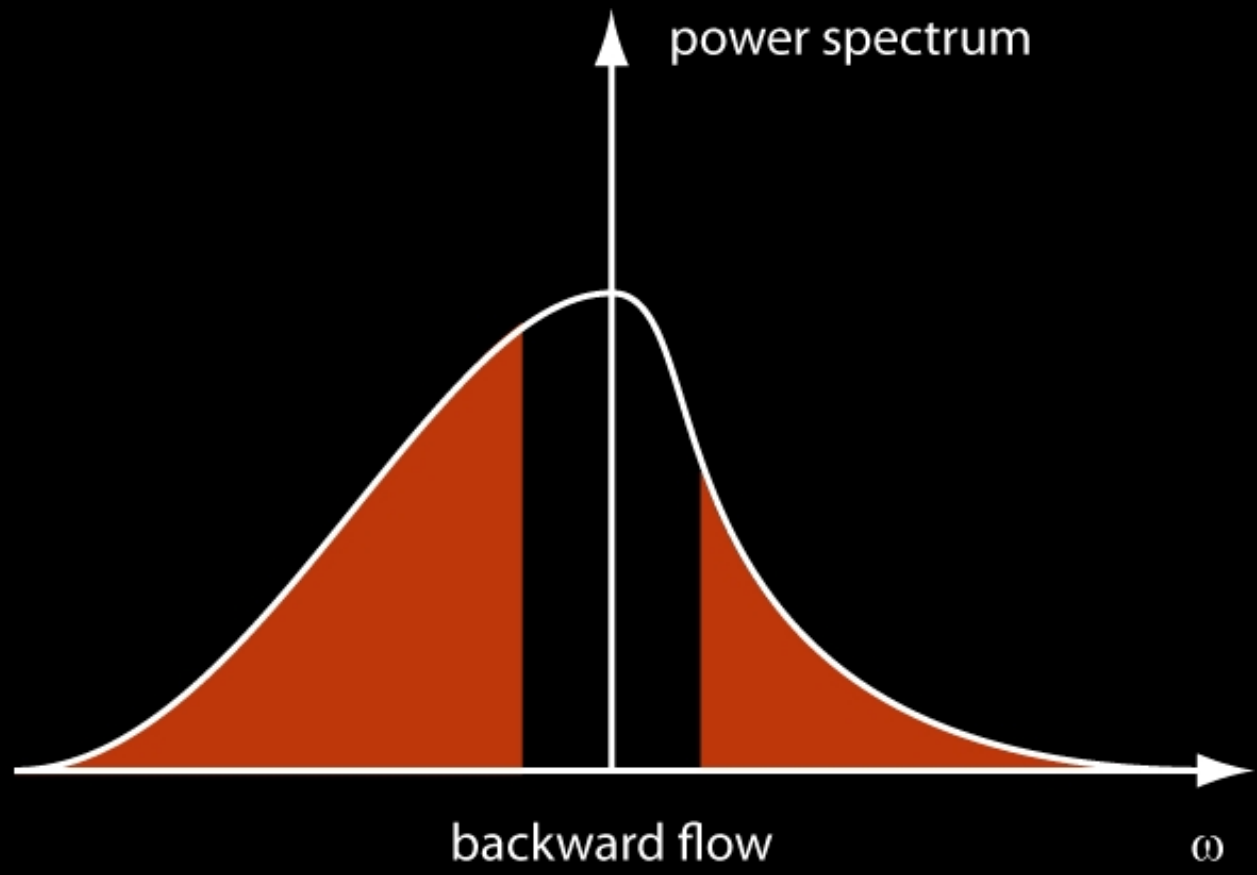
low/high flows

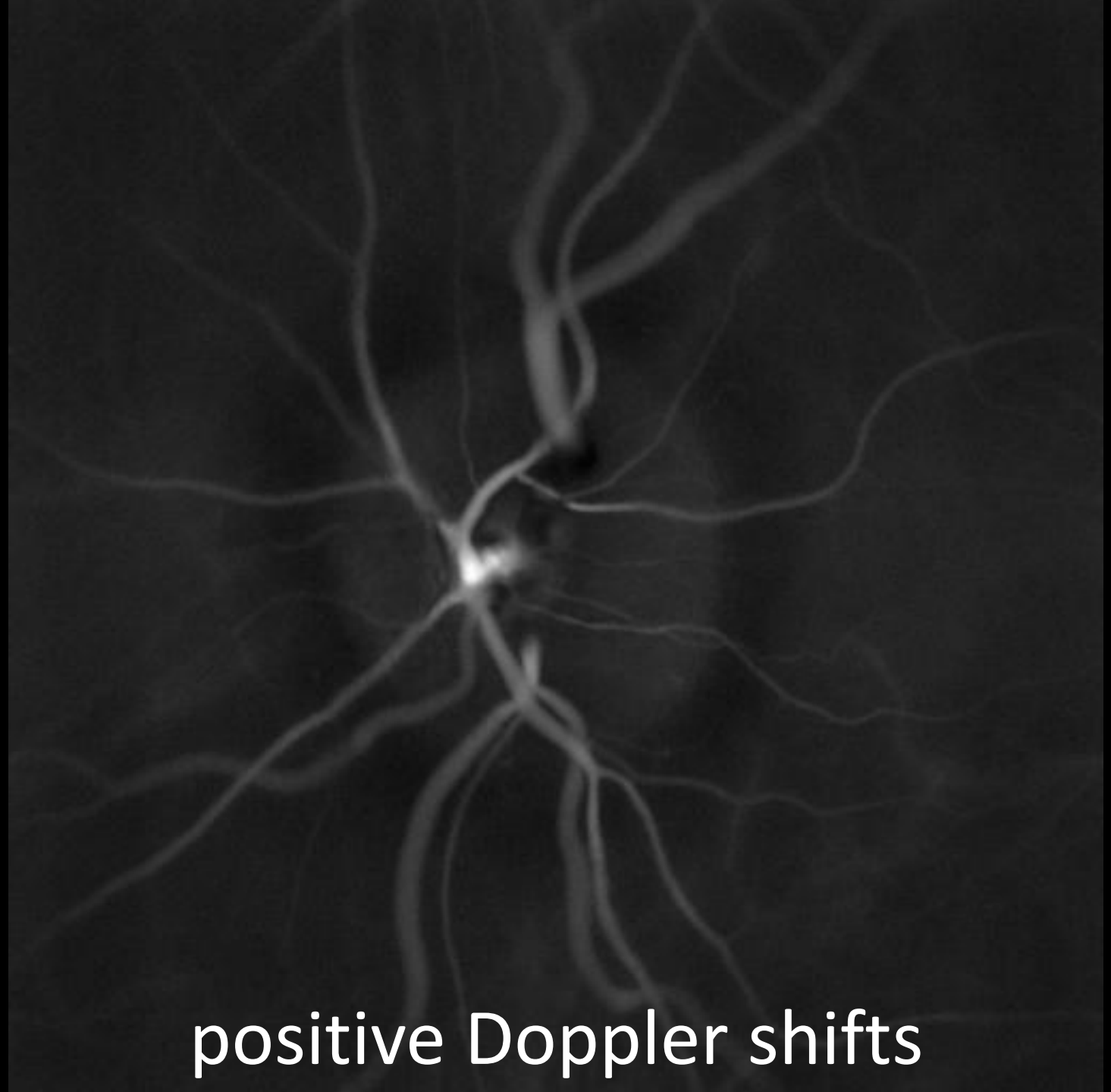

systole
diastole
0.3
0.25
0.2
0.15
0.1
0.05
0
0.5
1
1.5
2
2.5
3
3.5
Time (s)



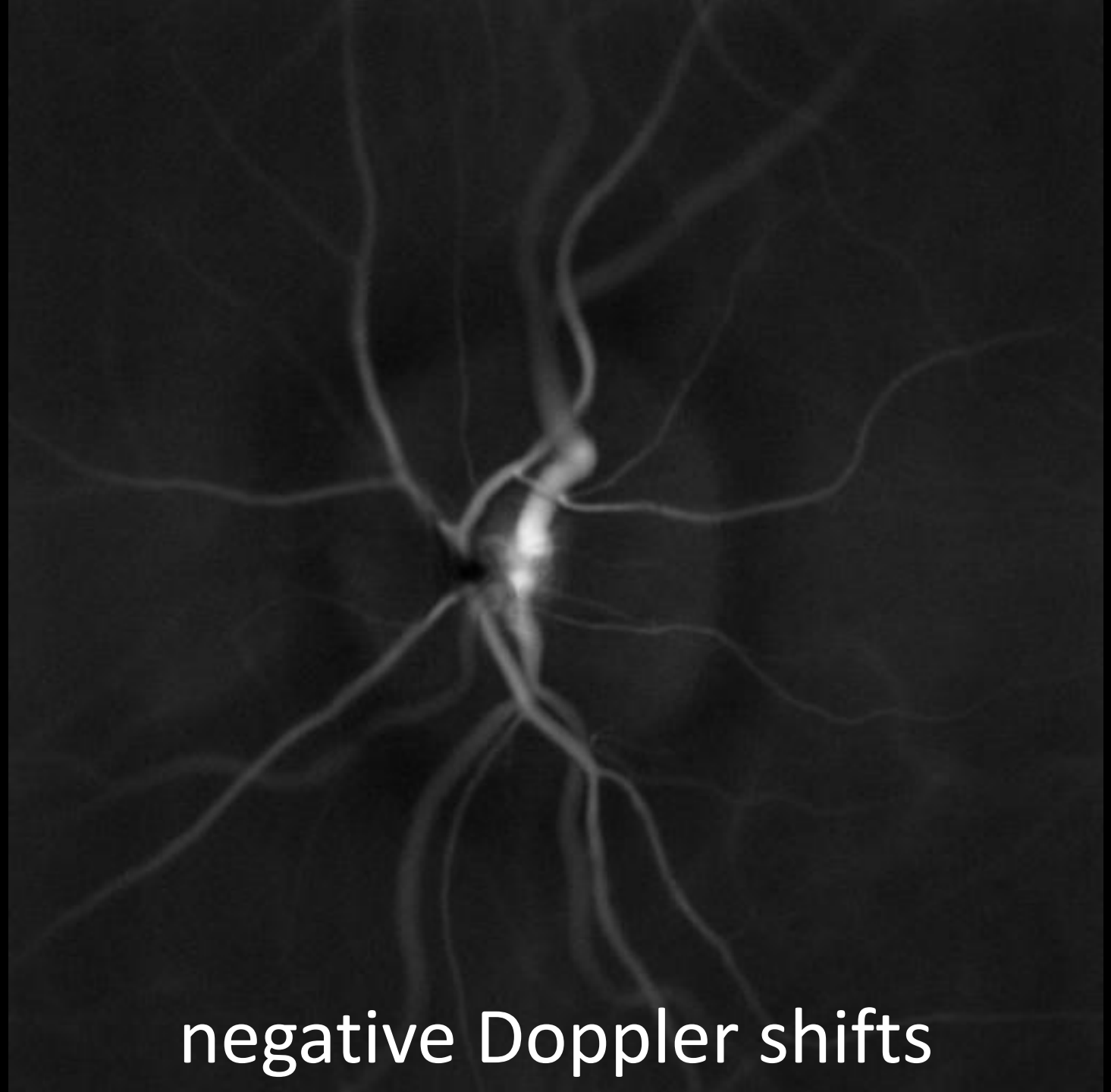
retinal arteries/veins


power spectrum
forward flow
ω

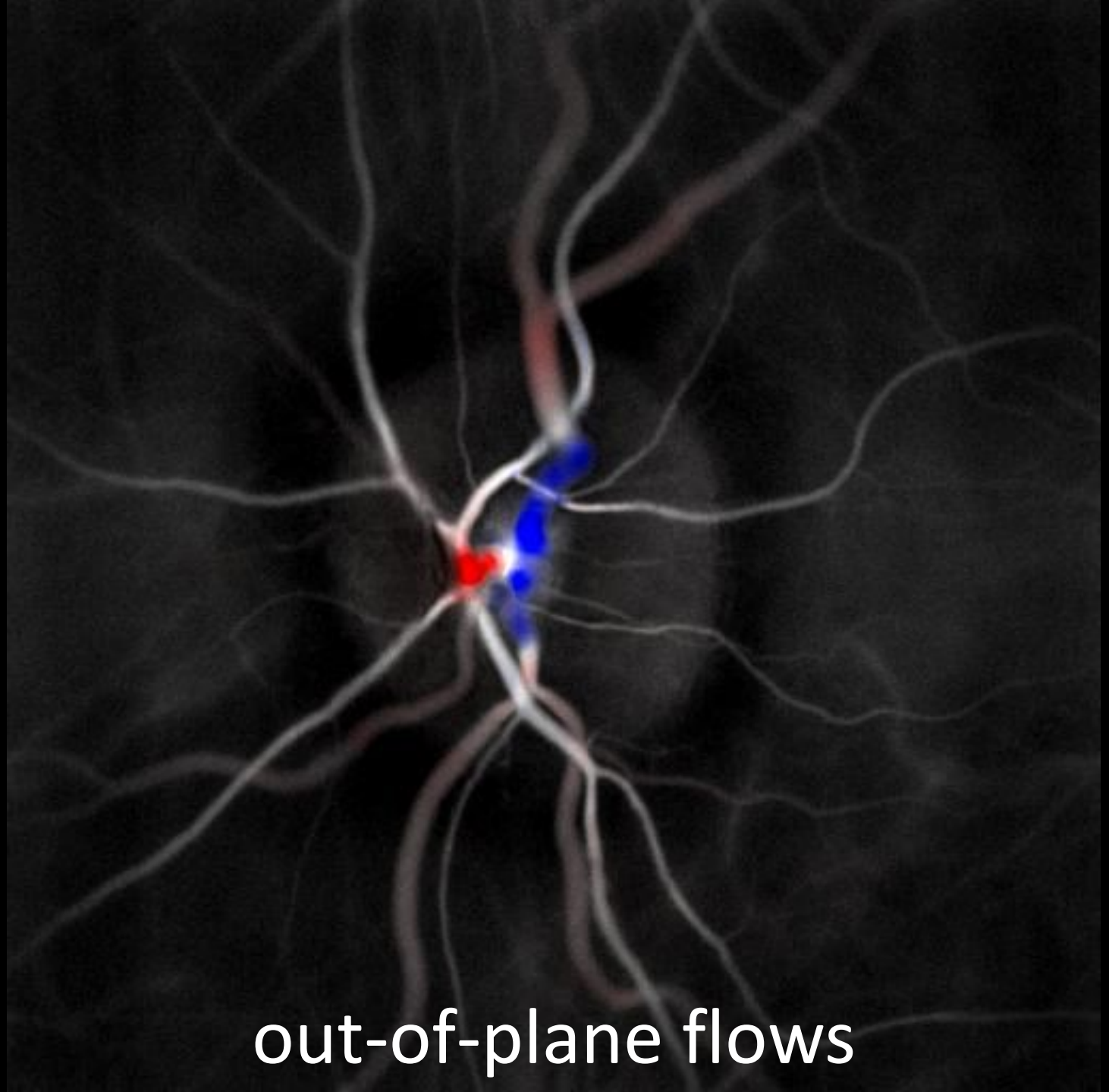

power spectrum
backward flow
ω



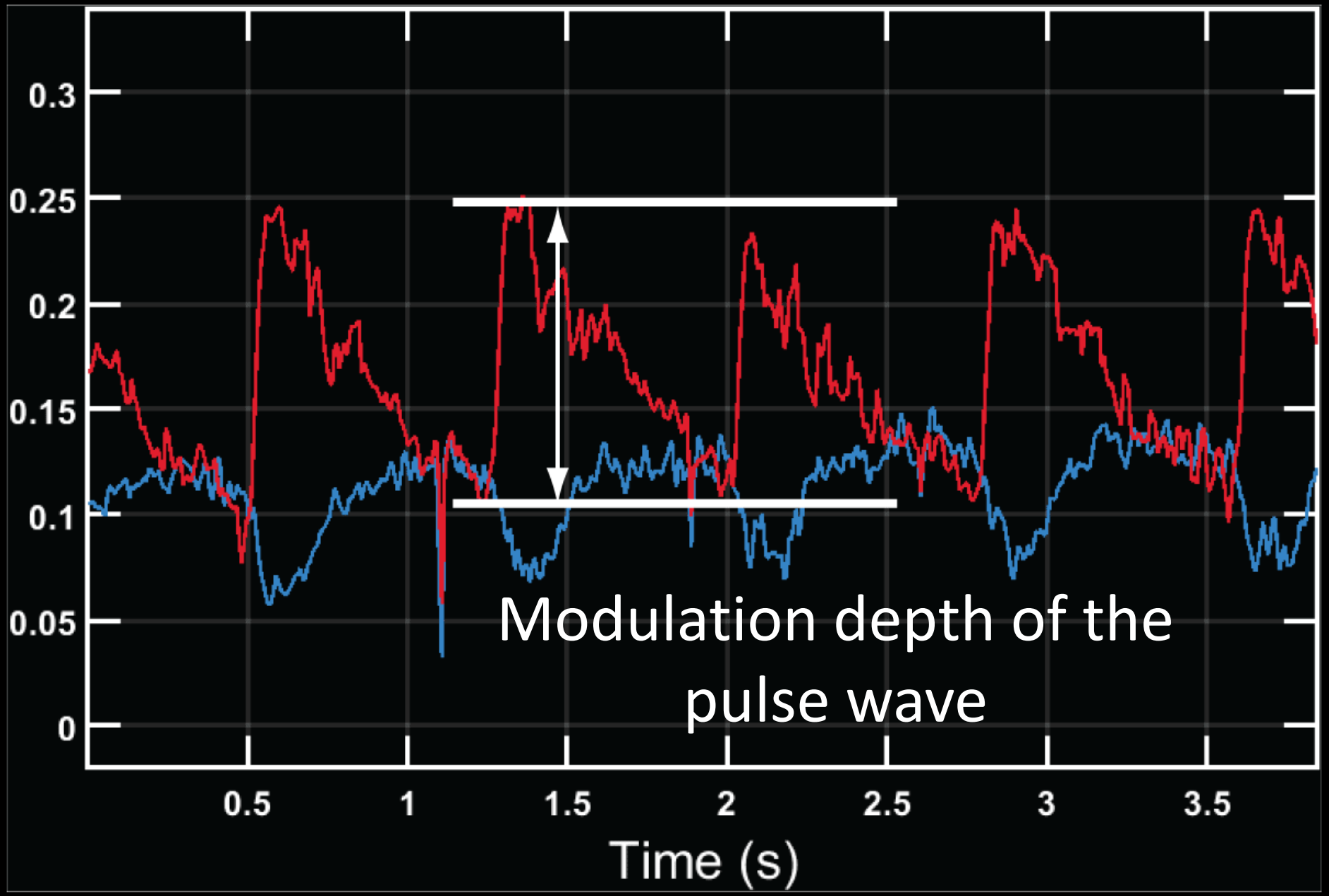
positive Doppler shifts

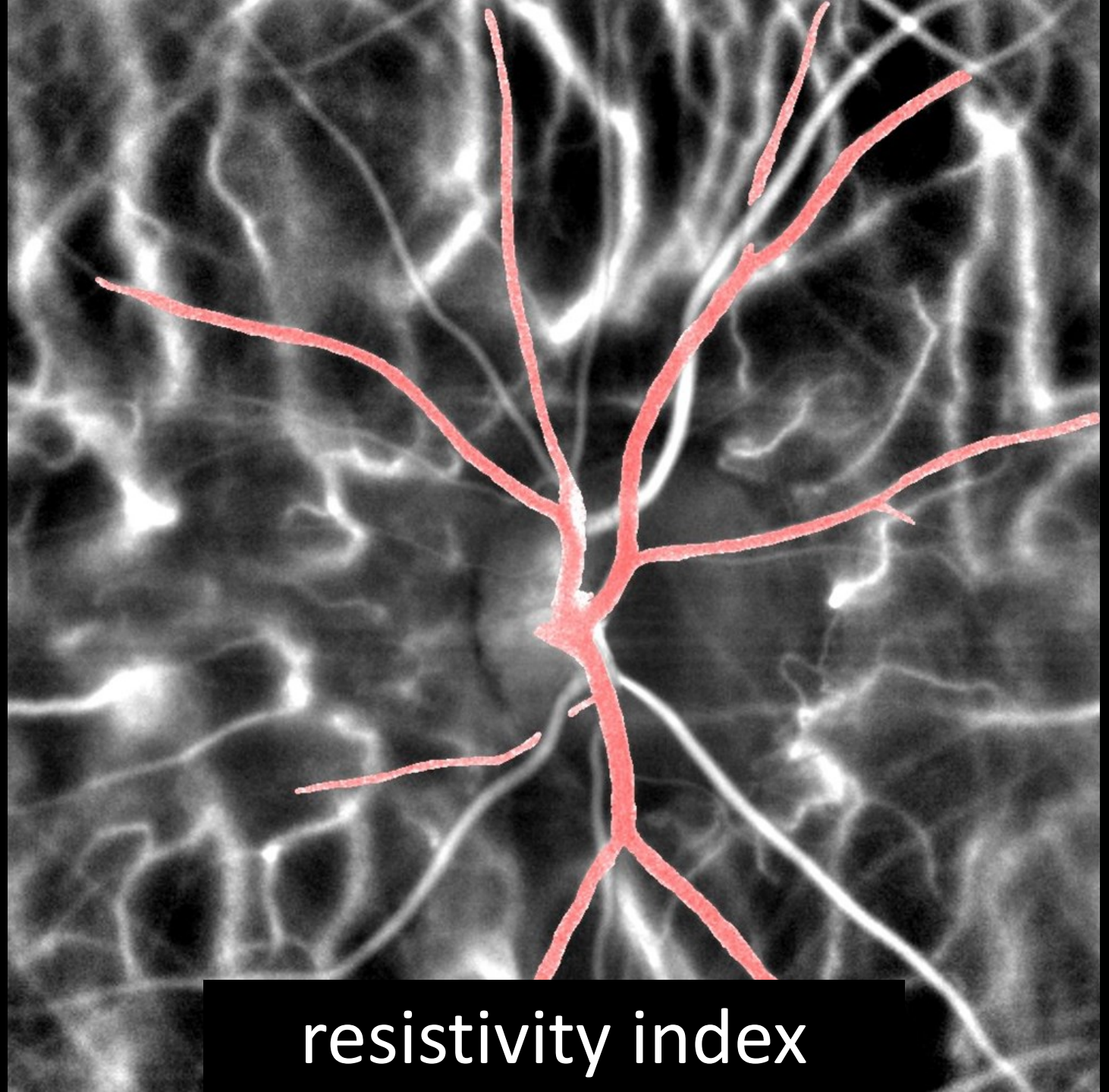


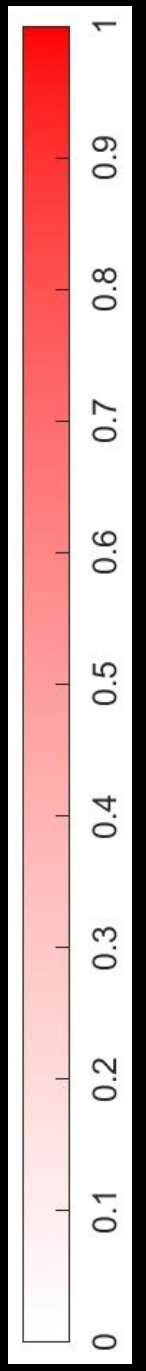
negative Doppler shifts



out-of-plane flows


0.3
0.25
0.2
0.15
0.1
0.05
0
0.5
1
1.5
2
2.5
3
3.5
Time (s)
Modulation depth of the pulse wave

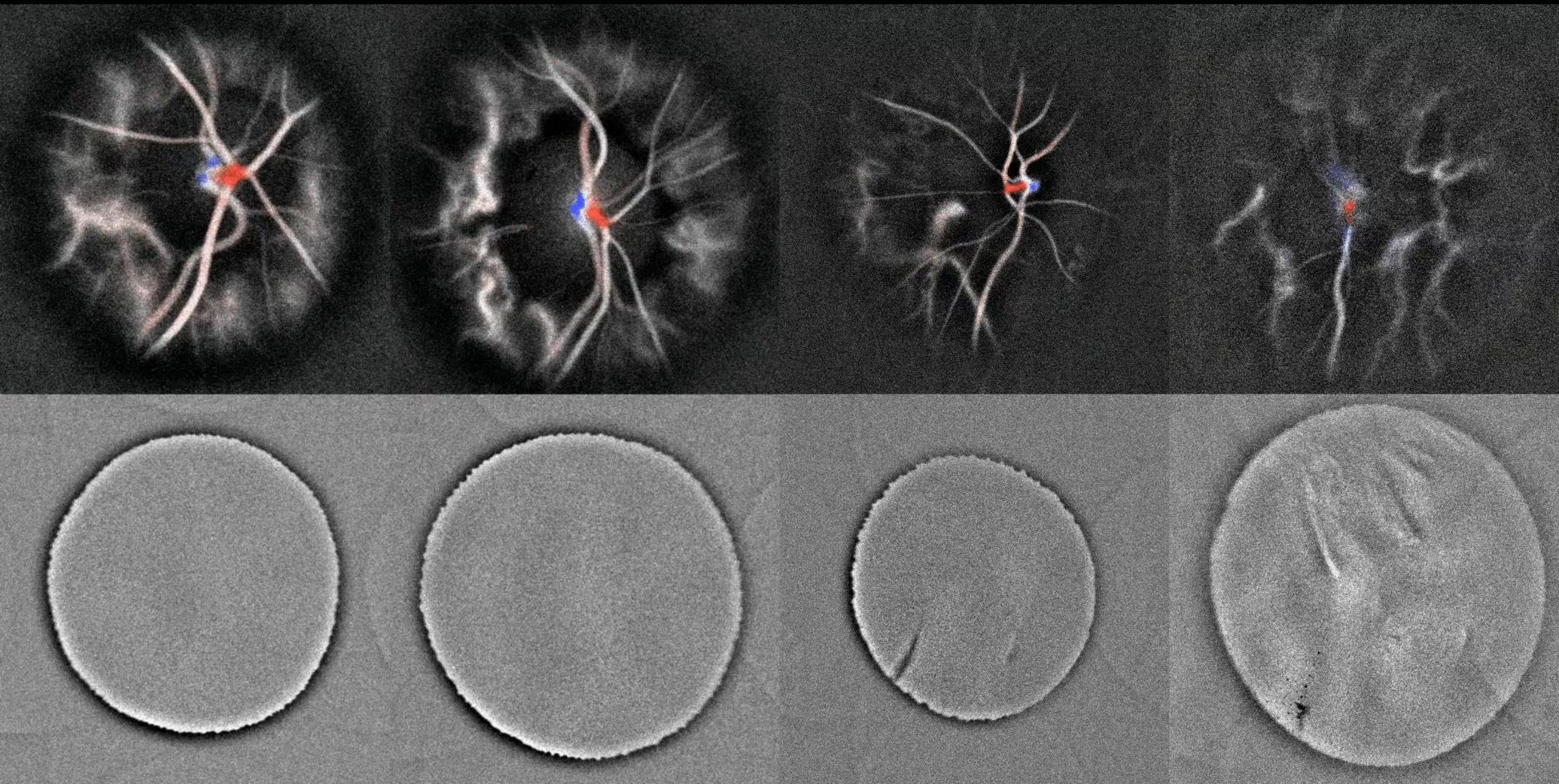




Avg. arterial resistivity index : 0.25

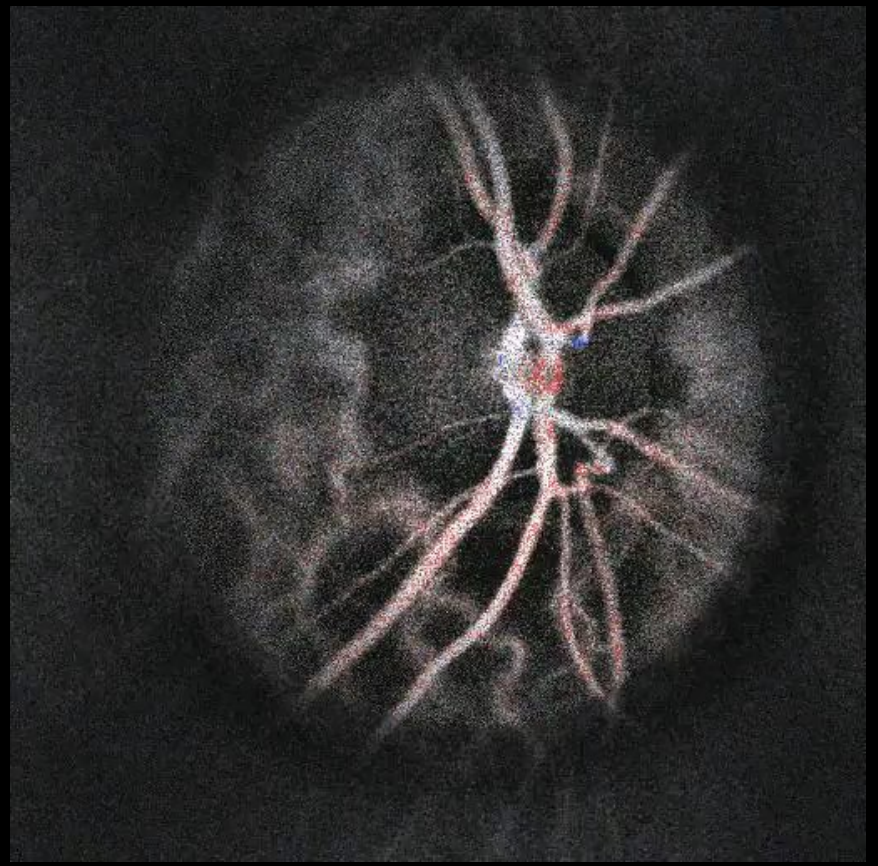
Anterior and posterior segment imaging

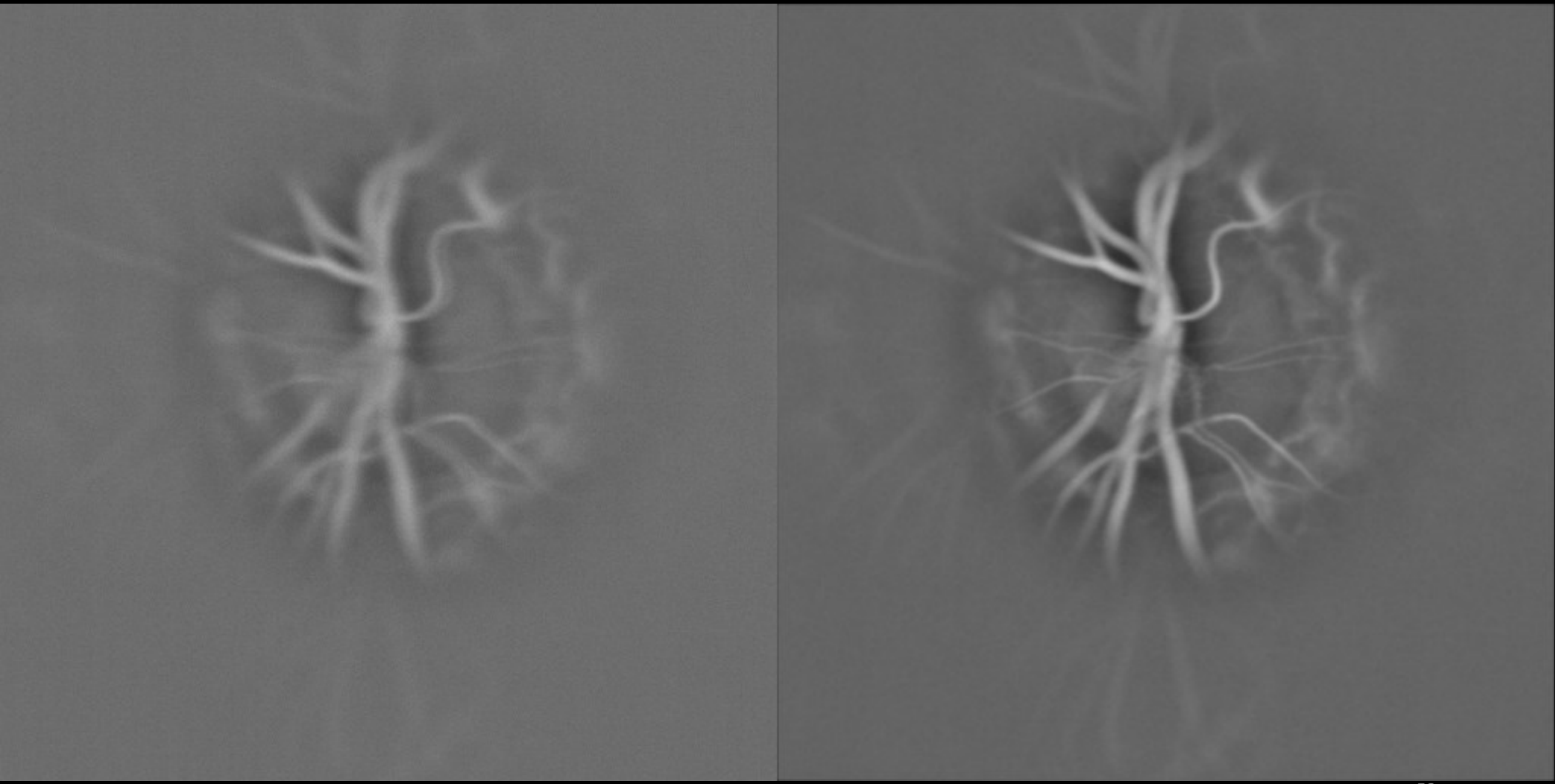
Puyo, Léo, Clémentine David, Rana Saad, Sami Saad, Josselin Gautier, José Alain Sahel, Vincent Borderie, Michel Paques, and Michael Atlan. "Laser Doppler holography of the anterior segment for blood flow imaging, eye tracking, and transparency assessment." *Biomedical optics express* 12, no. 7 (2021): 4478-4495.

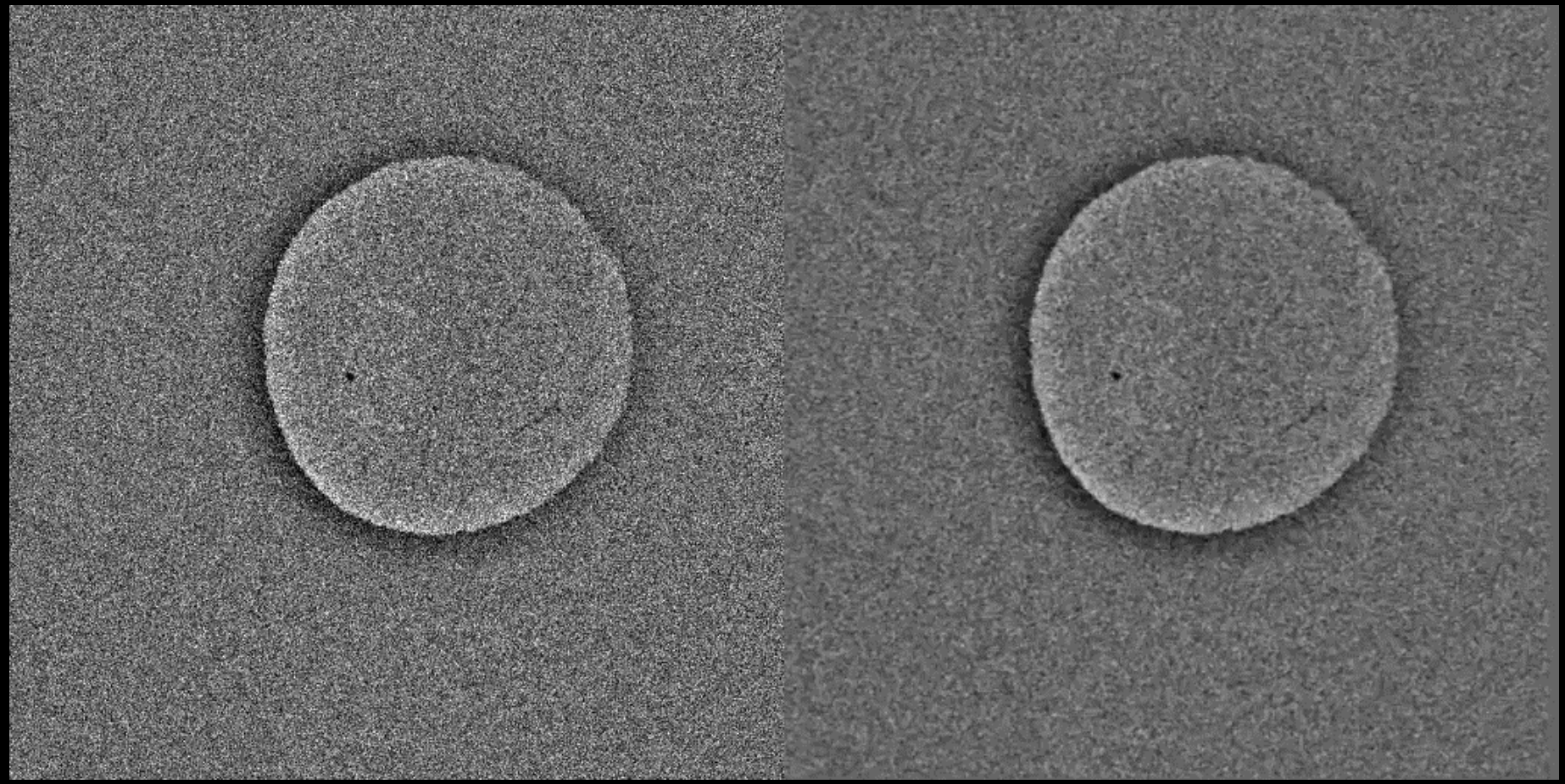


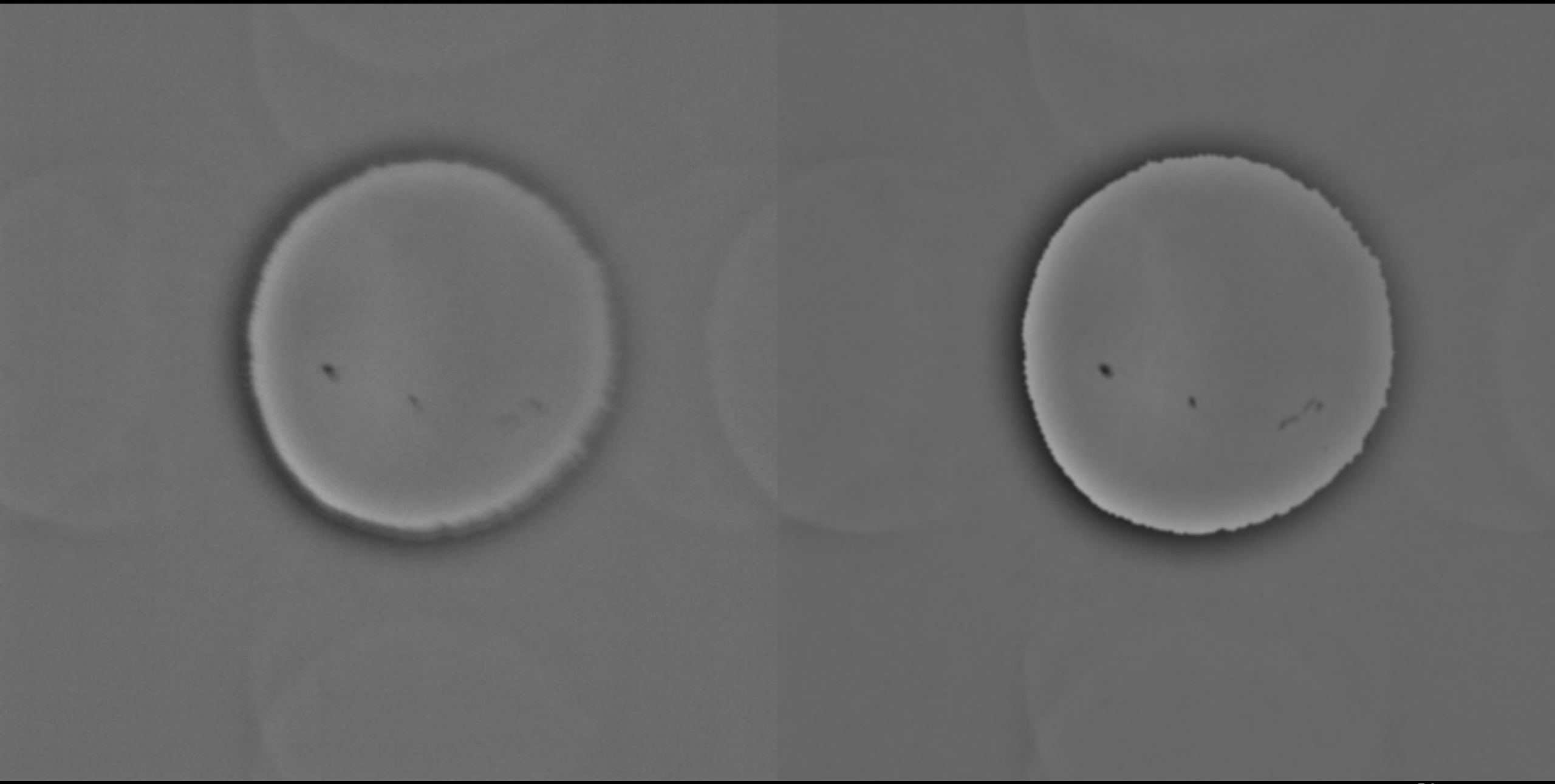
micron and millisecond
3d motion

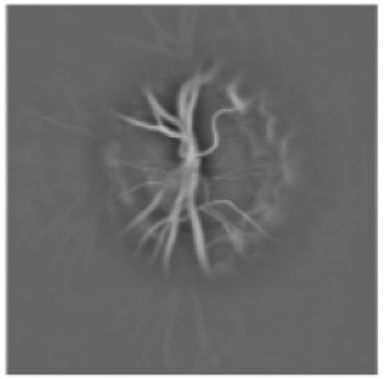
Puyo, Léo, Clémentine David, Rana Saad, Sami Saad, Josselin Gautier, José Alain Sahel, Vincent Borderie, Michel Paques, and Michael Atlan. "Laser Doppler holography of the anterior segment for blood flow imaging, eye tracking, and transparency assessment." *Biomedical optics express* 12, no. 7 (2021): 4478-4495.

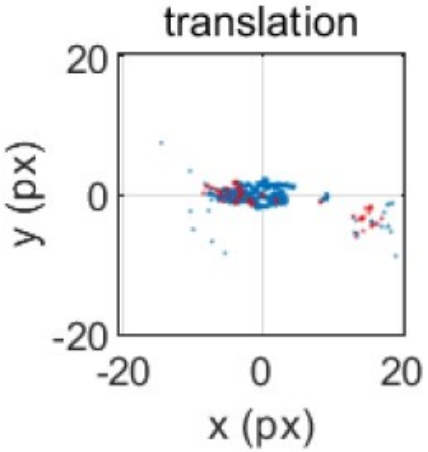


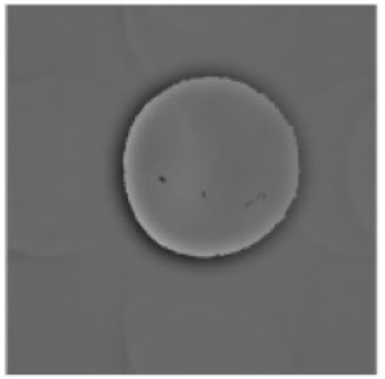


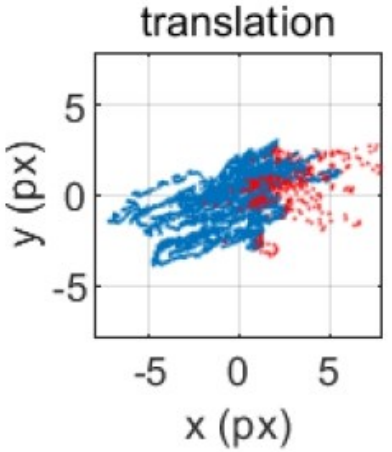


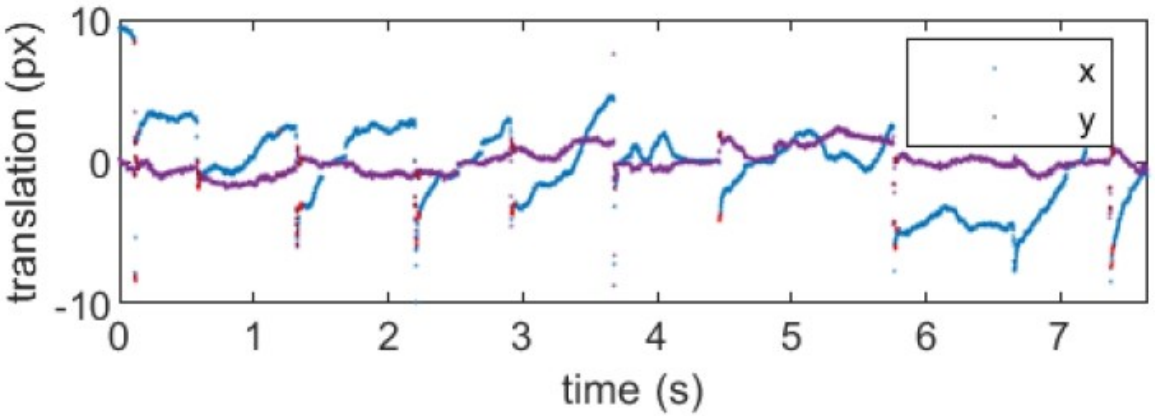


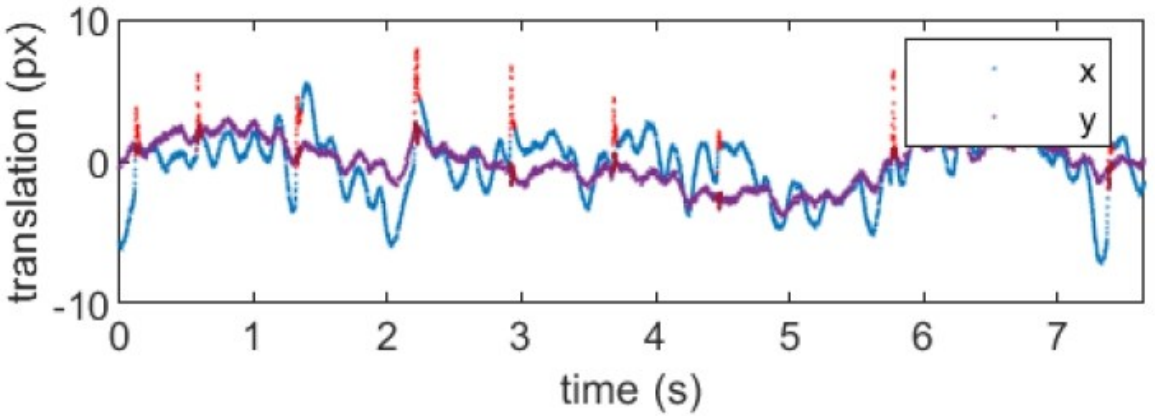


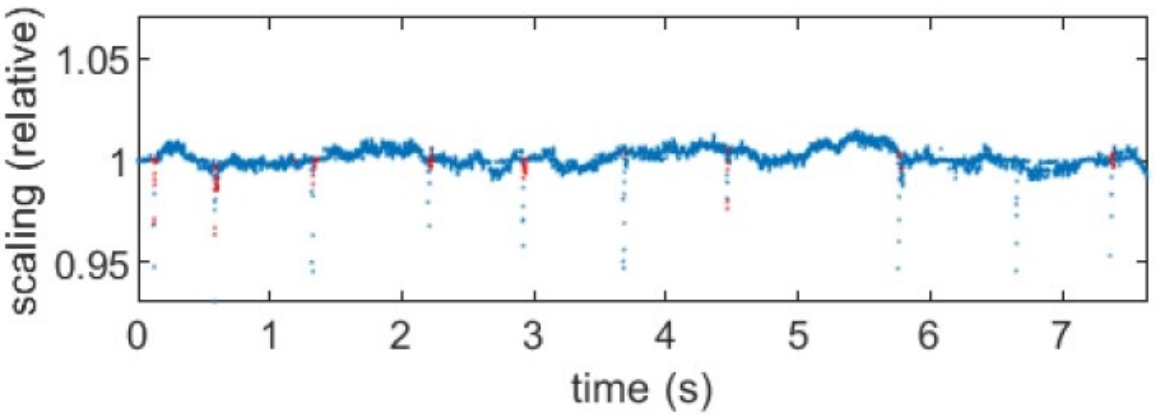

translation
20
0
-20
y (px)
-20
0
20
x (px)

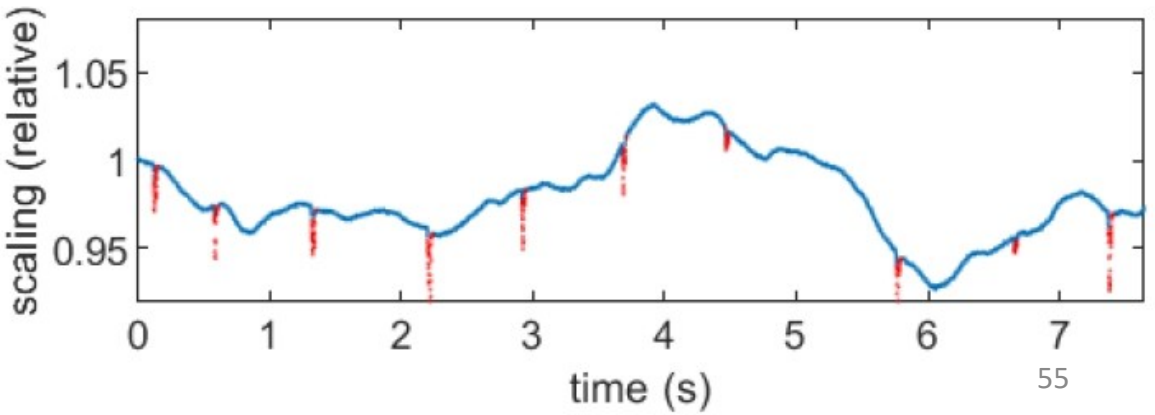



translation
5
0
-5
y (px)
-5
0
5
x (px)


translation (px)
10
0
-10
0
1
2
3
4
5
6
7
time (s)
x
y

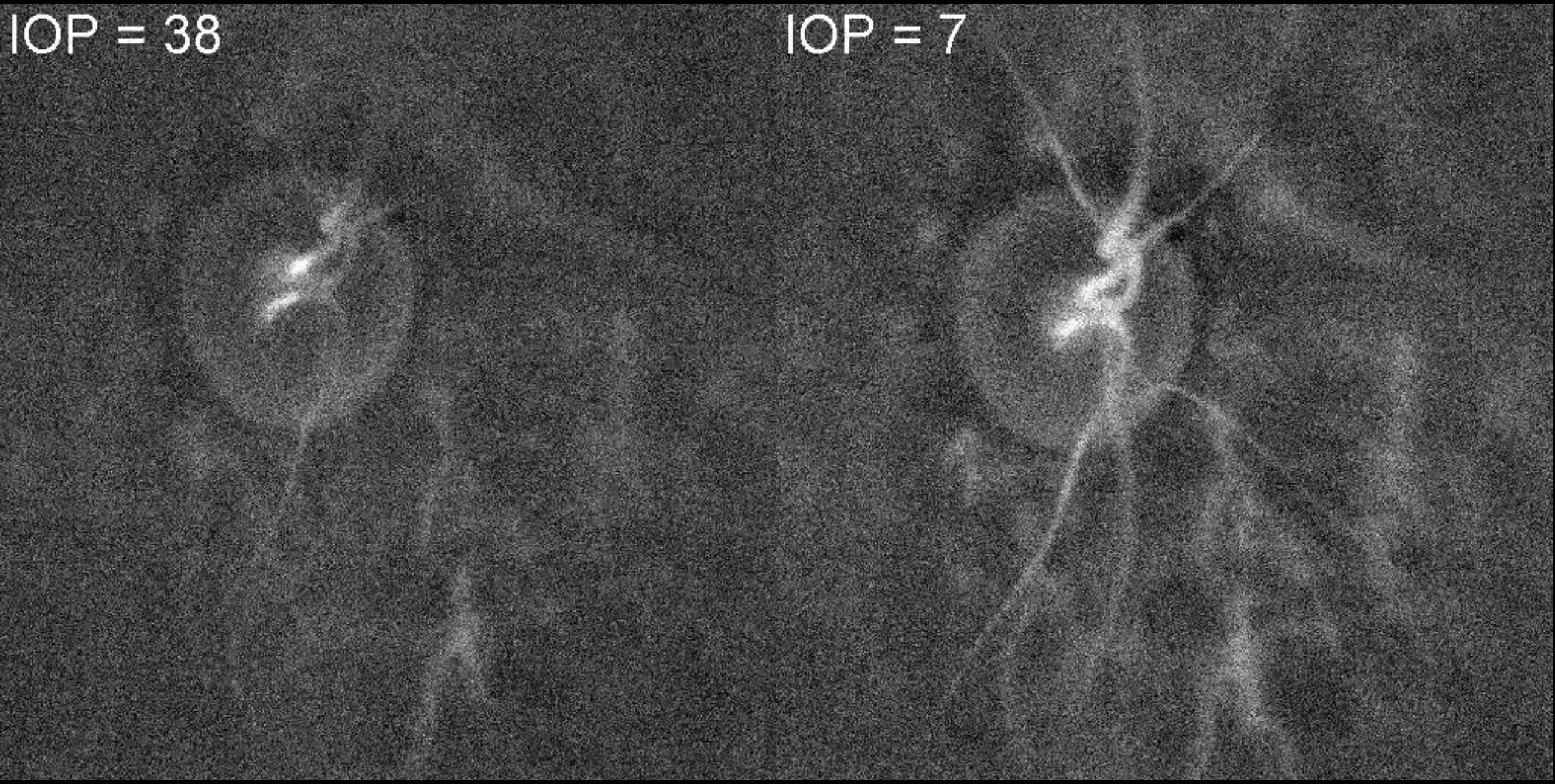

translation (px)
10
0
-10
0
1
2
3
4
5
6
7
time (s)
x
y


scaling (relative)
1.05
1
0.95
0
1
2
3
4
5
6
7
time (s)

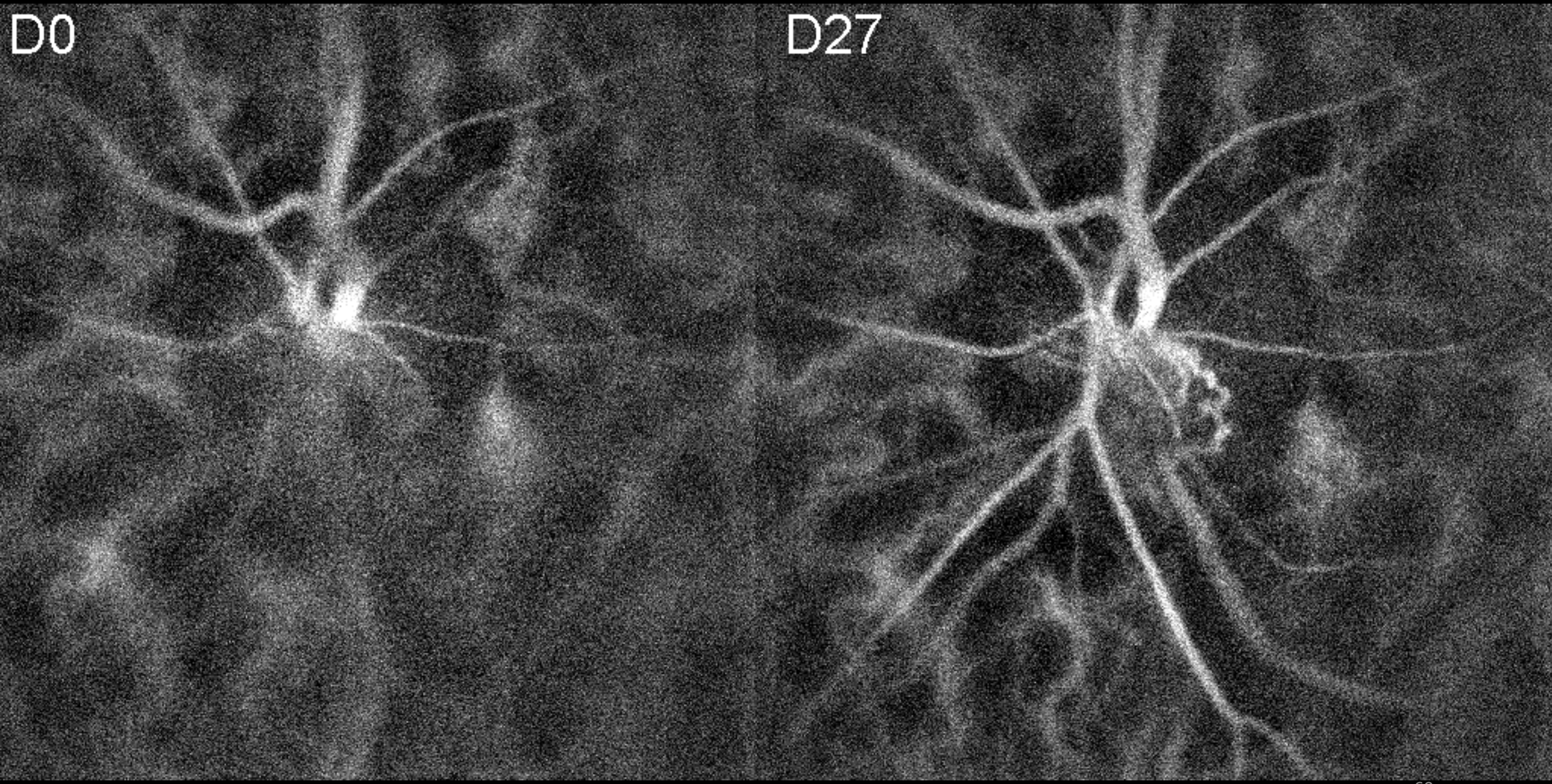

scaling (relative)
1.05
1
0.95
0
1
2
3
4
5
6
7
time (s)

Quelle utilisation clinique ?

Glaucome

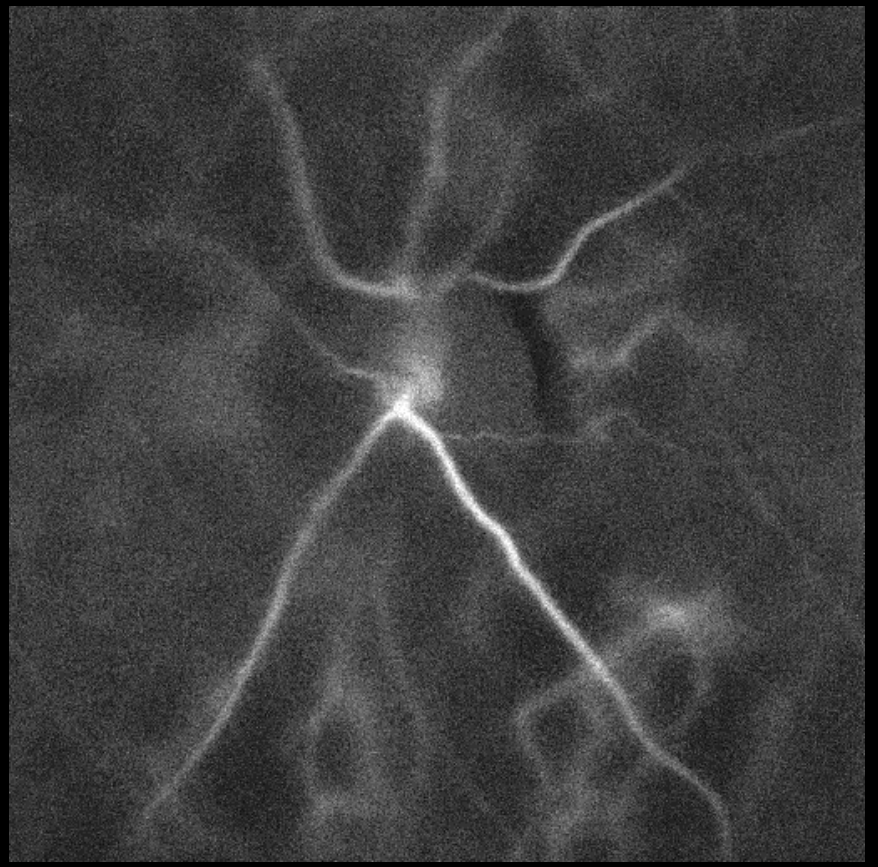

IOP = 38
IOP = 7

Occlusion de la veine centrale de la rétine


D0
D27

Neuropathie optique ischémique antérieure

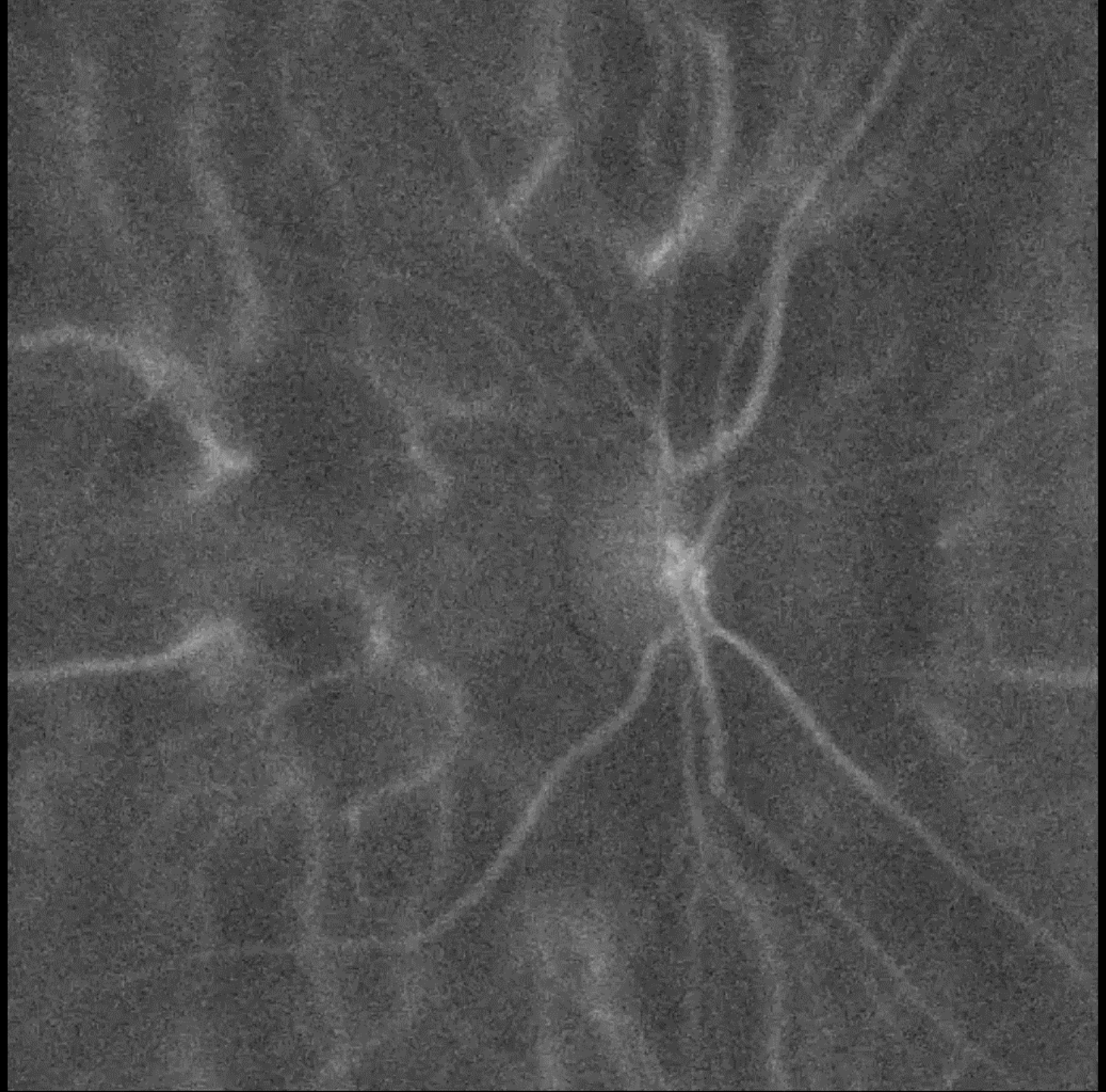
contralateral eye



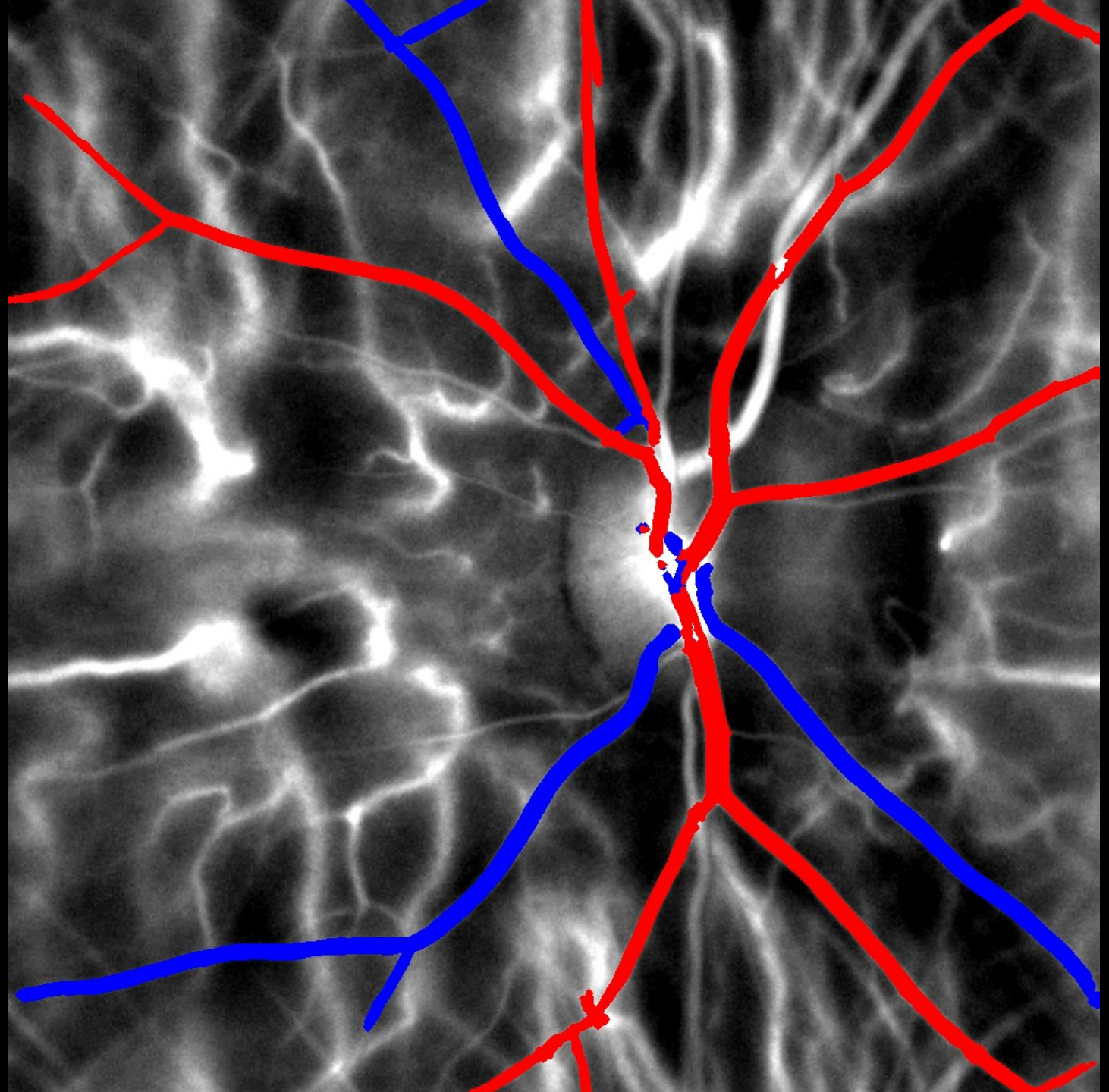
ONH oedema

Évaluation quantitative du flux sanguin rétinien

Power Doppler

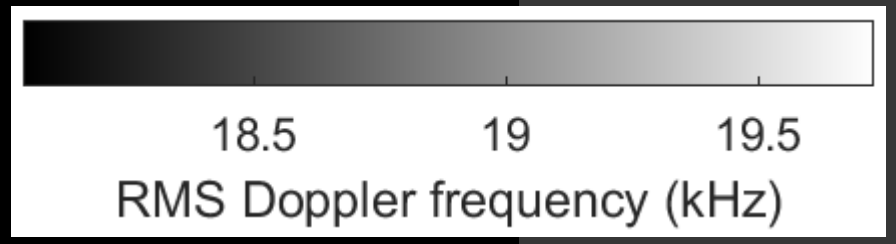


Retinal Arteries And veins



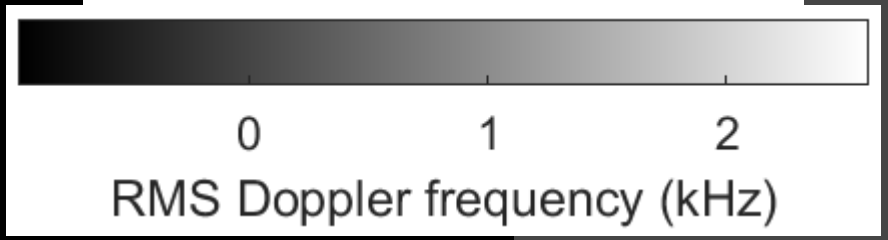
Retinal Arteries

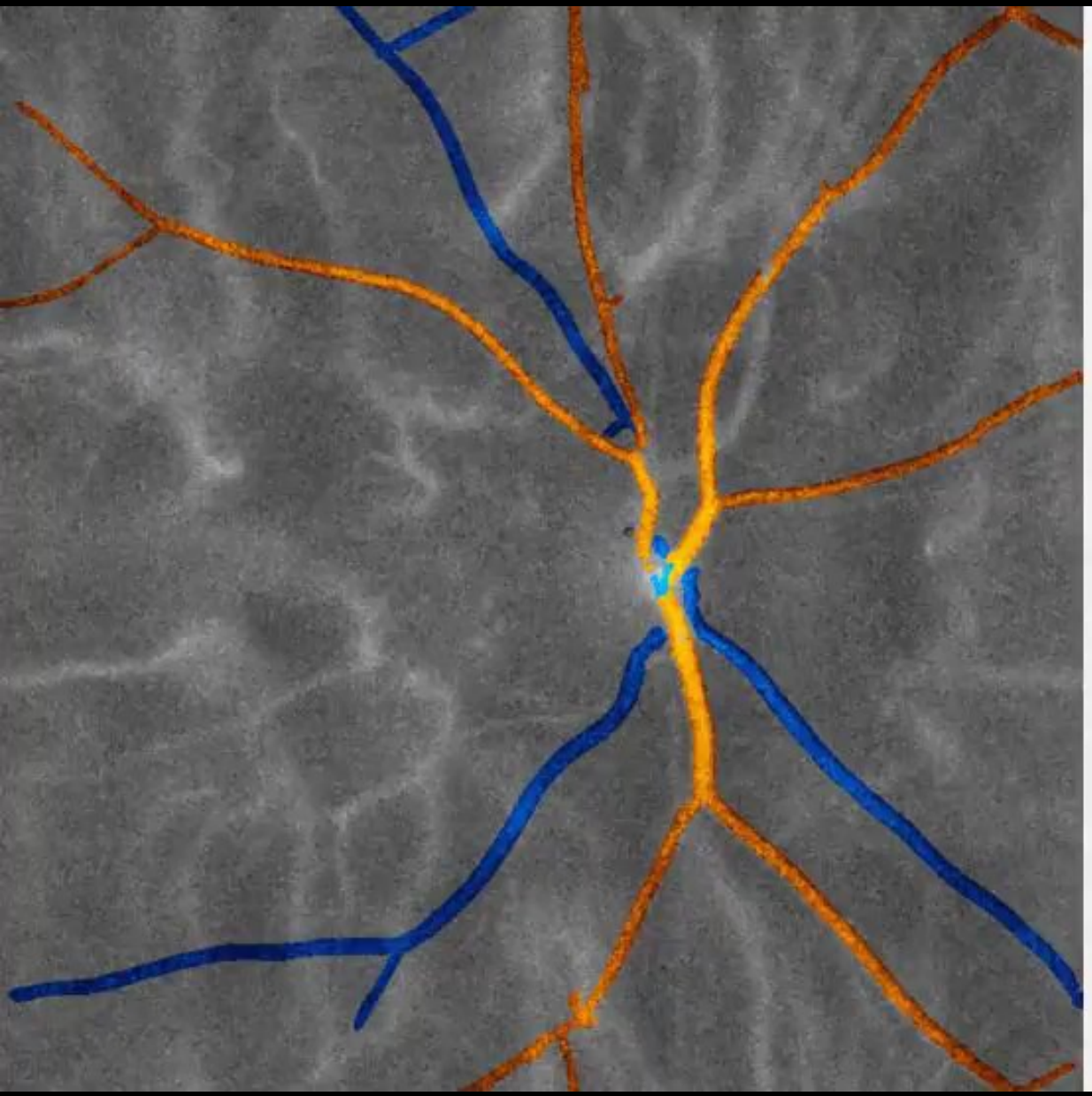
Local background

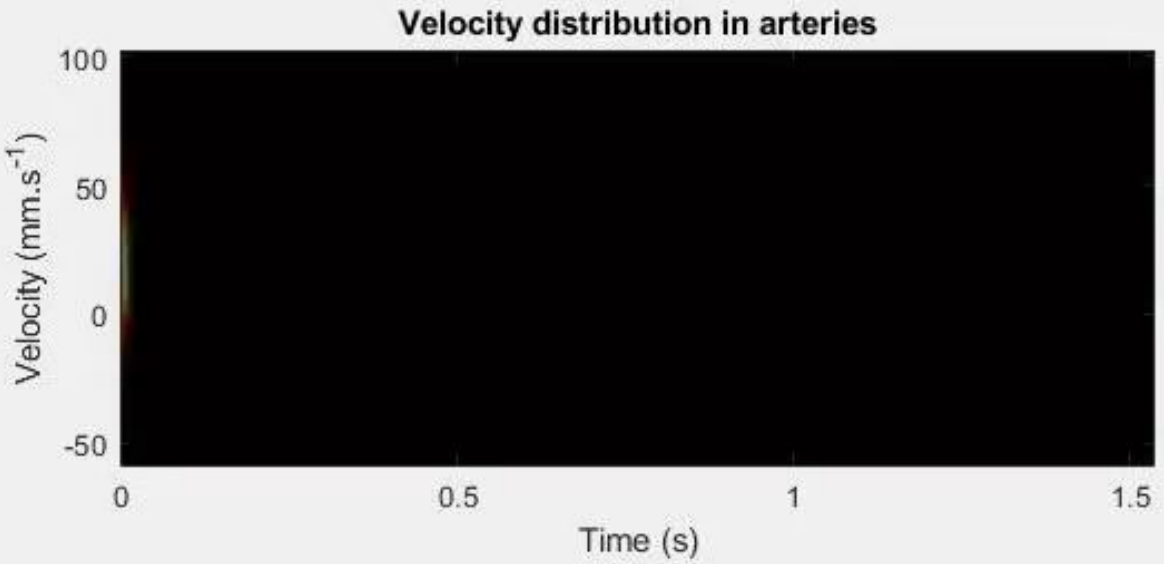


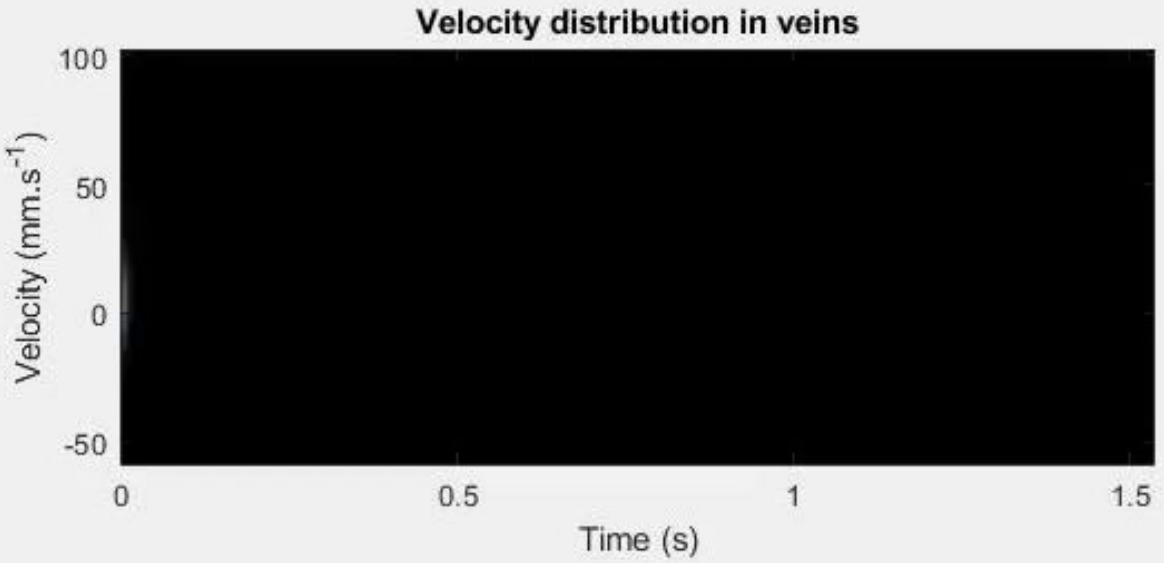
Frequency width increase With respect to Local background

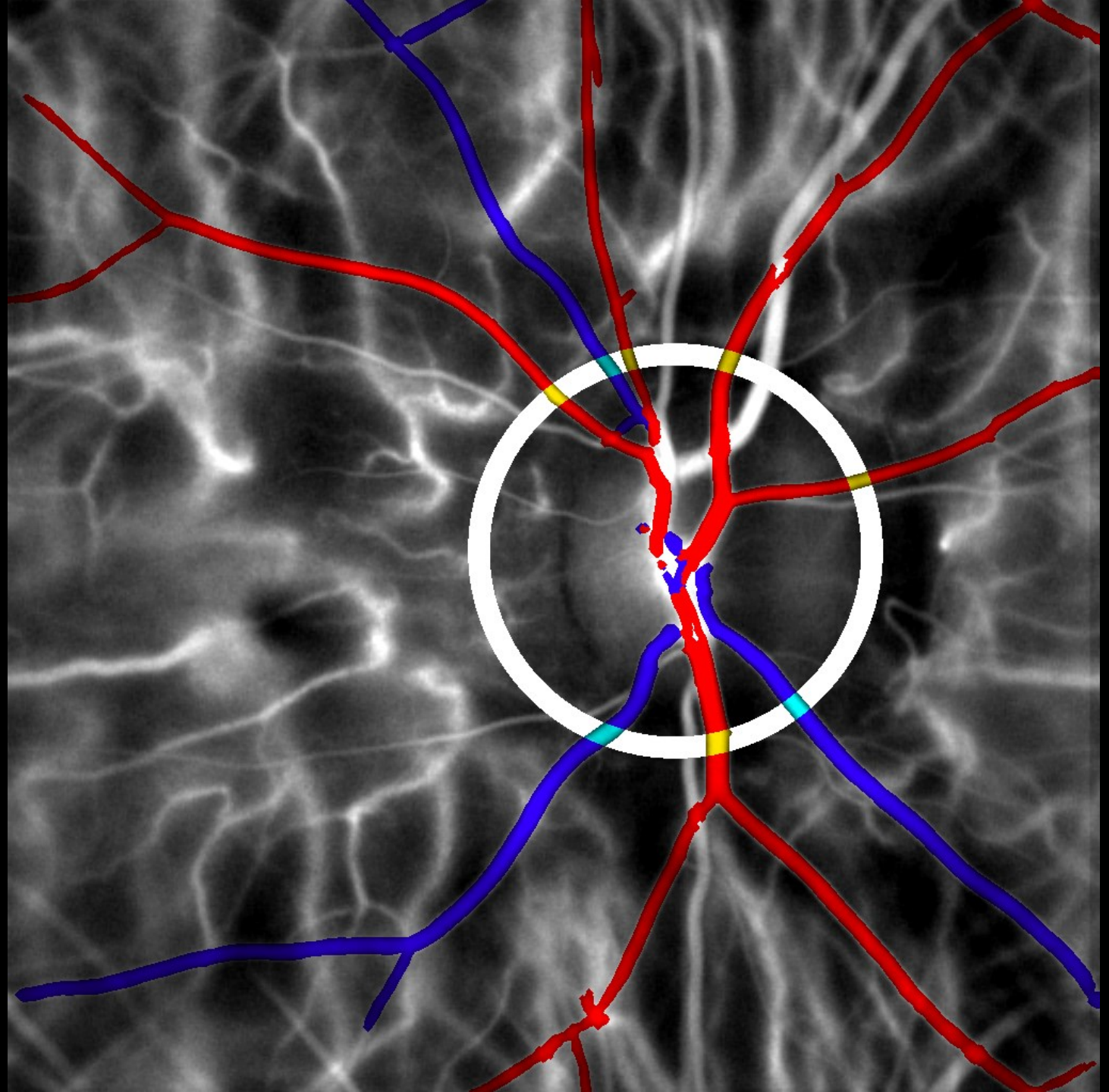
$$V = \frac{\lambda}{2\pi}\sqrt{\frac{3}{\theta}} \cdot \Delta\omega_{\mathrm{RMS}}$$

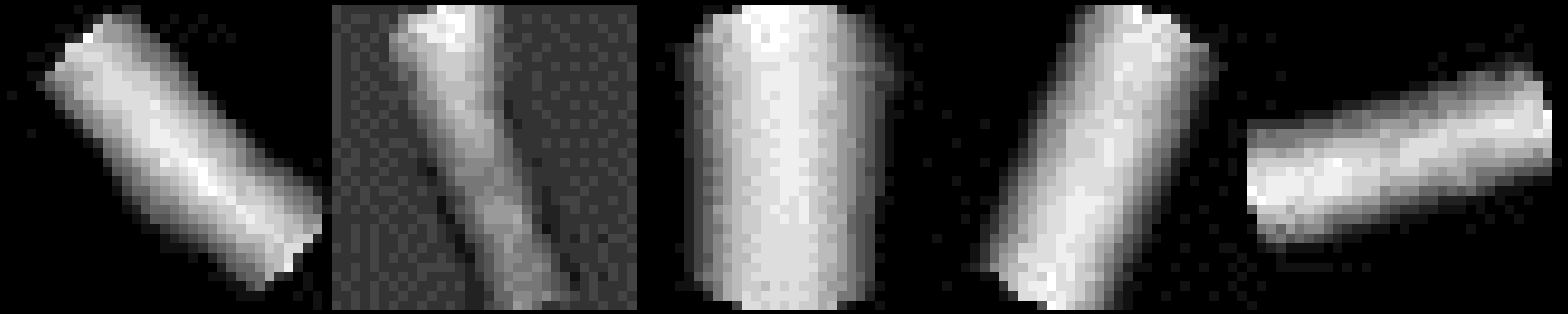


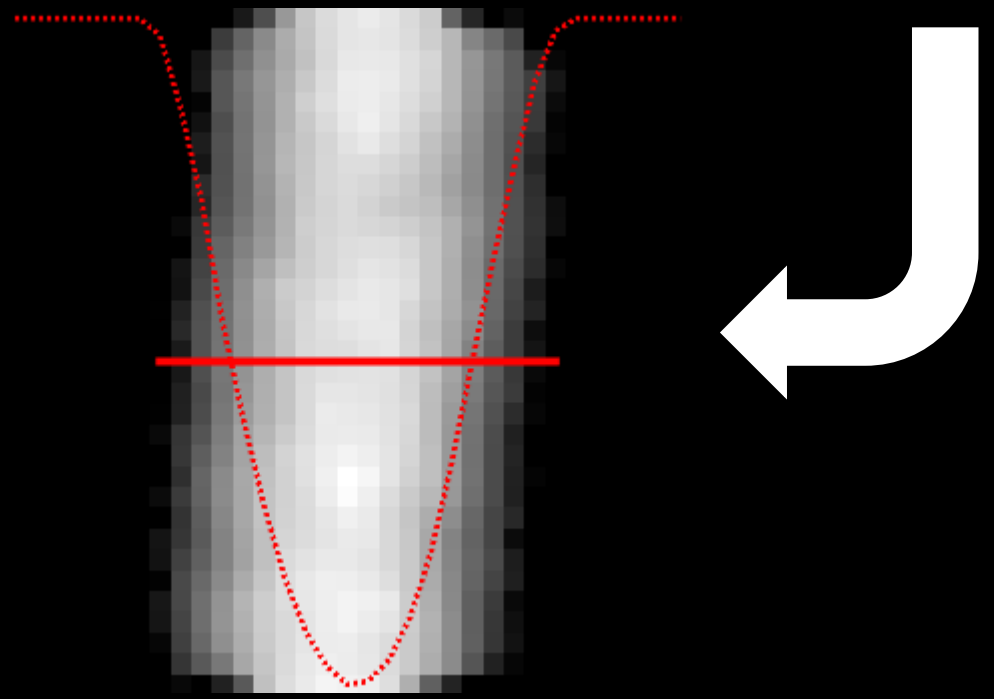


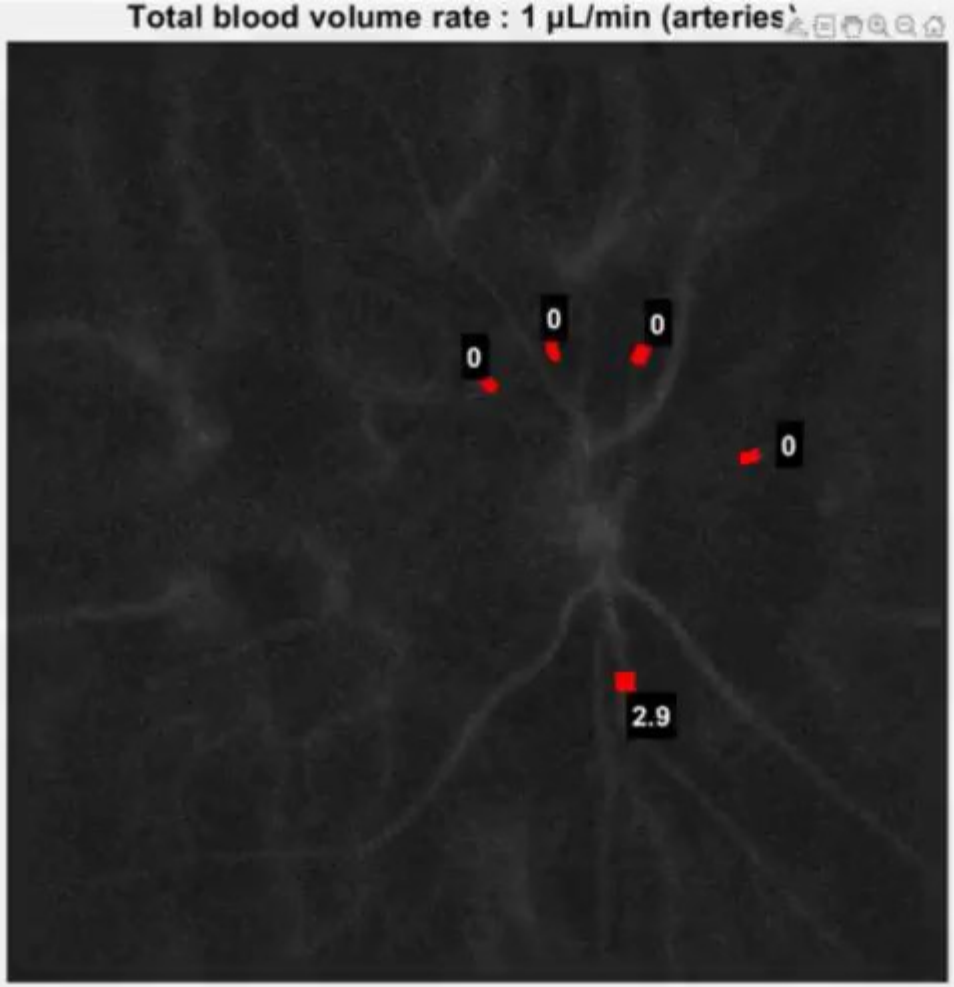

Velocity distribution in arteries
100
50
0
-50
Velocity (mm.s-1)
0
0.5
1
1.5
Time (s)

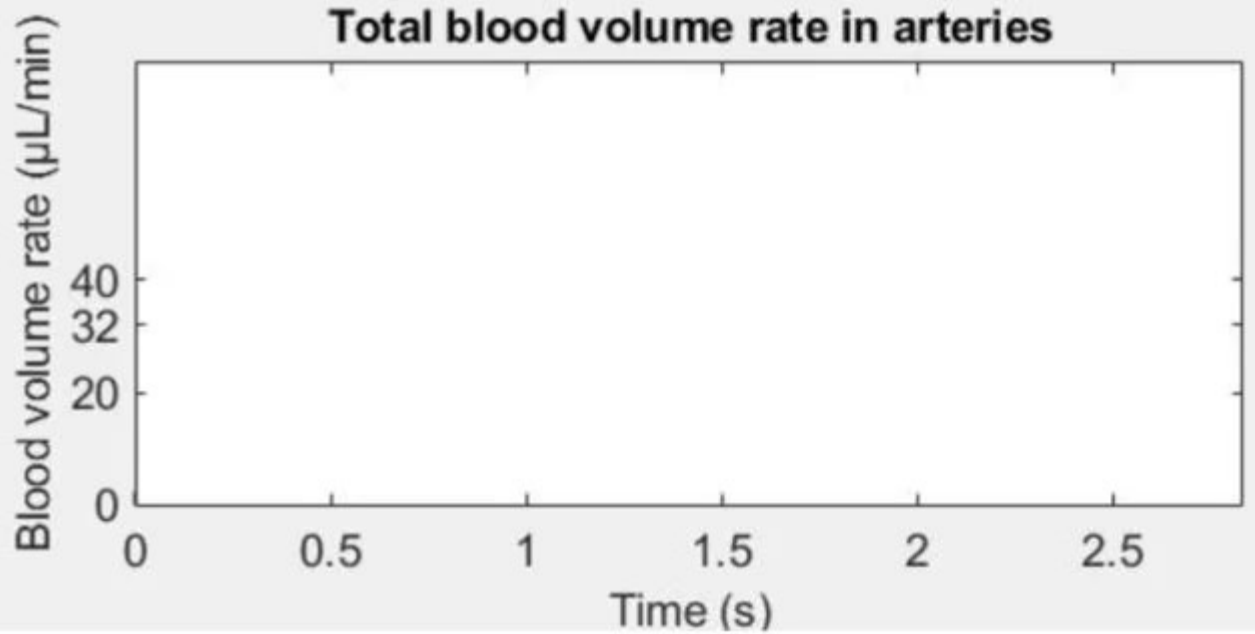

Velocity distribution in veins
100
50
0
-50
Velocity (mm.s-1)
0
0.5
1
1.5
Time (s)








Total blood volume rate : 1 µL/min (arteries)
0
0
0
0
2.9

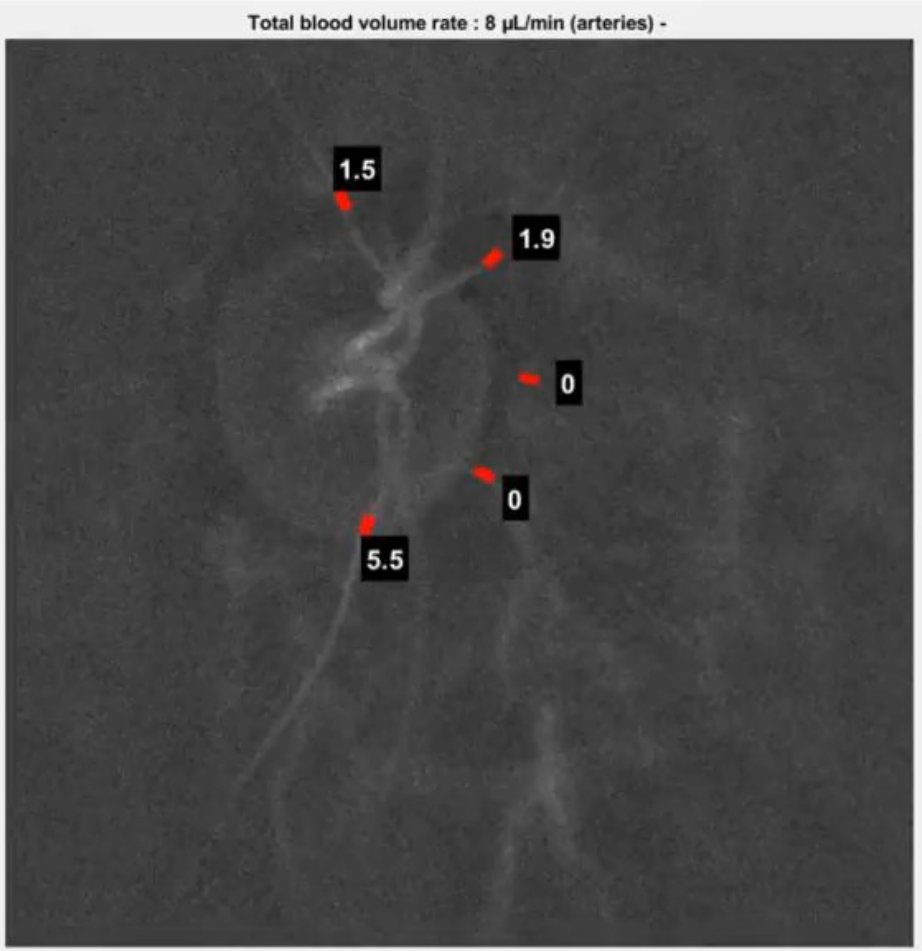

Total blood volume rate in arteries
Blood volume rate (µL/min)
40
32
20
0
0
0.5
1
1.5
2
2.5
Time (s)

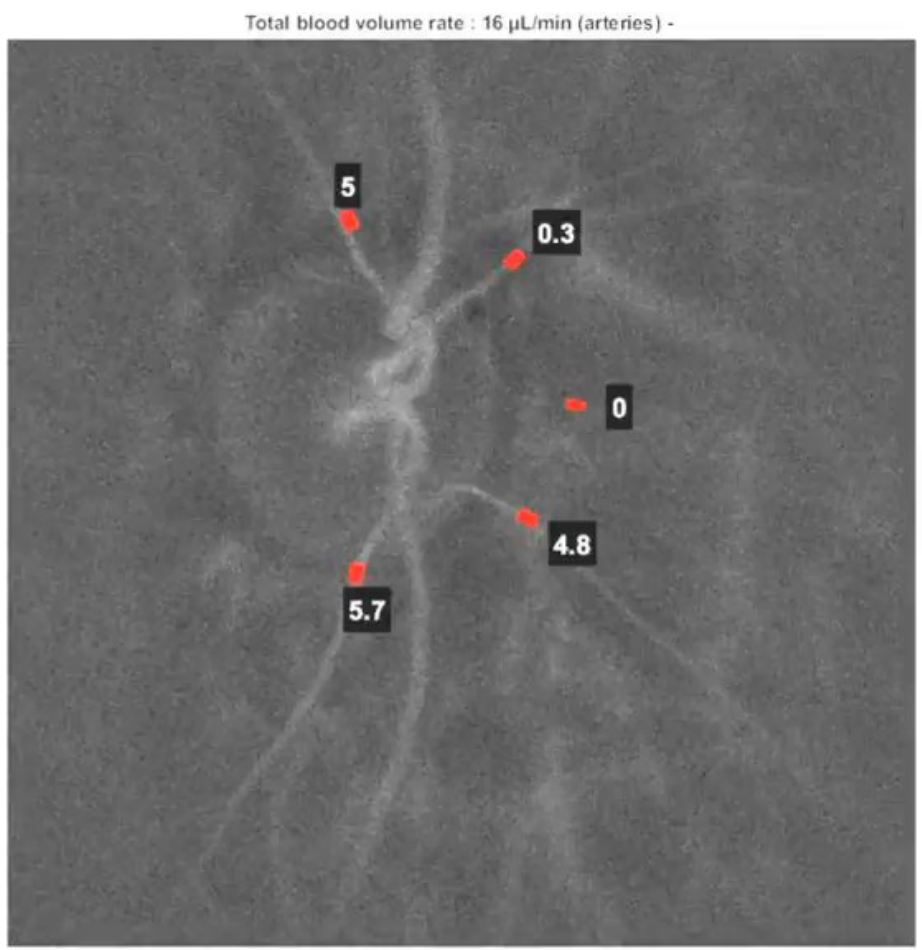
Glaucome

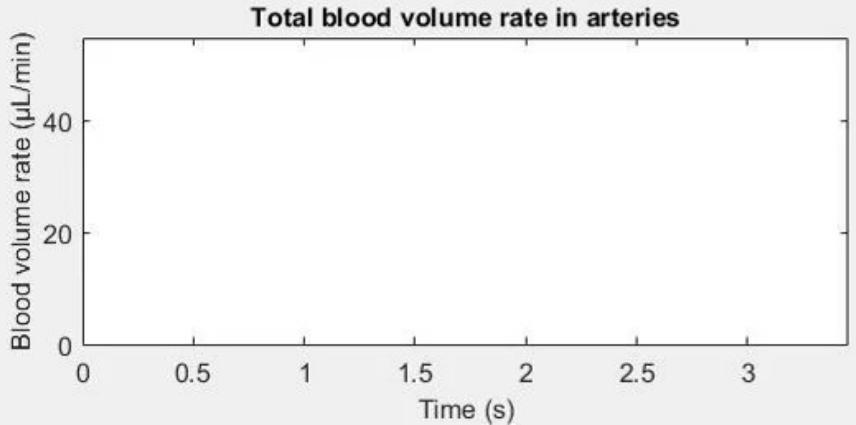
IOP
38mmHg

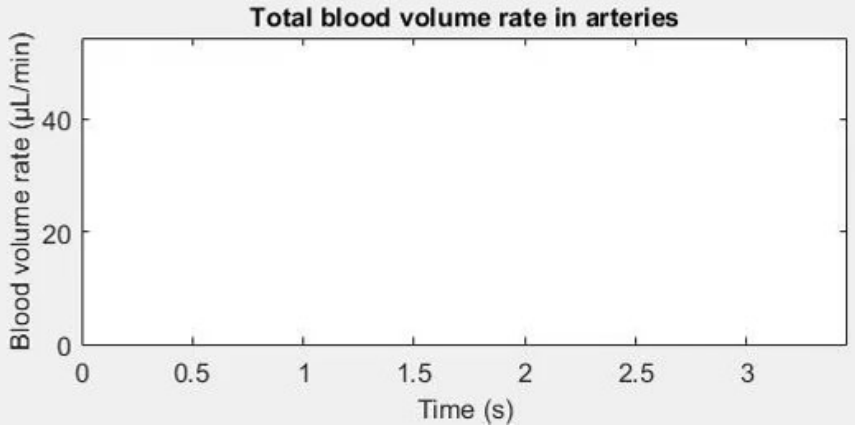
Vs.

IOP
7mmHg







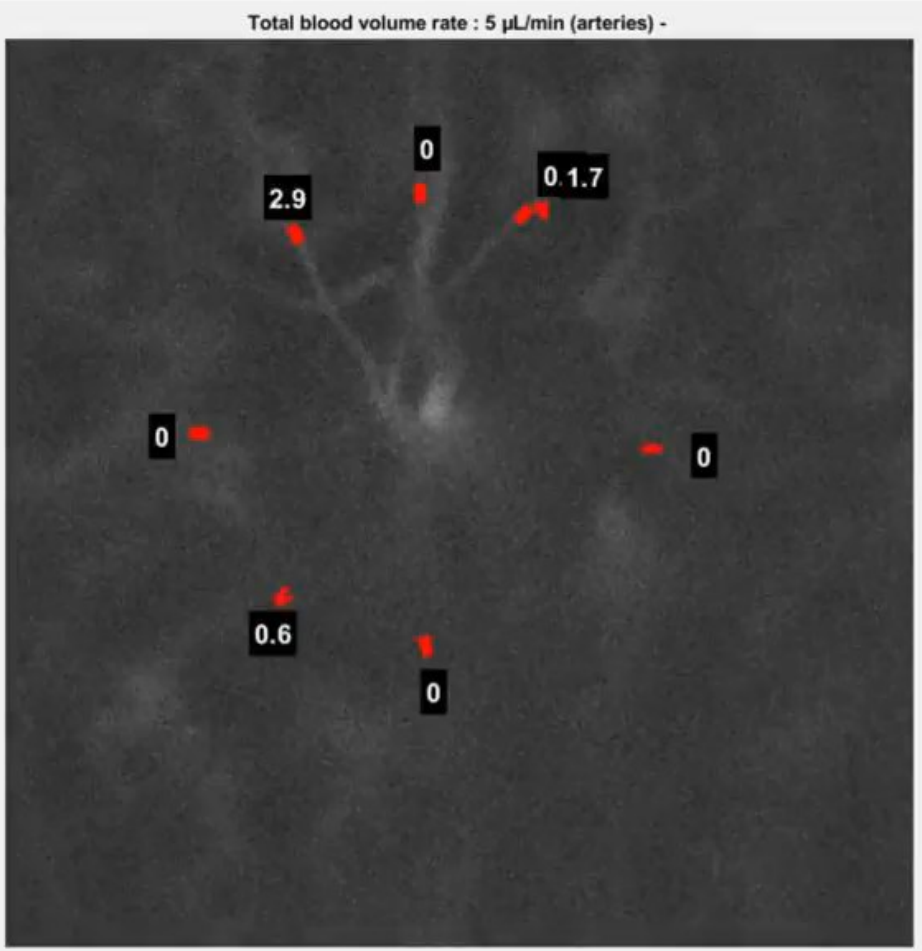


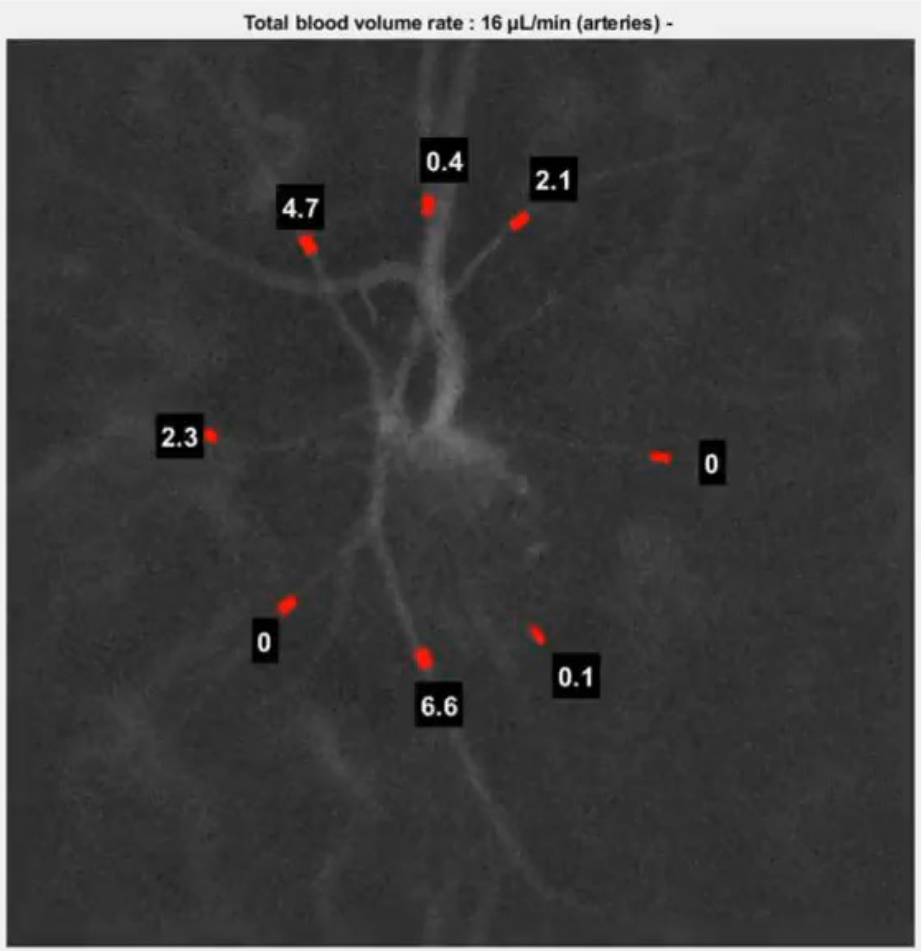
Occlusion de la veine centrale de la rétine

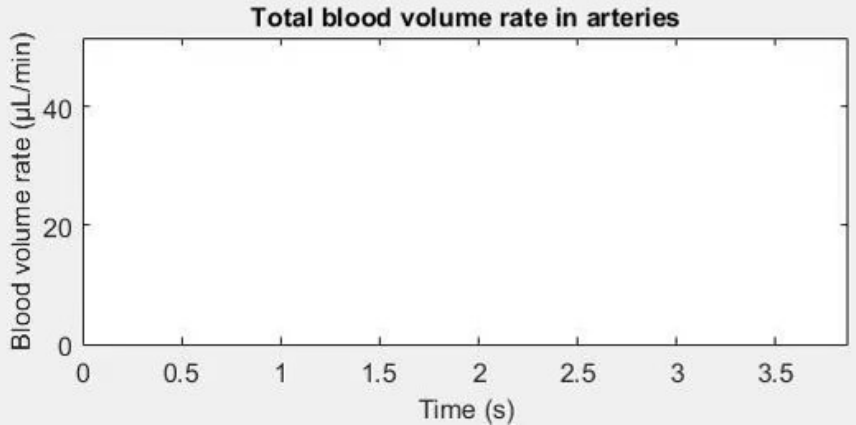
CRVO

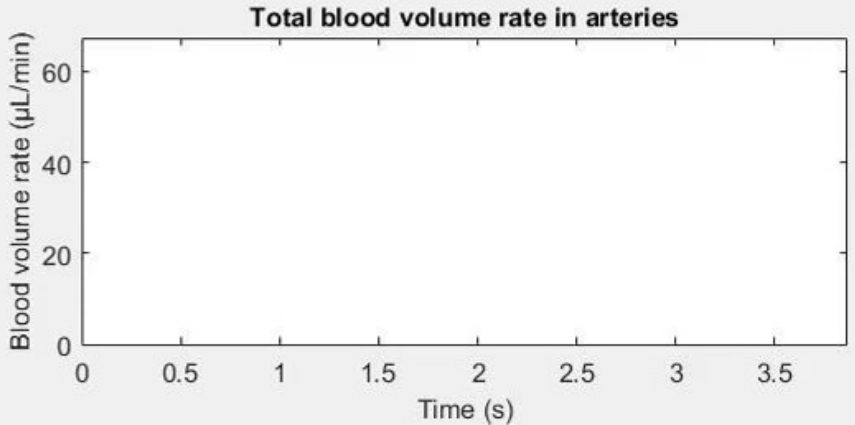
No treatment

28-day interval







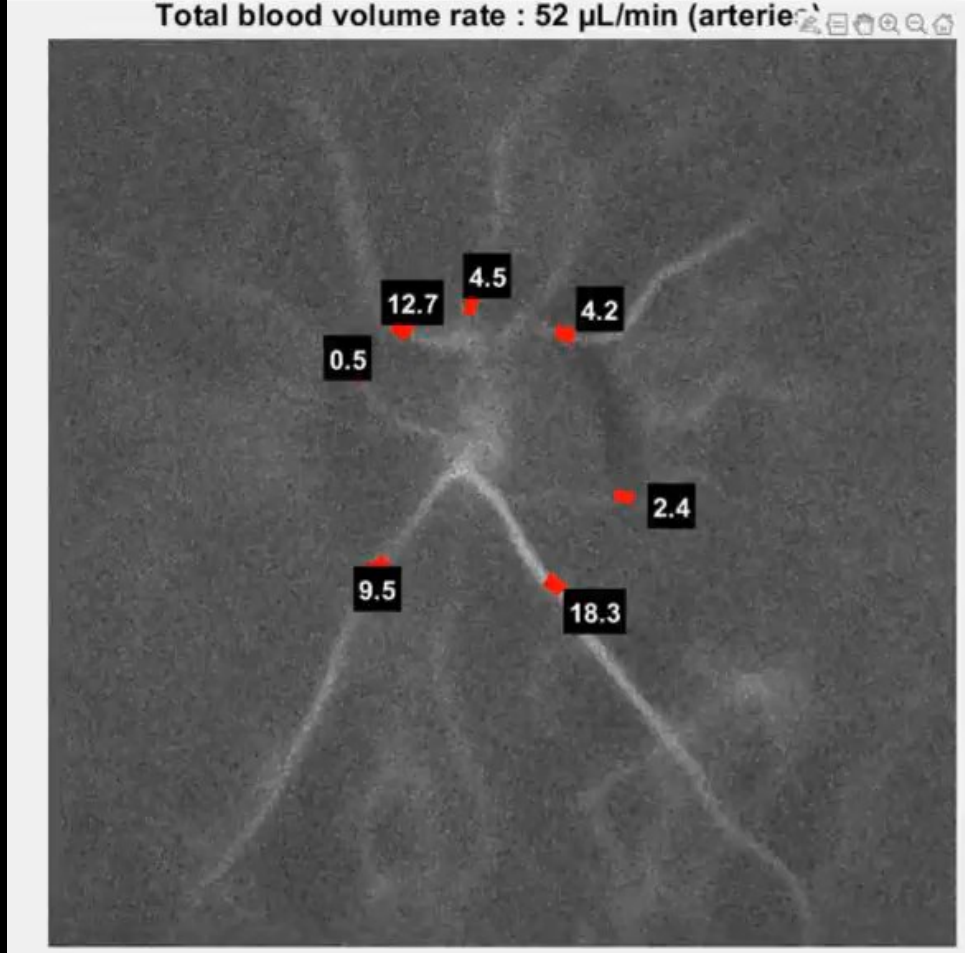


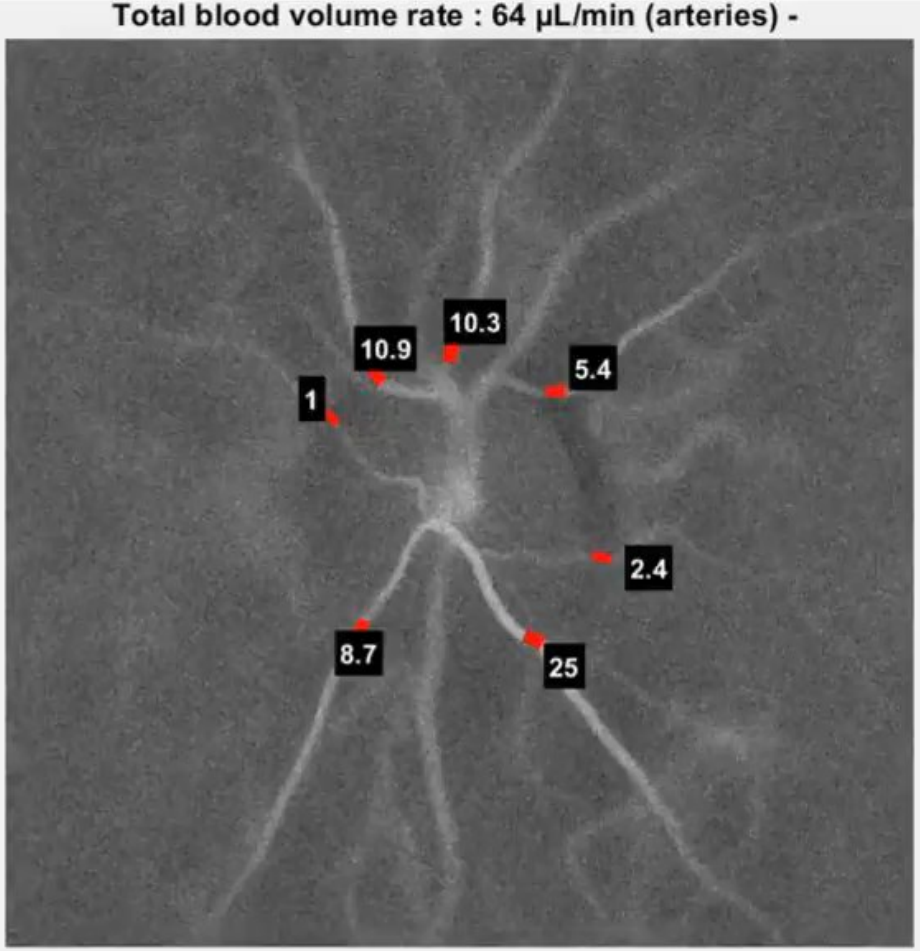
Neuropathie optique ischémique antérieure

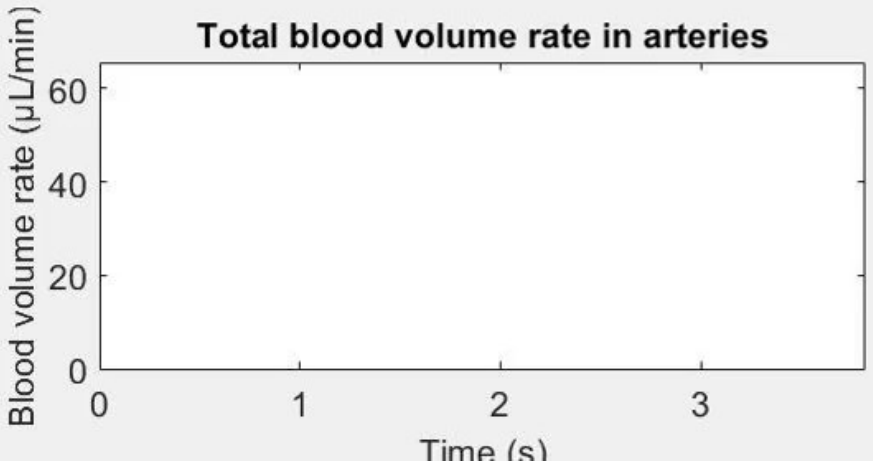
AION

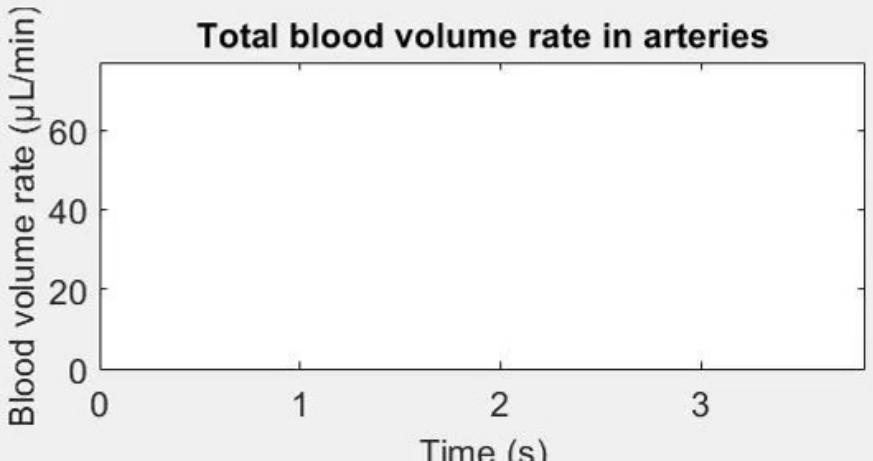
Cortico steroid treatment

17-day interval









Holographie Doppler en temps réel avec une caméra en streaming

~ 512x512 px frame, 12-bit, 20 kHz

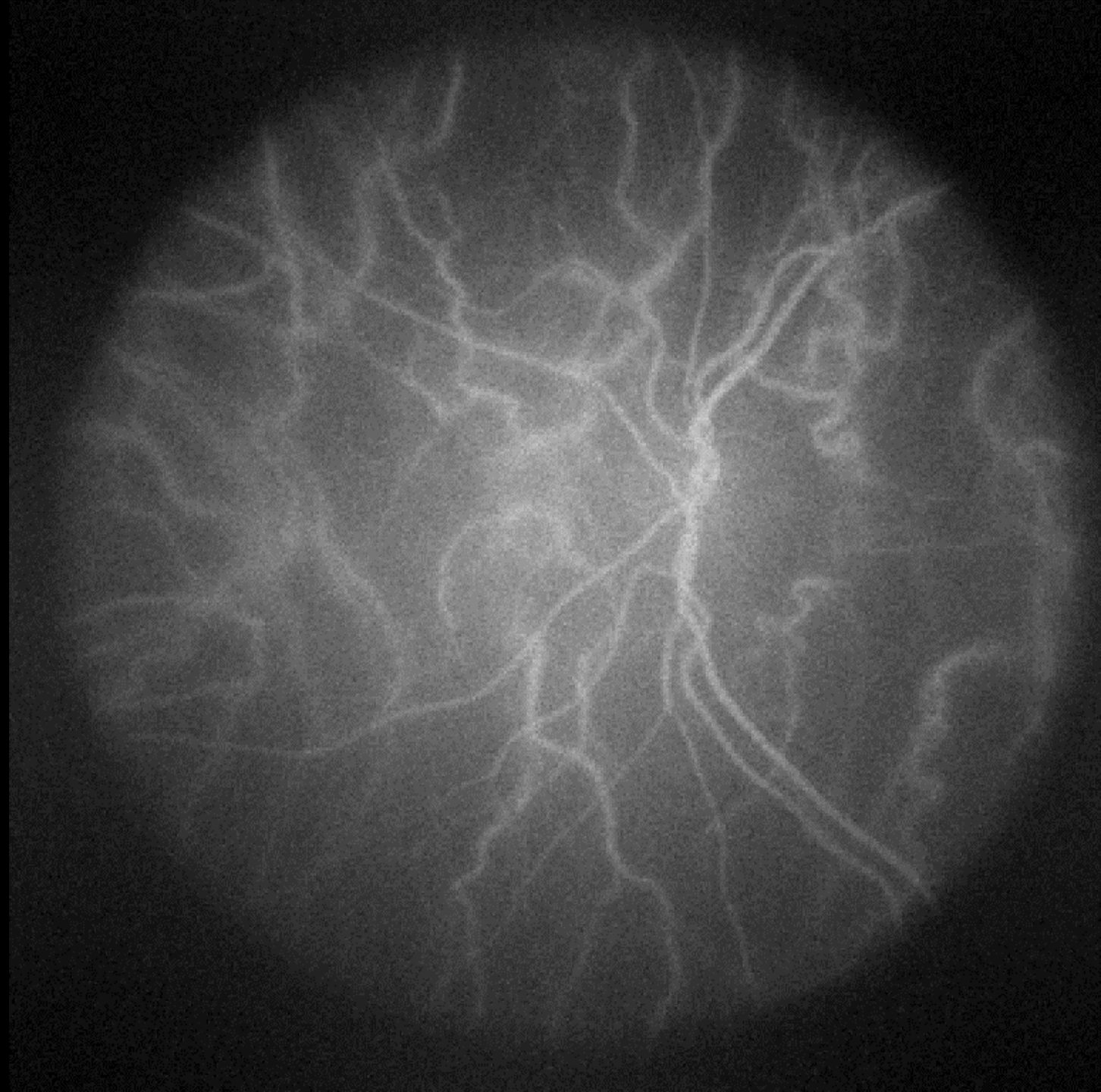
streaming camera
Ametek Phantom S710
Input throughput:
~10GB/s

~ 512*512 px frame, 12-bit, 20 kHz

streaming camera
Ametek Phantom S710

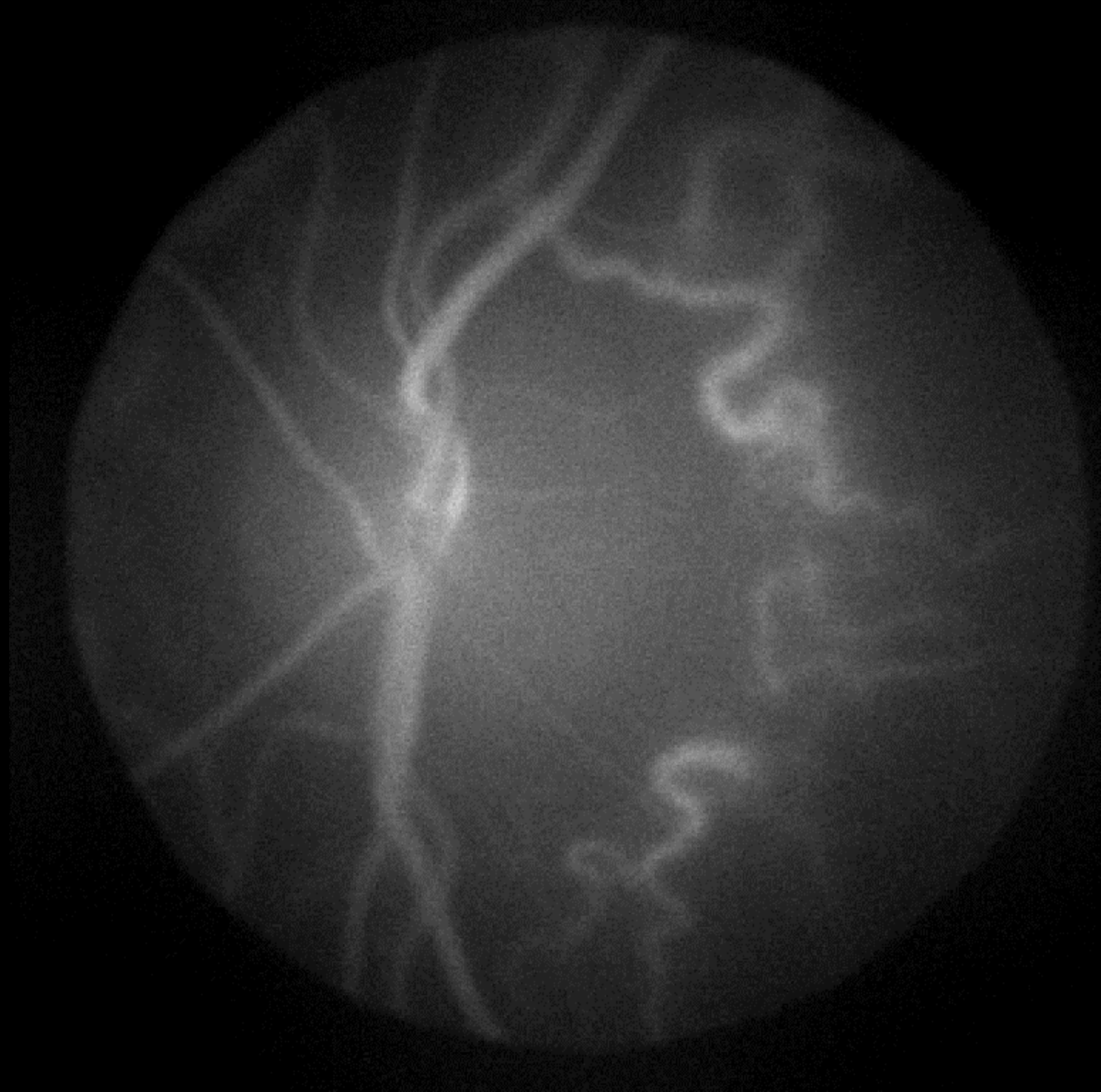
~ 512*512 px frame, 12-bit, 25 kHz

streaming camera
Ametek Phantom S710



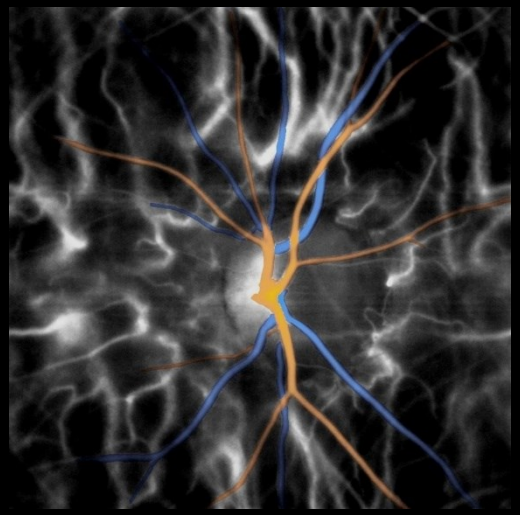
~ 512*512 px frame, 12-bit, 25 kHz

streaming camera
Ametek Phantom S710



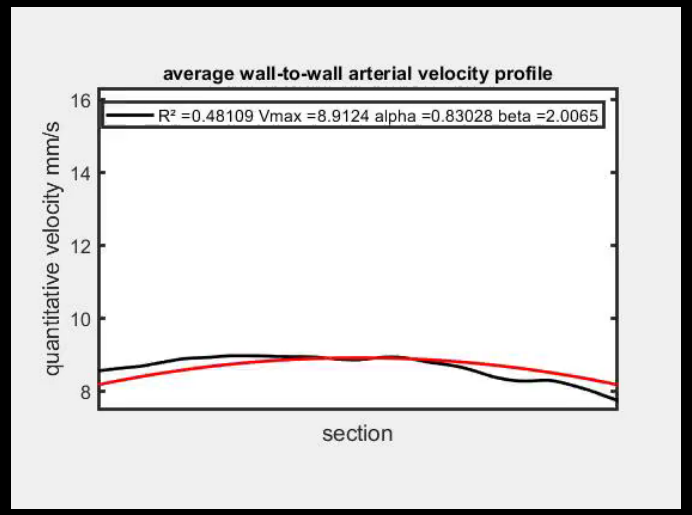
Biomarqueurs quantitatifs issus de l'holographie Doppler

Quantitative hemodynamics



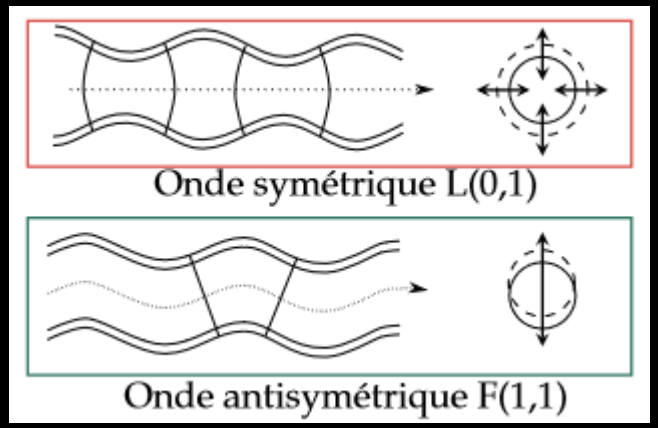
Blood volume rate
+
Arterial resistivity index

Micro rheology



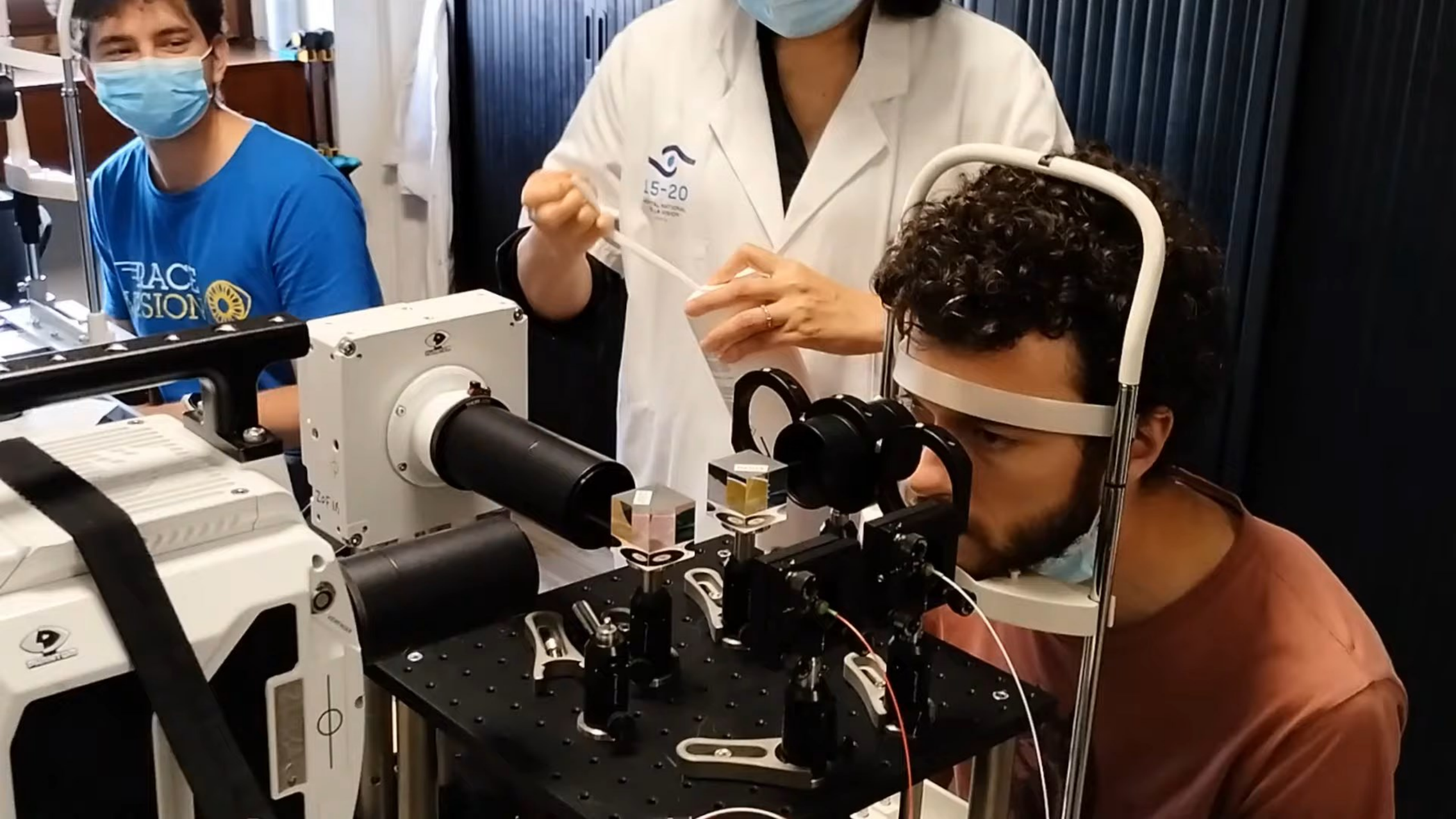
Blood viscosity assessed from velocity profiles

Passive elastography



Velocity of bending waves in arteries

Measurement of the arterial wall elasticity using the velocity of flexural waves in retinal blood vessels
Gabrielle Laloy-Borgna; Léo Puyo; Michael Atlan; Stefan Catheline J Acoust Soc Am 150, A168 (2021)


15-20

OCT holographique en temps réel

Interferogram data courtesy of Maciej Wojtkowski & Egidijus Auksorius (ICTER). OCT rendering : 512x512 px , 12-bit, 20 kHz

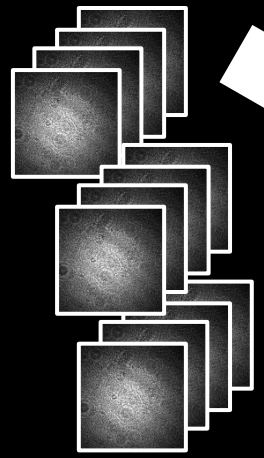
Clinical study generation from batch processing of Doppler holograms

clinical study design

Statistical analysis

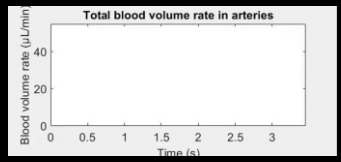
Prototyping of analysis routines

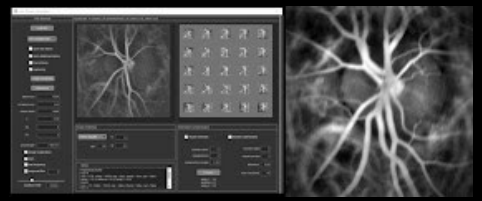
Software implementation



open source software → Technology transfer

Batch processing of PBs of source data





Medical raw data → Medical research

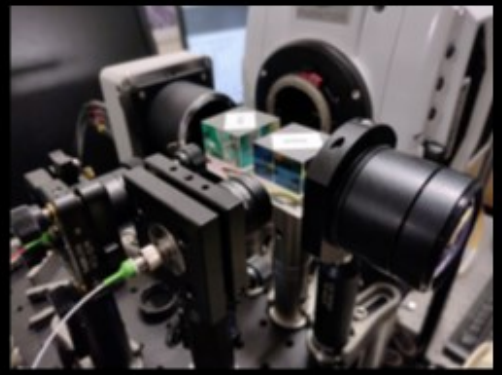
Source data

multicentric

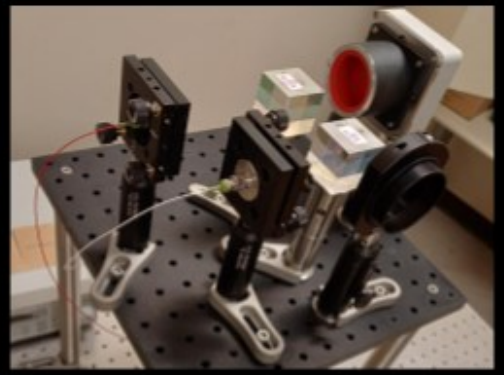
Rendering routines & parameters

Absolute measurements inter-patient validation

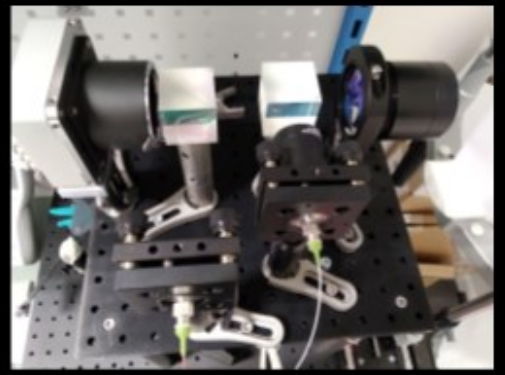
Quinze-Vingts hospital Paris



Rothschild Foundation hospital Paris



Advanced Ophthalmic Imaging Laboratory, University of Pittsburgh

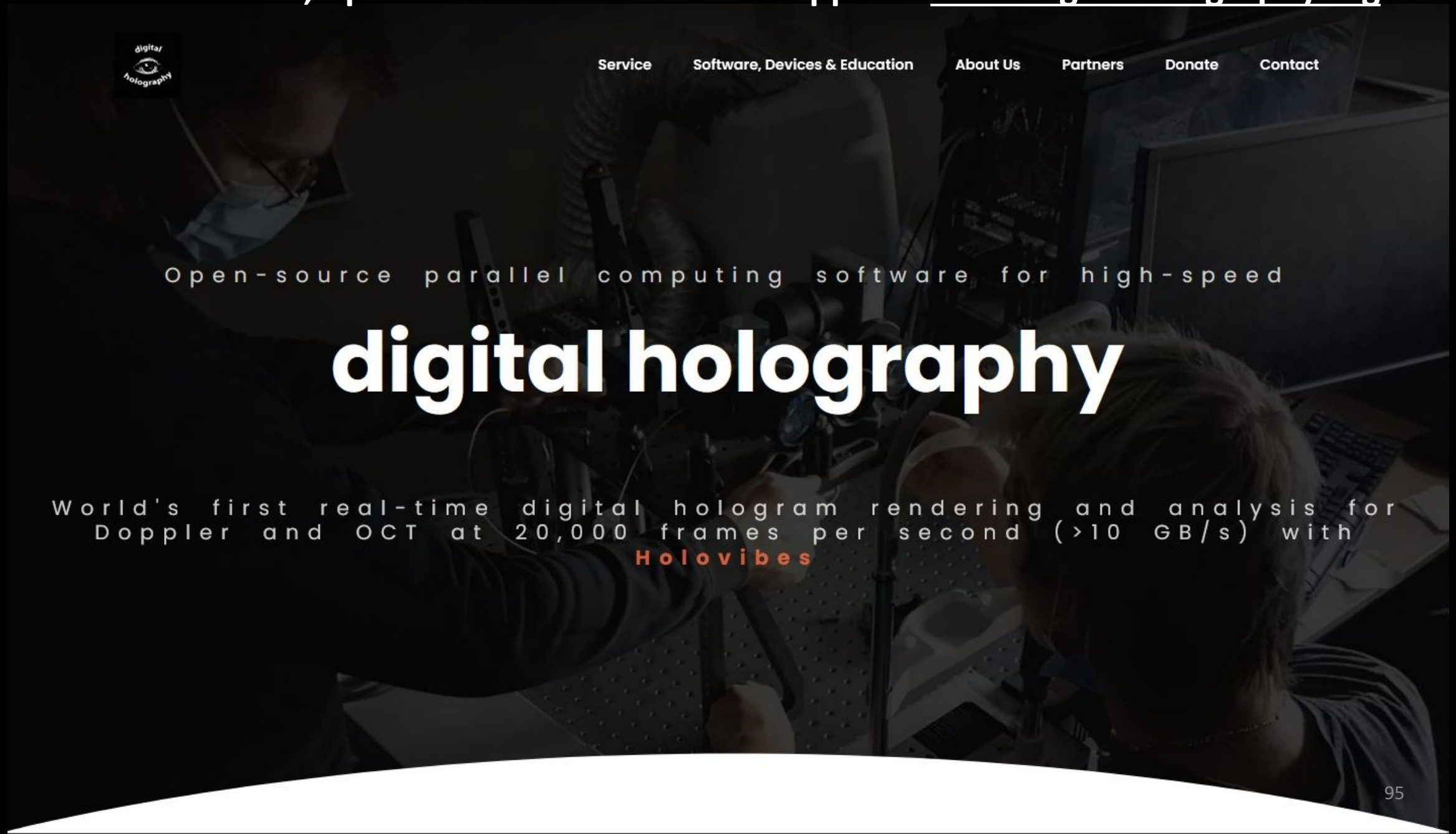


Lumibird Quantel Medical Clermont-Ferrand

ONERA Châtillon

Engaging in Open Source Software for high-performance imaging

Free software, open source codebase and support : www.digitalholography.org



Free software, open source codebase and support : www.digitalholography.org

Langevin Institute, CNRS, ESPCI
Paris, France

ONERA, the French Aerospace Lab
Châtillon, France

Essilor-Luxottica. Essilor instruments
Créteil, France

Lumibird Quantel Medical
Cournon d'Auvergne, France

Rothschild Foundation Hospital
Paris, France

Quinze-Vingts National Eye Hospital, INSERM
Paris, France

Bar-Ilan University
Tel-Aviv, Israel

SharpEye
Paris, France

The University of Pittsburgh. Dept. of Ophthalmology, UPMC
Pittsburgh, PA, USA

The University of Copenhagen Dept. of Clinical Medicine
Copenhagen, Denmark

University College London (UCL) Dept. of Med. Phys. and Biomedical Eng.
London, United Kingdom

The University of Melbourne. Faculty of Medicine, Dentistry and Health Sciences
Melbourne, Australia

L V Prasad Eye Institute K. V. Chowdary Campus
Vijayawada, Andhra Pradesh, India

University of California, Davis College of Engineering
Davis, CA, USA

Le Mans University. Institut d'Acoustique - Graduate School
Le Mans, France

Center for Physical Sciences and Technology FTMC
Vilnius, Lithuania

Ametek Vision Research Phantom High Speed
Wayne, New Jersey, USA

Euresys Liège Science Park
Seraing, Belgium

Nvidia Corporation nvidia.com
Santa Clara, CA, USA

Vision Institute institut-vision.org
Paris, France

Fondation Voir et Entendre FVE
Paris, France

ICTER International Centre for Translational Eye Research
Warsaw, Poland

University of Luebeck Institute of Biomedical Optics
Luebeck, Germany

New York Mount Sinai Hospital Department of Ophthalmology
New York, USA

Implementation, education & support for academia & Technology transfer to industrial companies

Volunteer ?

Get your Doppler holography eye fundus at the Quinze-Vingts Eye hospital in Paris, France

References.

Puyo, L., Paques, M., Fink, M., Sahel, J. A., & Atlan, M. (2018). In vivo laser Doppler holography of the human retina. *Biomedical optics express*, *9*(9), 4113-4129.

Puyo, L., Paques, M., Fink, M., Sahel, J. A., & Atlan, M. (2019). Choroidal vasculature imaging with laser Doppler holography. *Biomedical optics express*, *10*(2), 995-1012.

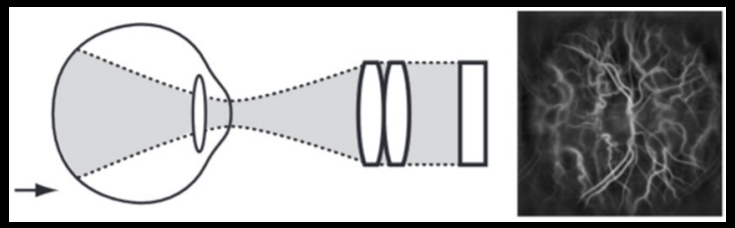
Puyo, L., Paques, M., Fink, M., Sahel, J. A., & Atlan, M. (2019). Waveform analysis of human retinal and choroidal blood flow with laser Doppler holography. *Biomedical Optics Express*, *10*(10), 4942-4963.

Puyo, Léo, Michel Paques, and Michael Atlan. Spatio-temporal filtering in laser Doppler holography for retinal blood flow imaging." *Biomedical Optics Express* 11, no. 6 (2020): 3274-3287.

Puyo, Leo, Michel Paques, and Michael Atlan. Low frame rate laser Doppler holography." *arXiv preprint arXiv:2004.00007* (2020).

offline camera 67 kHz

streaming camera 20 kHz



Puyo, Leo , et al. *Spatio-temporal filtering in laser Doppler holography for retinal blood flow imaging*. *Biomedical Optics Express* 11, no. 6 (2020): 3274-3287.

Leo Puyo, et al. *Real-time digital holography of the retina by principal component analysis.* arXiv:2004.00923 (2020).

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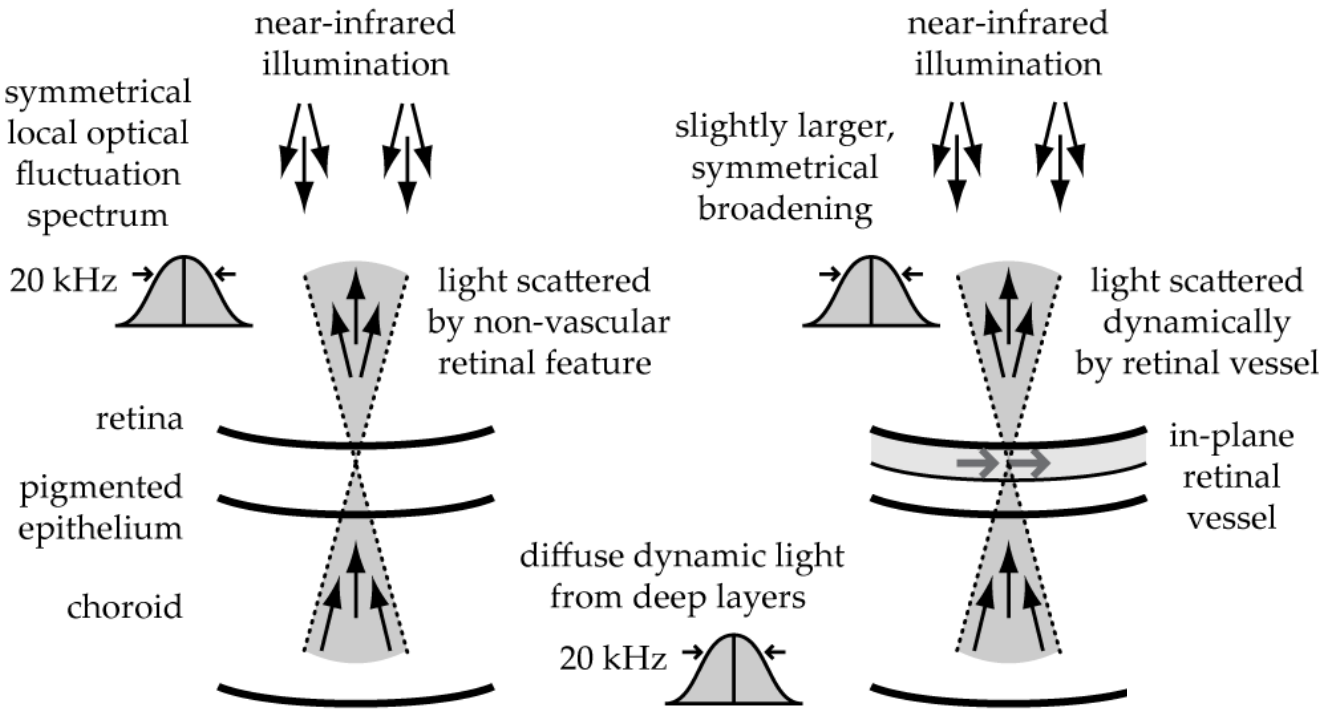
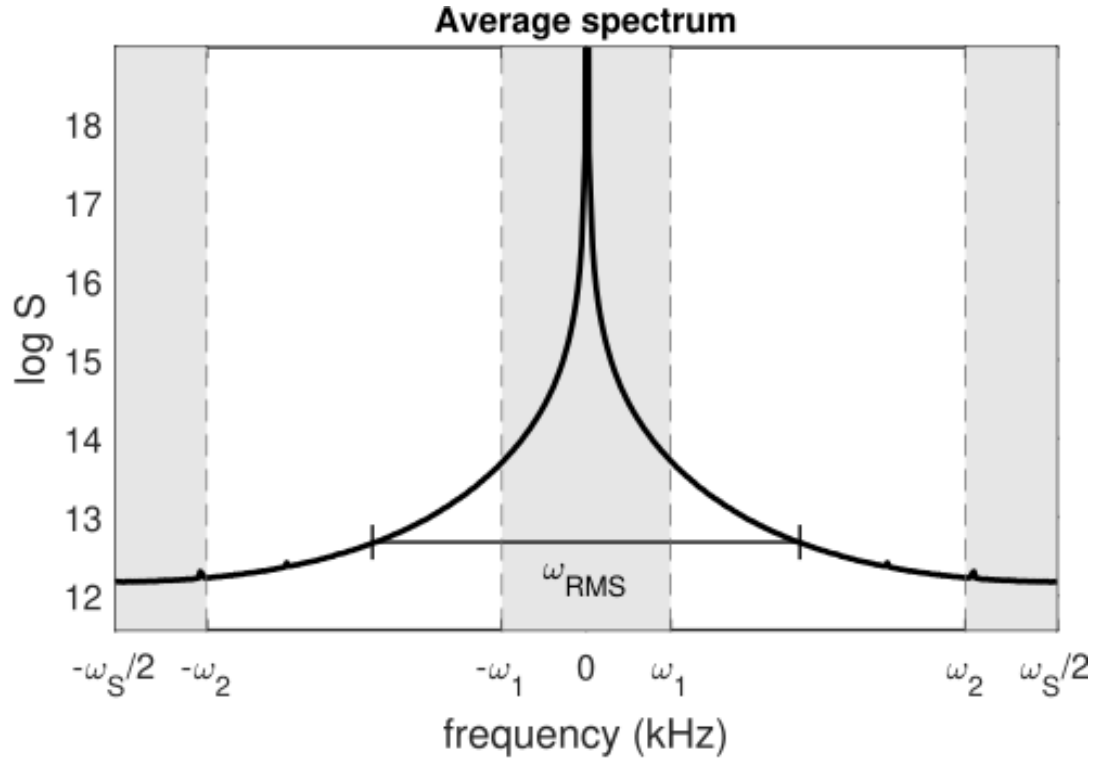
Open source software : holovibes & holowaves
The Digital Holography Foundation

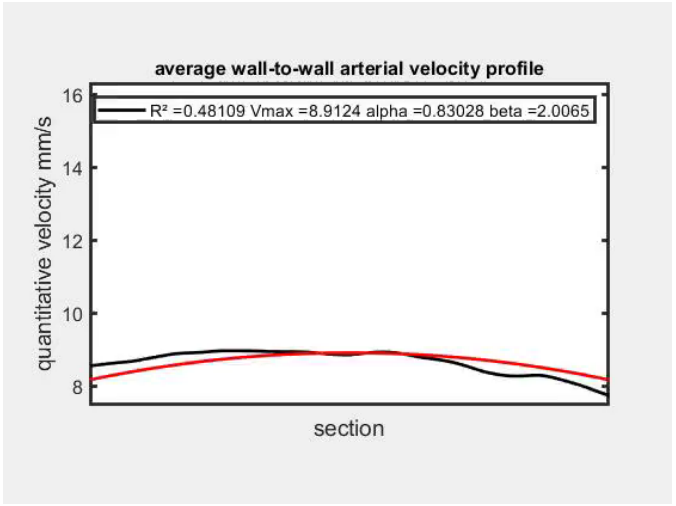
www.digitalholography.org

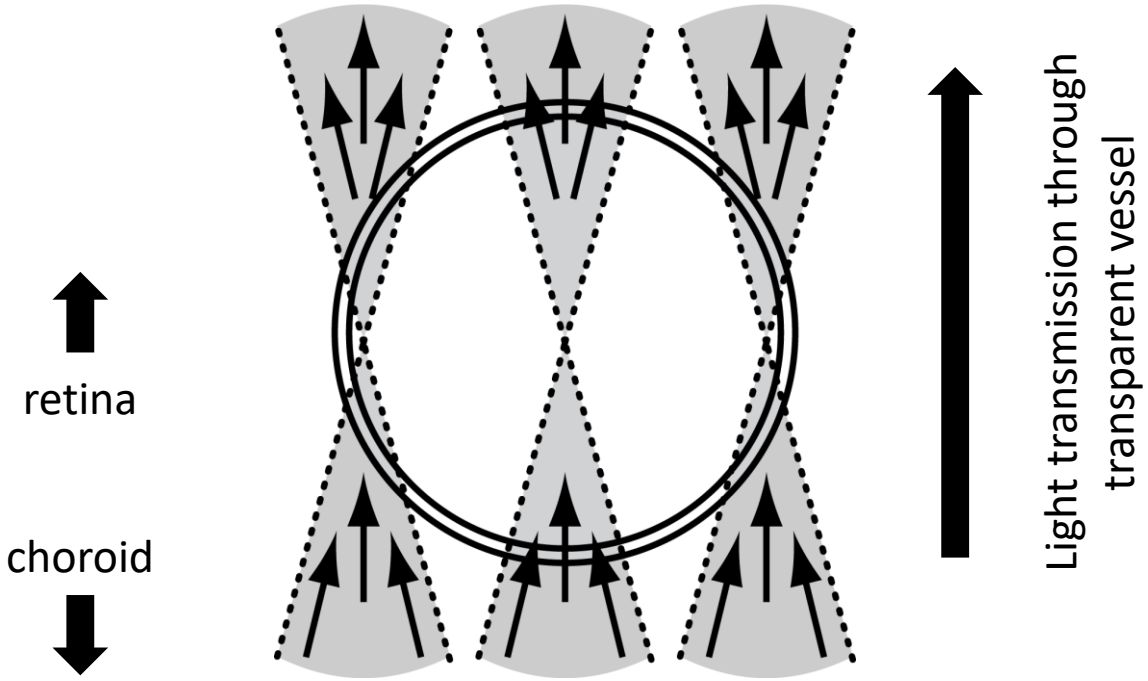
Light transmission through retinal vessels from a diffuse, Doppler-broadened secondary source





$$\Delta\omega_{\mathrm{RMS}} = \sqrt{\left\langle \left(\vec{k}\cdot\vec{v}\right)^2 \right\rangle} \qquad V = \frac{\lambda}{2\pi}\sqrt{\frac{3}{\theta}}\cdot\Delta\omega_{\mathrm{RMS}}$$


average wall-to-wall arterial velocity profile
R² =0.48109 Vmax =8.9124 alpha =0.83028 beta =2.0065
quantitative velocity mm/s
16
14
12
10
8
section


retina
choroid
Light transmission through transparent vessel