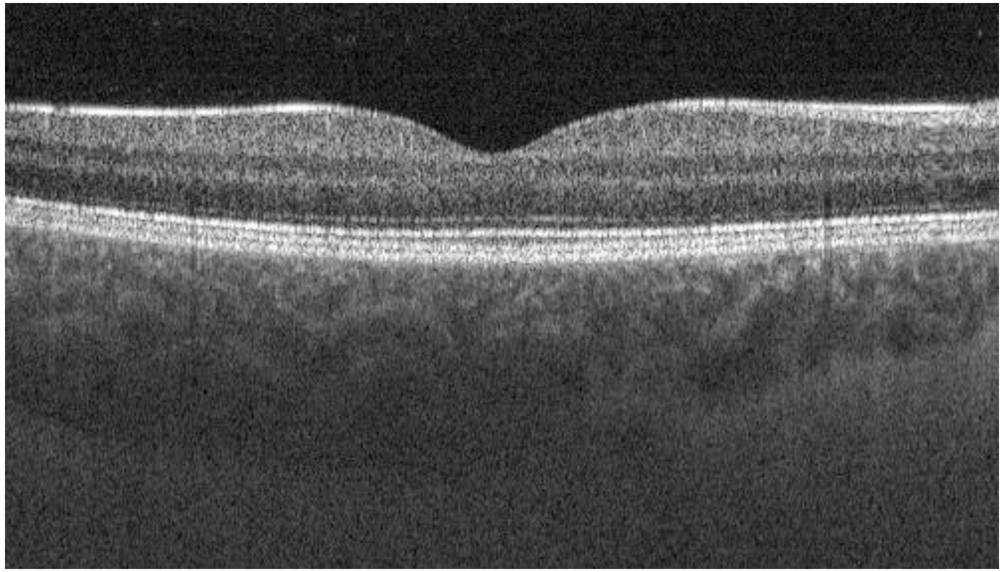
3-D OCT Motion Correction Efficiently Enhanced with OCT Angiography

Stefan B. Ploner, MF Kraus, L Husvogt, EM Moult, AY Alibhai, J Schottenhamml, T Geimer, C Rebhun, B Lee, CR Baumal, NK Waheed, JS Duker, JG Fujimoto, AK Maier

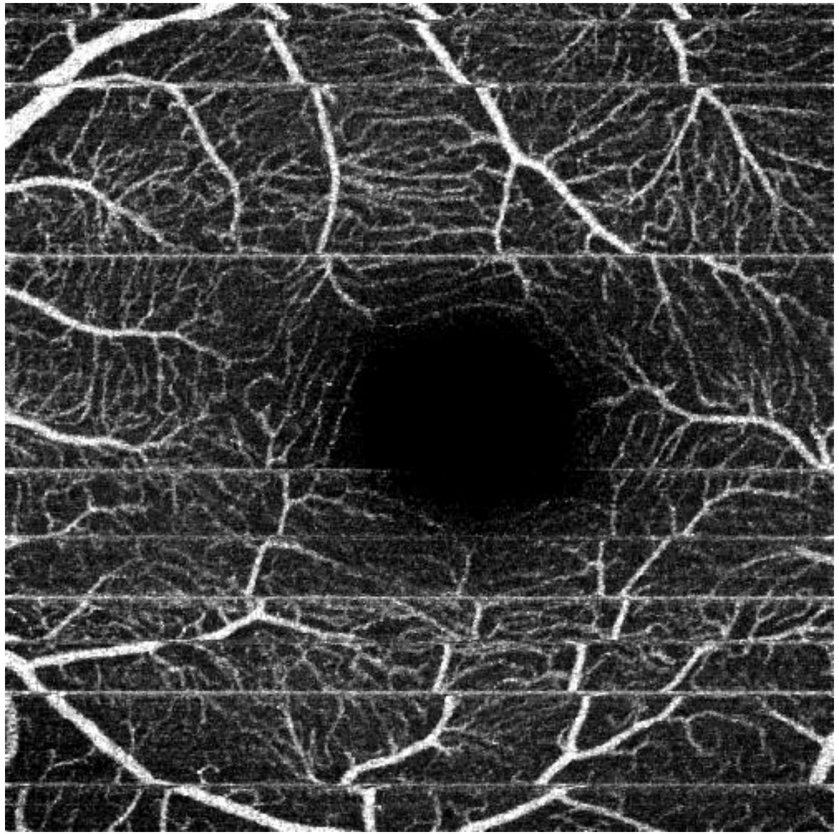
ARVO Annual Meeting 2018

New England Eye Center

Motivation

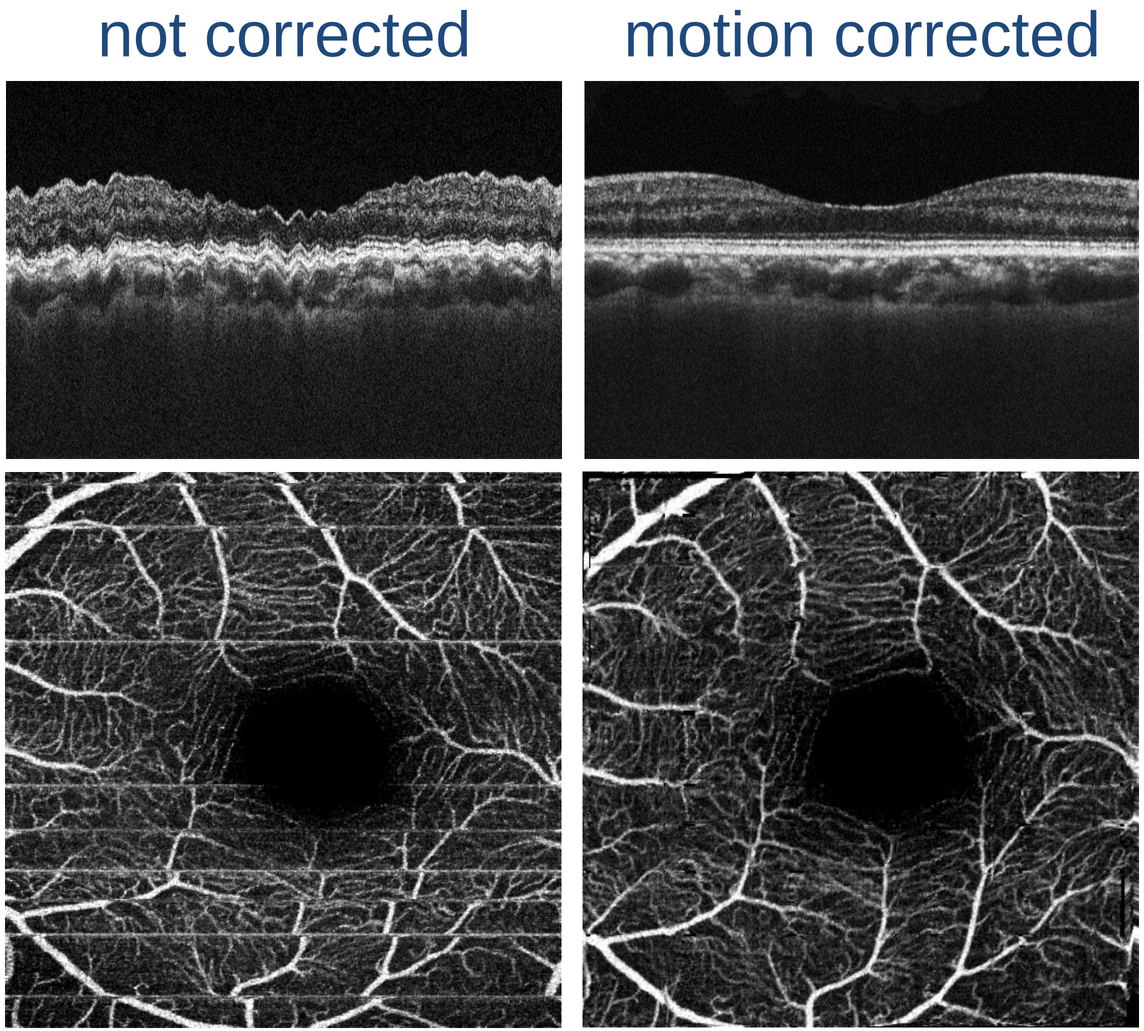


Distortion between B-scans



Aims of Motion Correction

- Arbitrary slicing
- Accurate & reproducible disease metrics
- Directly compare with follow-up scans
- Prevent gaps from blinks and saccades



Registration-based Motion Correction

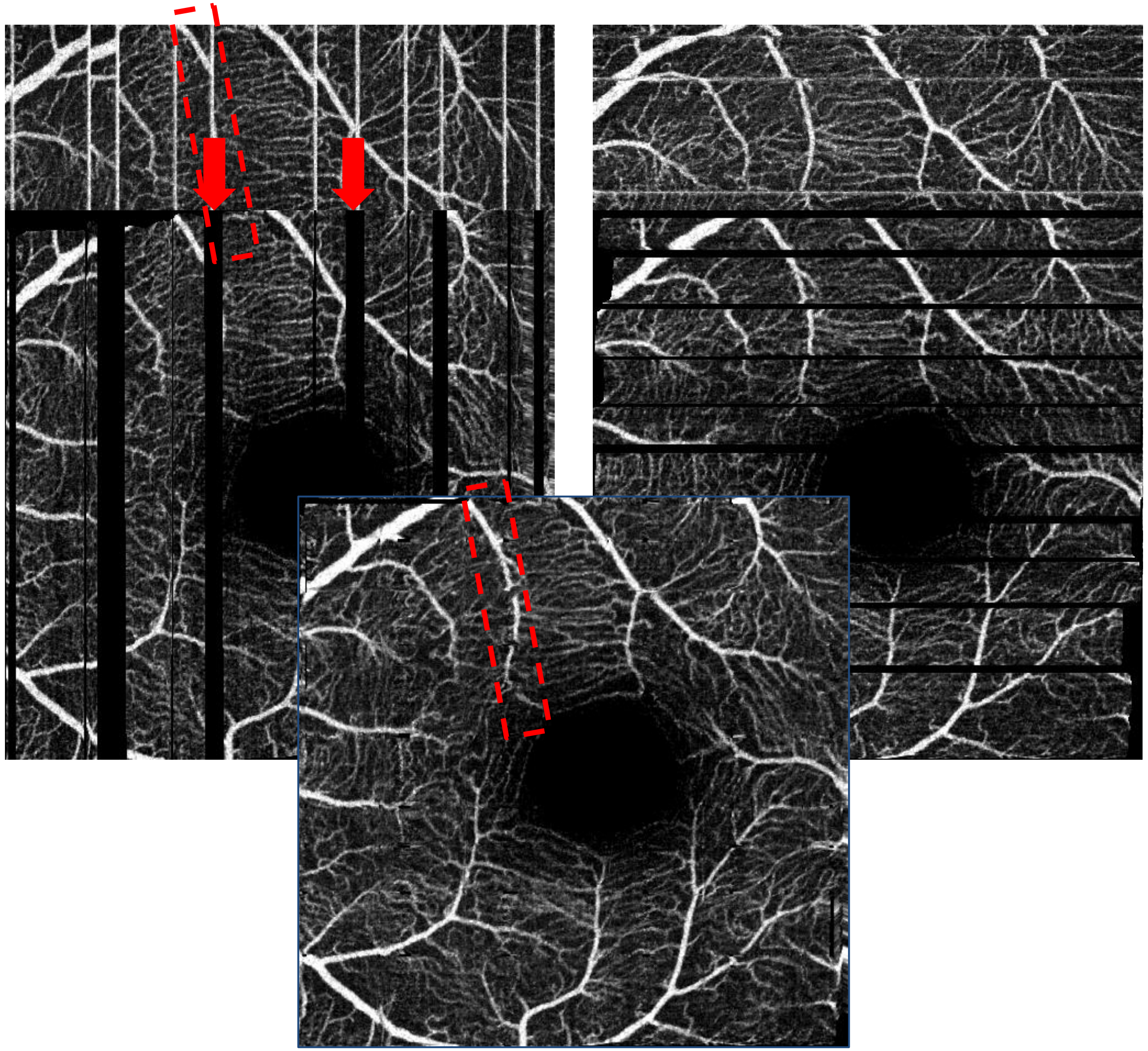
Acquisition
(>= 2 scans)

↓

Registration

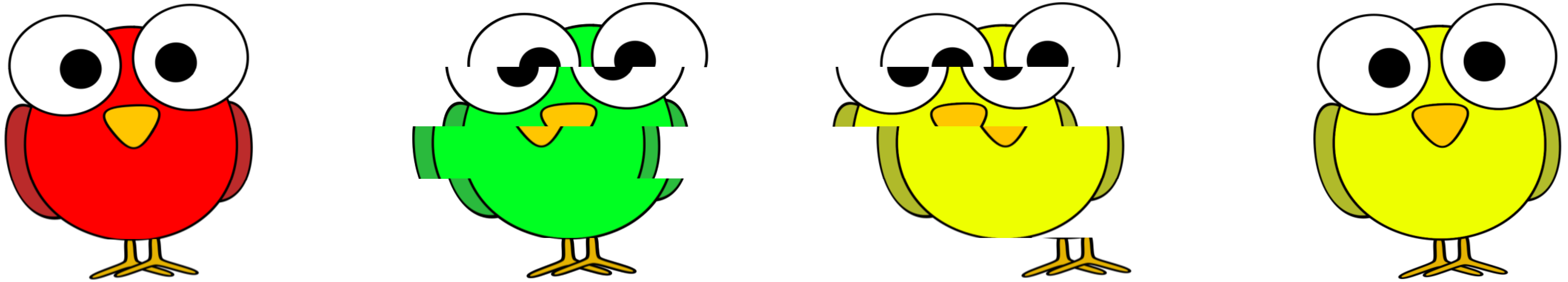
↓

Merging



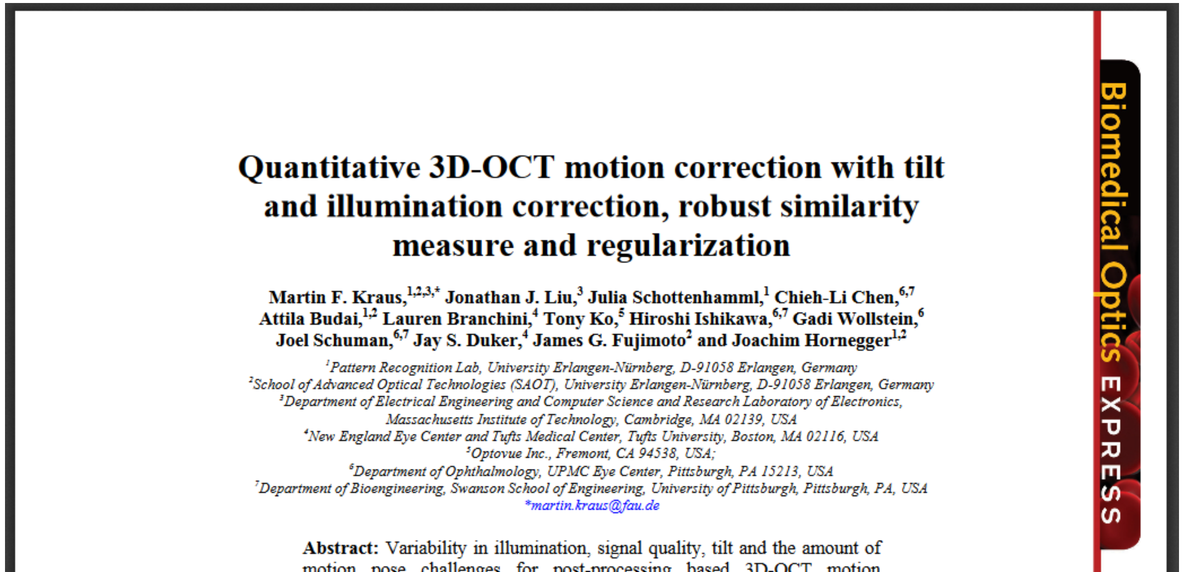
Scan Alignment vs. Motion Correction

	Alignment	Motion Correction
Align scans	✓	✓
SNR improvement	✓	✓
Correct distortions	✗	✓



Scan 1 Scan 2 Aligned $\Leftarrow$ $\not\Rightarrow$ Motion corrected

3-D OCT Motion Correction by Kraus et. al.



Biomedical Optics EXPRESS

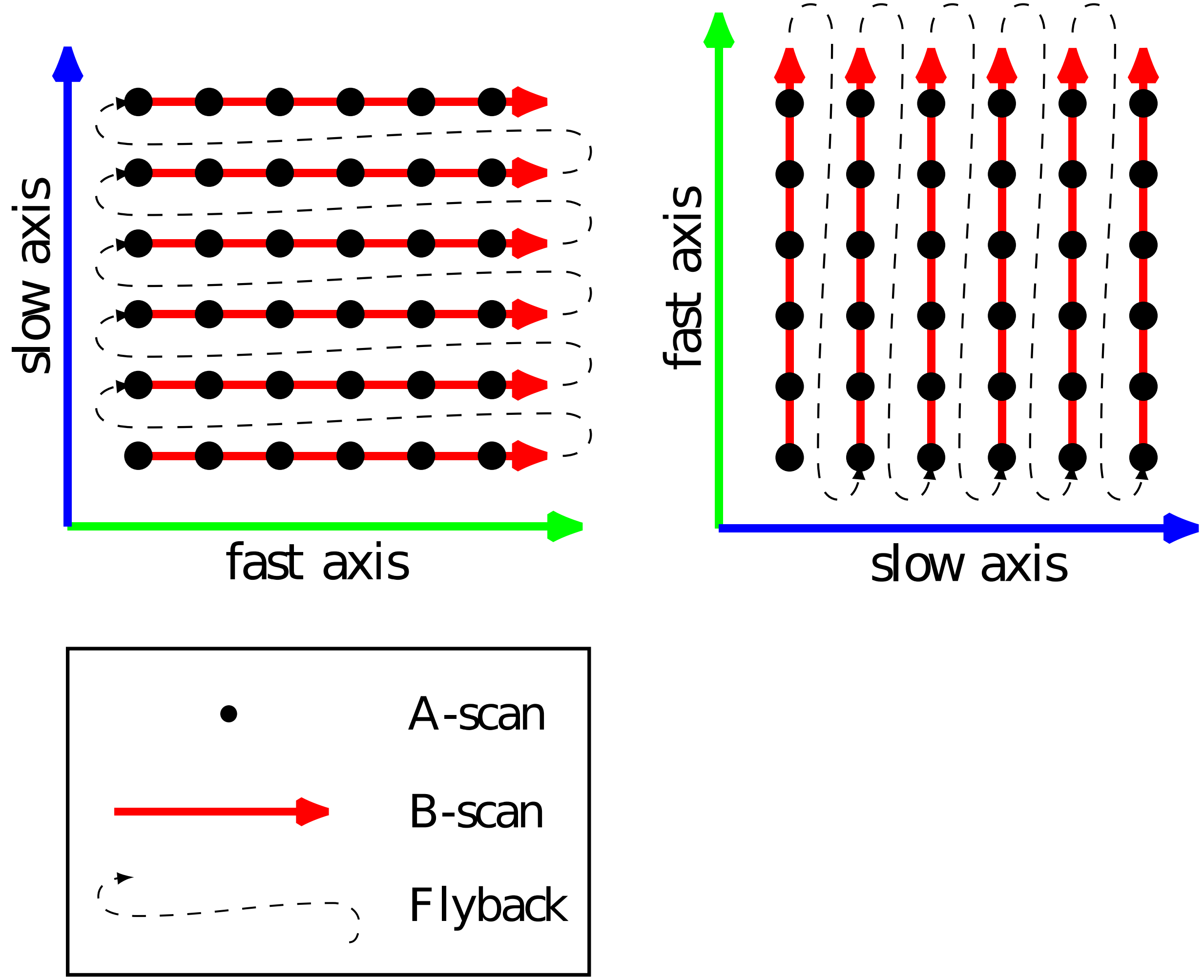
Quantitative 3D-OCT motion correction with tilt and illumination correction, robust similarity measure and regularization

Martin F. Kraus,[1,2,3,*] Jonathan J. Liu,[3] Julia Schottenhamml,[1] Chieh-Li Chen,[6,7] Attila Budai,[1,2] Lauren Branchini,[4] Tony Ko,[5] Hiroshi Ishikawa,[6,7] Gadi Wollstein,[6] Joel Schuman,[6,7] Jay S. Duker,[4] James G. Fujimoto[2] and Joachim Hornegger[1,2]

[1]*Pattern Recognition Lab, University Erlangen-Nürnberg, D-91058 Erlangen, Germany*
[2]*School of Advanced Optical Technologies (SAOT), University Erlangen-Nürnberg, D-91058 Erlangen, Germany*
[3]*Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[4]*New England Eye Center and Tufts Medical Center, Tufts University, Boston, MA 02116, USA*
[5]*Optovue Inc., Fremont, CA 94538, USA;*
[6]*Department of Ophthalmology, UPMC Eye Center, Pittsburgh, PA 15213, USA*
[7]*Department of Bioengineering, Swanson School of Engineering, University of Pittsburgh, Pittsburgh, PA, USA*
**martin.kraus@fau.de*

Abstract: Variability in illumination, signal quality, tilt and the amount of motion pose challenges for post-processing based 3D-OCT motion

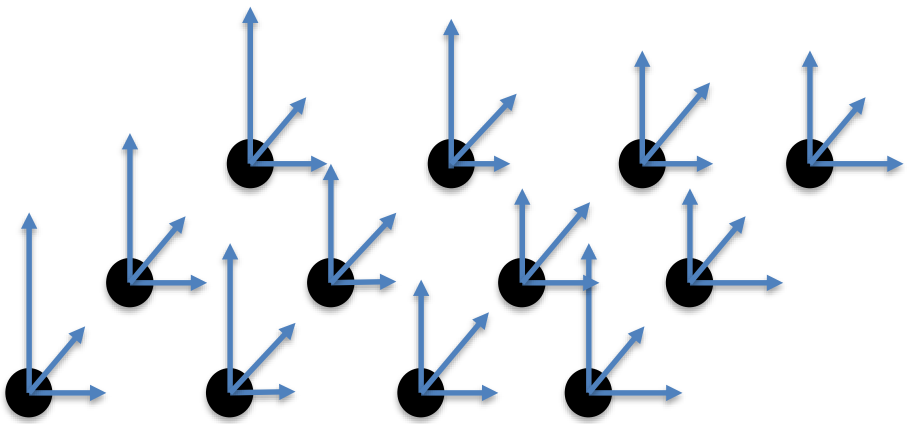
3-D OCT Motion Correction by Kraus et. al.



Key properties:

- Orthogonal scan based

3-D OCT Motion Correction by Kraus et. al.



Key properties:

- Orthogonal scan based
- Full 3-D per A-scan displacement field

● A-scan center

3-D displacement

(One displacement field *per volume*.)

3-D OCT Motion Correction by Kraus et. al.

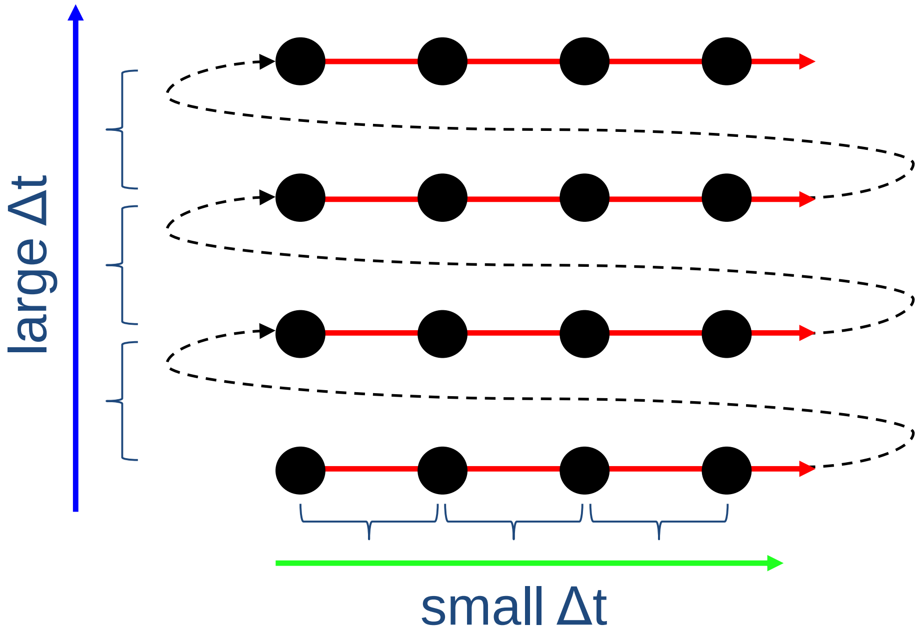
- $\min_{D} \overbrace{\mathcal{D}(V_1, V_2, D)}^{\text{Dissimilarity}} + \alpha \overbrace{\mathcal{R}(D)}^{\text{Regularizer}}$
  - V_i: OCT volumes
  - D: displacement field

Key properties:

- Orthogonal scan based
- Full 3-D per A-scan displacement field
- Gradient-based optimizer

  (L-BFGS)

3-D OCT Motion Correction by Kraus et. al.

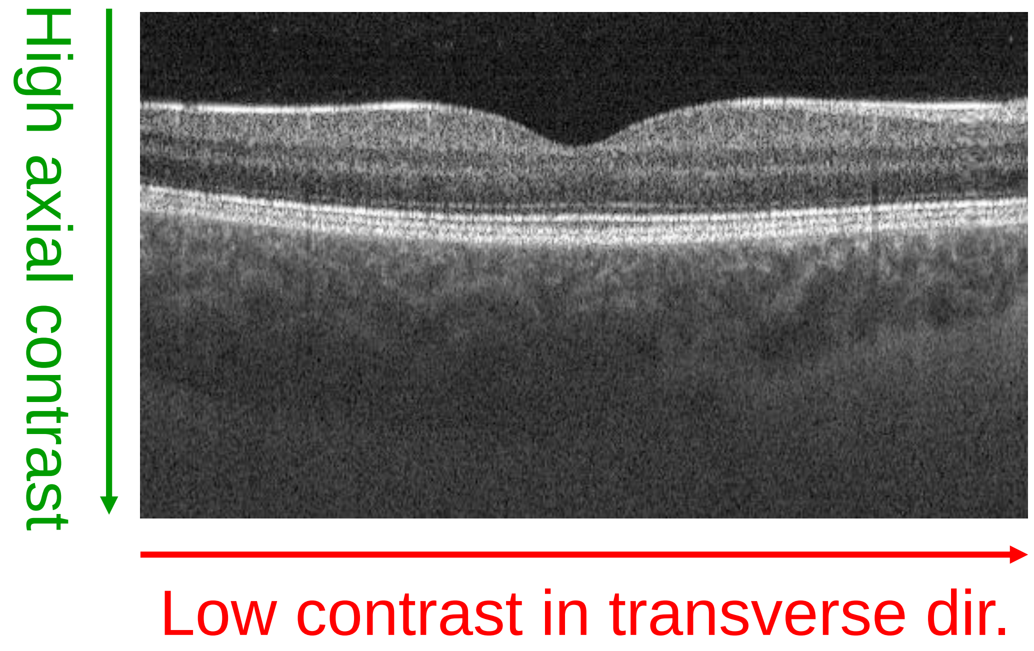


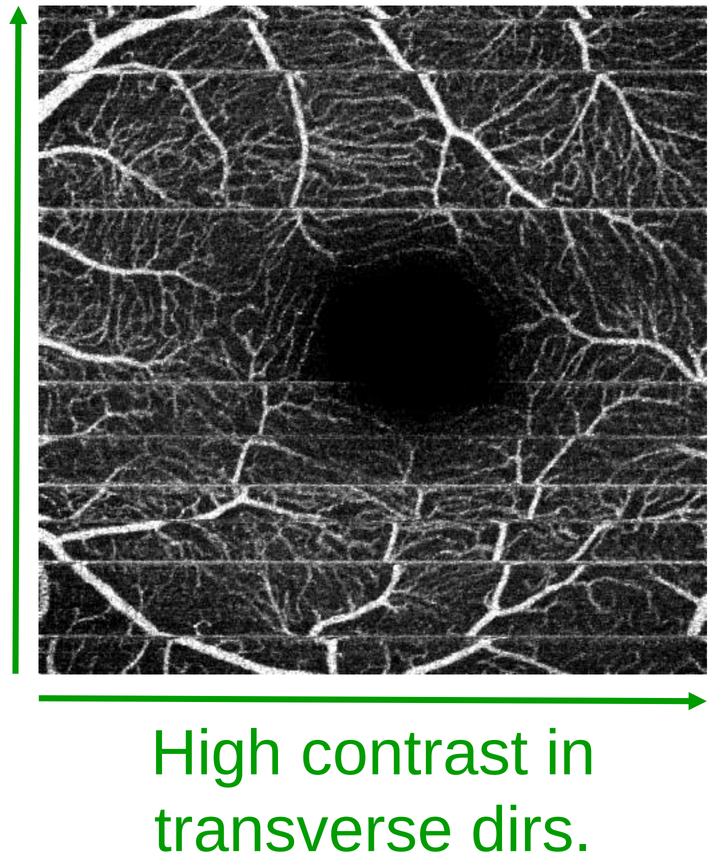
Penalize displacement changes along fast axis

Key properties:

- Orthogonal scan based
- Full 3-D per A-scan displacement field
- Gradient-based optimizer
- Physiologically reasonable displacements ($\mathcal{R}$)

Why add angiography data?

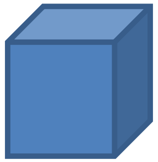




Efficient Use of Angiography Data

$$\min_{D} (1-\delta) \cdot \underbrace{\boldsymbol{\mathcal{D}}(V_1, V_2, D)}_{\text{OCT term}} + \delta \cdot \underbrace{\boldsymbol{\mathcal{D}}(A_1, A_2, D)}_{\text{OCTA term}} + \alpha \cdot \underbrace{\boldsymbol{\mathcal{R}}(D)}_{\text{Regularizer}}$$

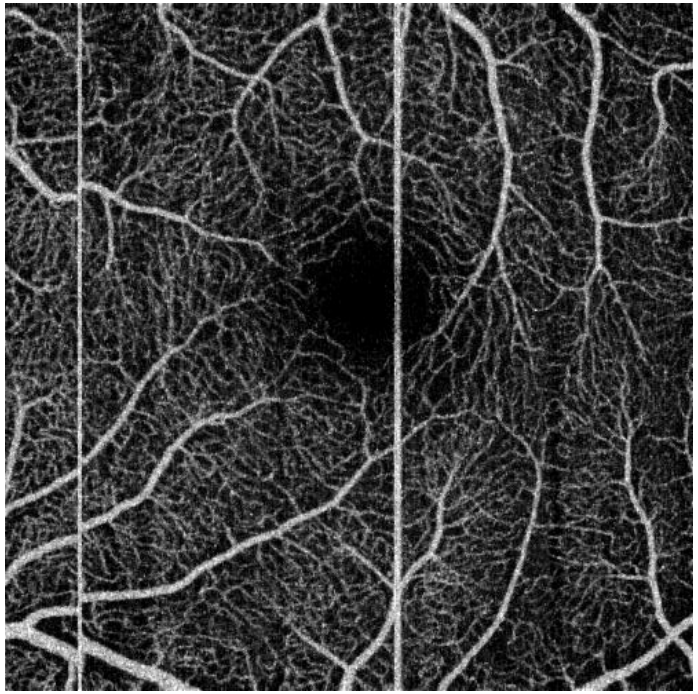
$\in O(n^3)$ $\in O(n^{\cancel{3}\,2})$ $\in O(n^2)$



- OCTA adds little information along depth
- Use 2-D en-face OCTA projections

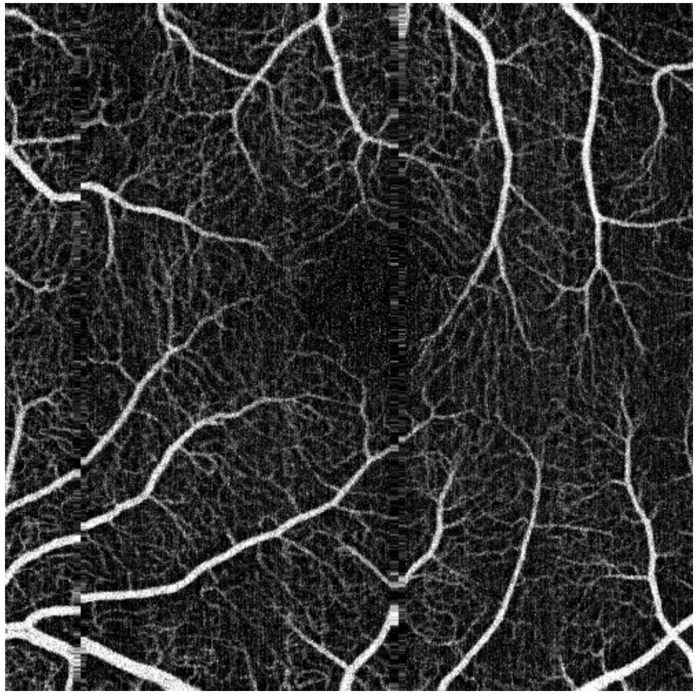
Fast Computation of OCTA Projections

Layer segmentation based



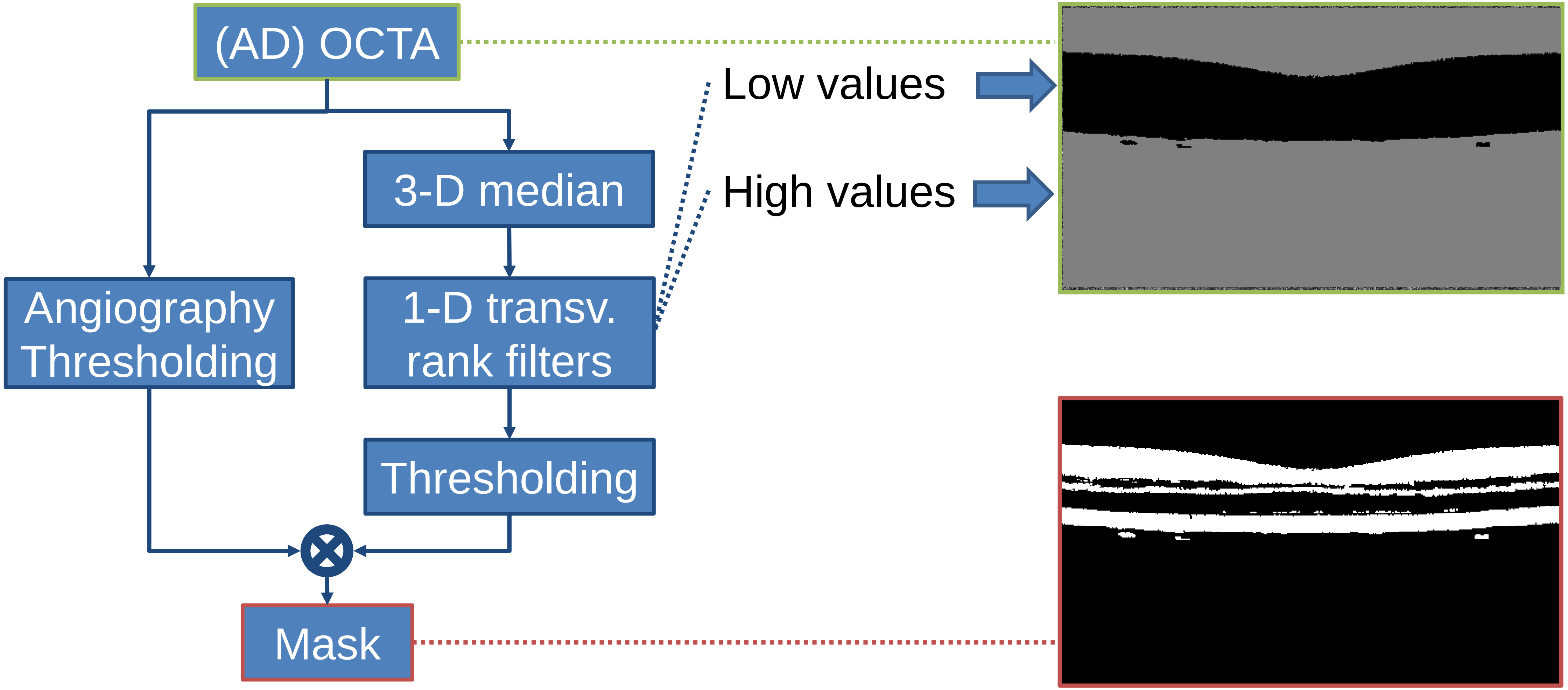
- Best quality
- Slow to compute

Our approach

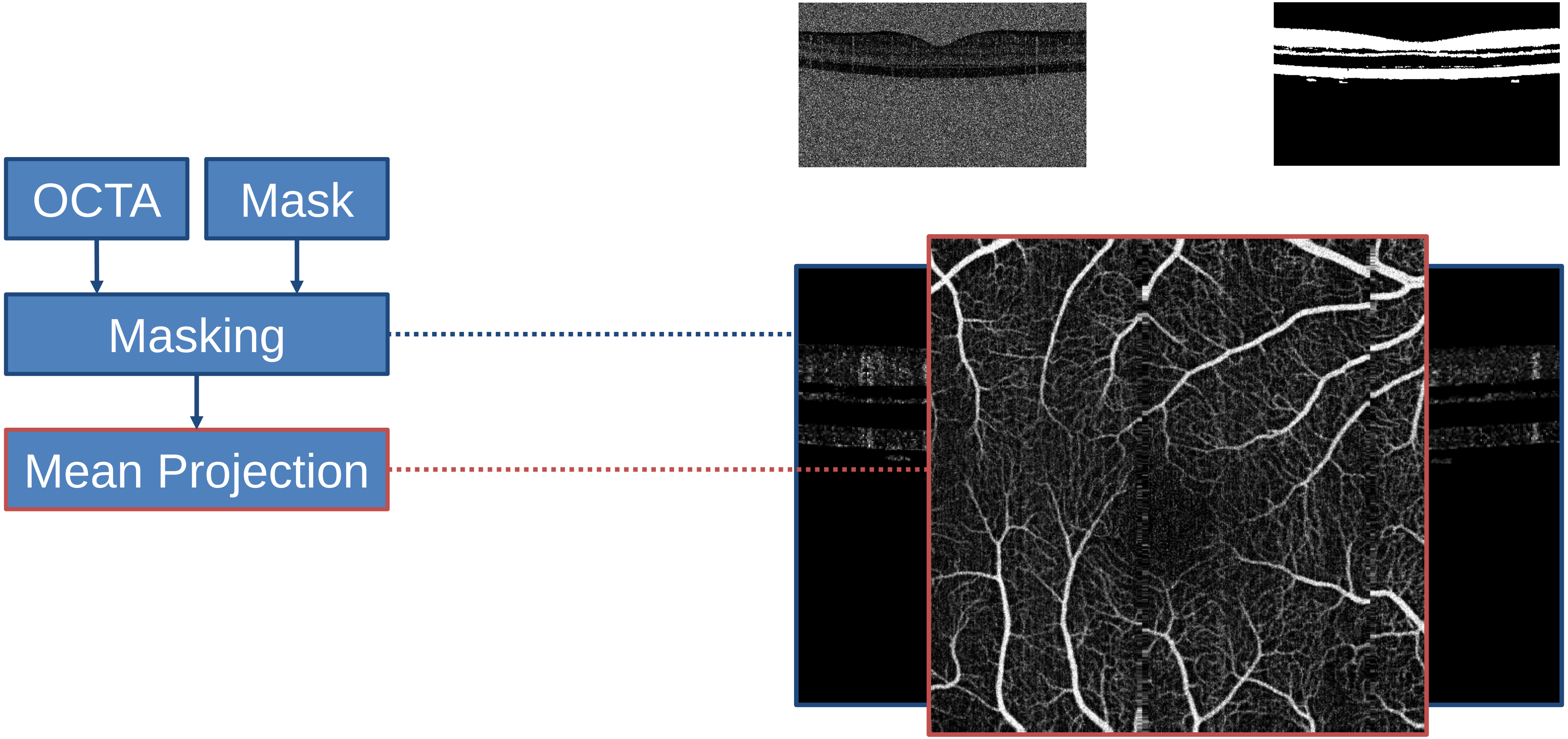


- Fast to compute
- Not as nice, but sufficient

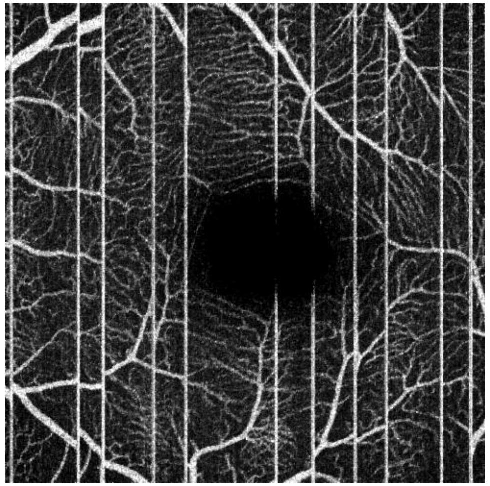
Fast Computation of OCTA Projections



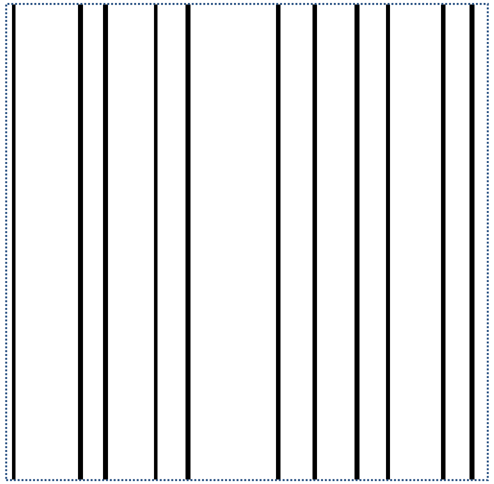
Fast Computation of OCTA Projections



Corrupted OCTA Data



En-face OCTA



OCTA validity

- Fall back to OCT only for saccadic B-scans

$$\min_D (1-\cancelto{0}{\delta}) \cdot \underbrace{\boldsymbol{\mathcal{D}}(V_1,V_2,D)}_{\text{OCT term}} + \cancelto{0}{\delta} \cdot \underbrace{\boldsymbol{\mathcal{D}}(A_1,A_2,D)}_{\text{OCTA term}} + \alpha \cdot \boldsymbol{\mathcal{R}}(D)$$

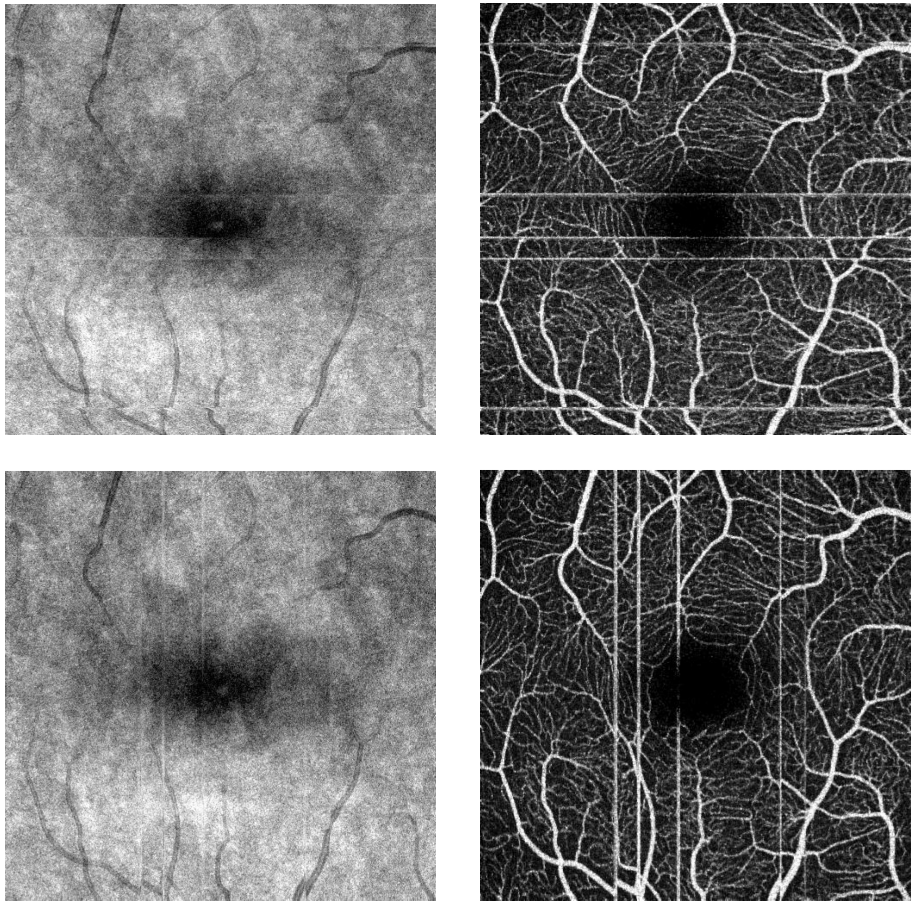
Evaluation

Qualitative Evaluation, OCT Data Only

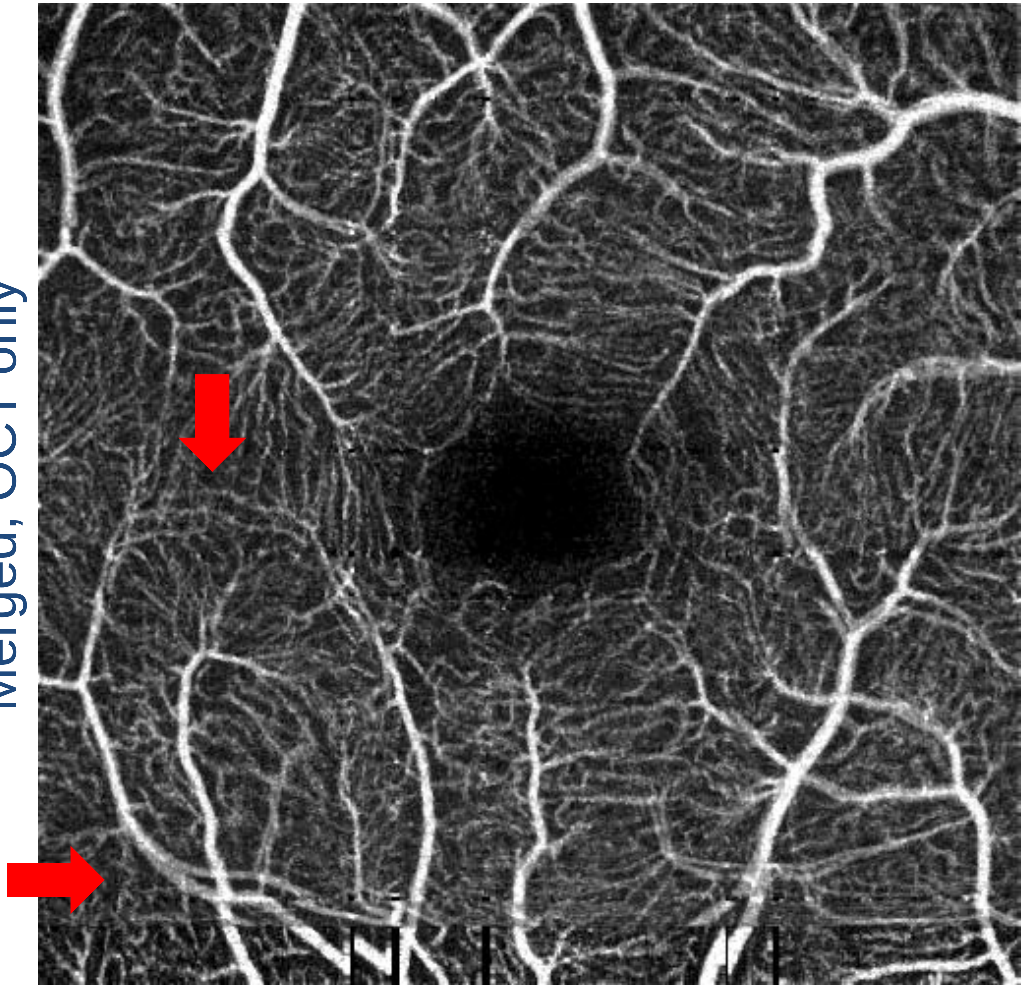
OCT OCTA

Scan 1

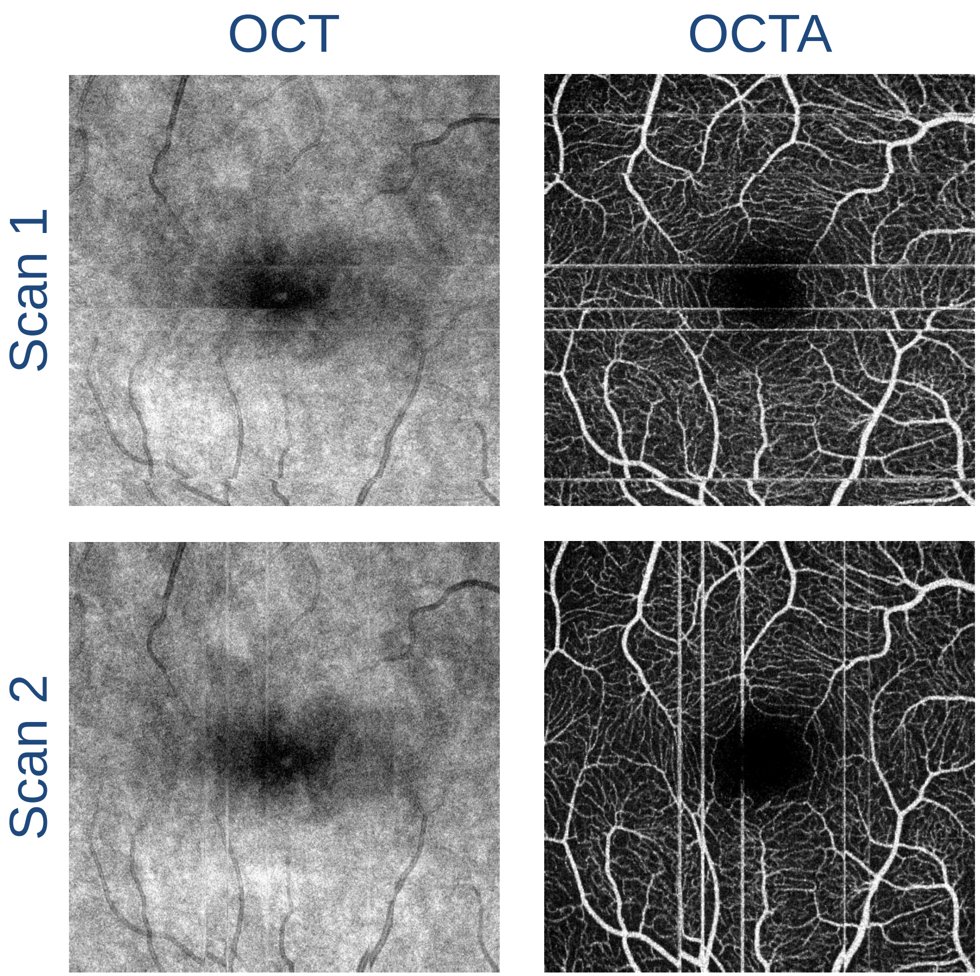
Scan 2

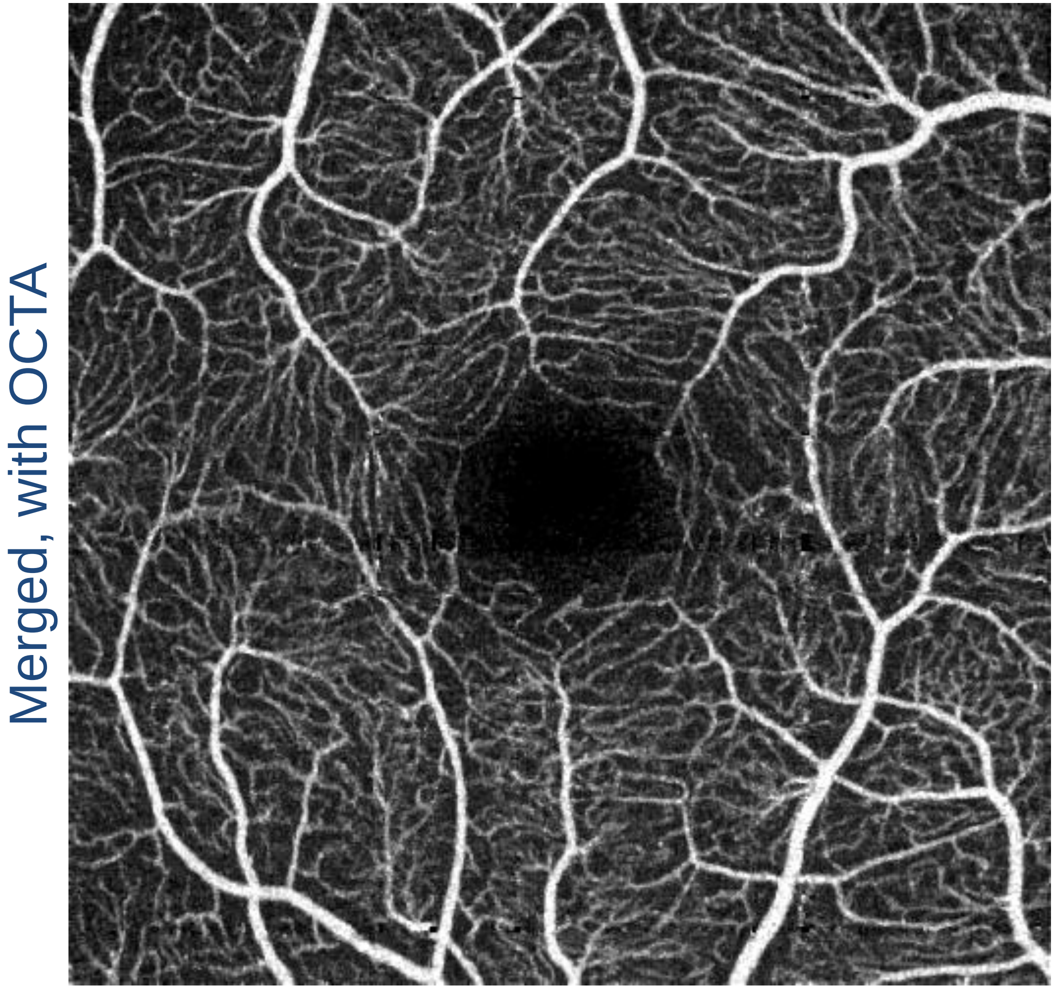


Merged, OCT only

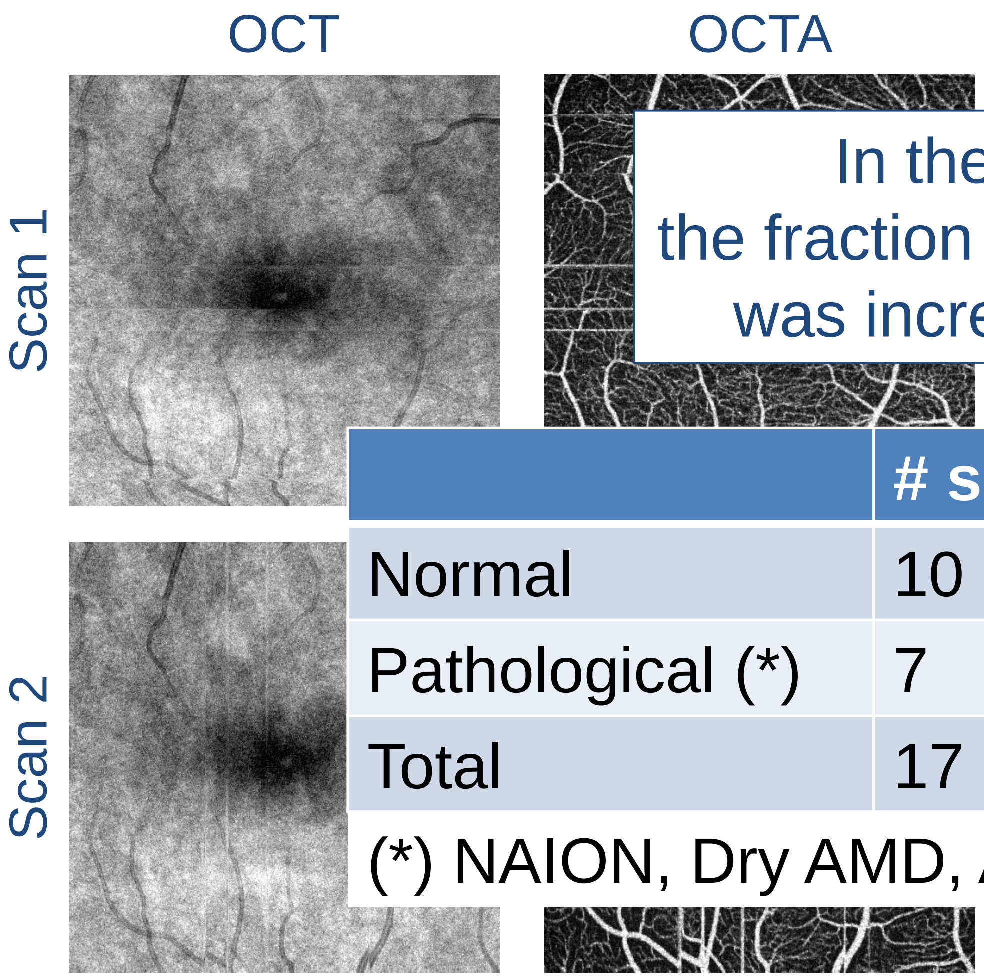


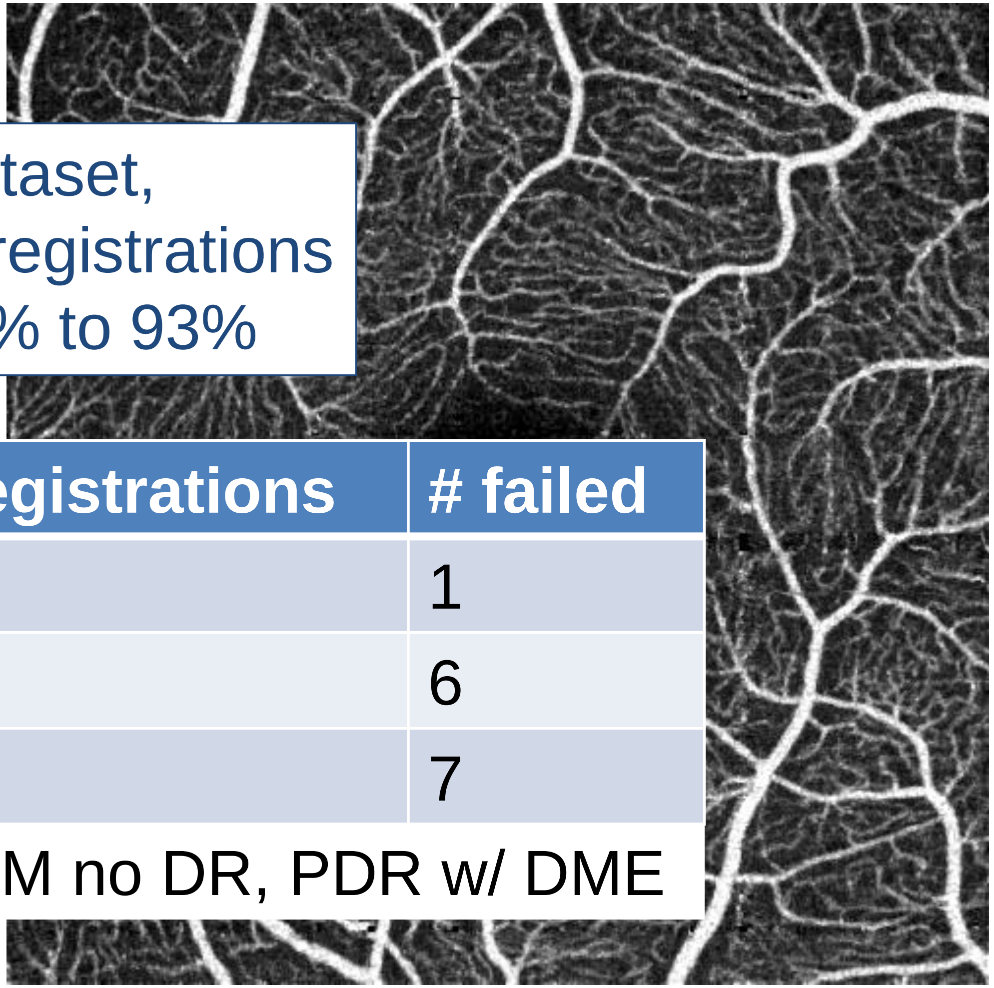
Qualitative Evaluation, with OCTA Data





Qualitative Evaluation, with OCTA Data





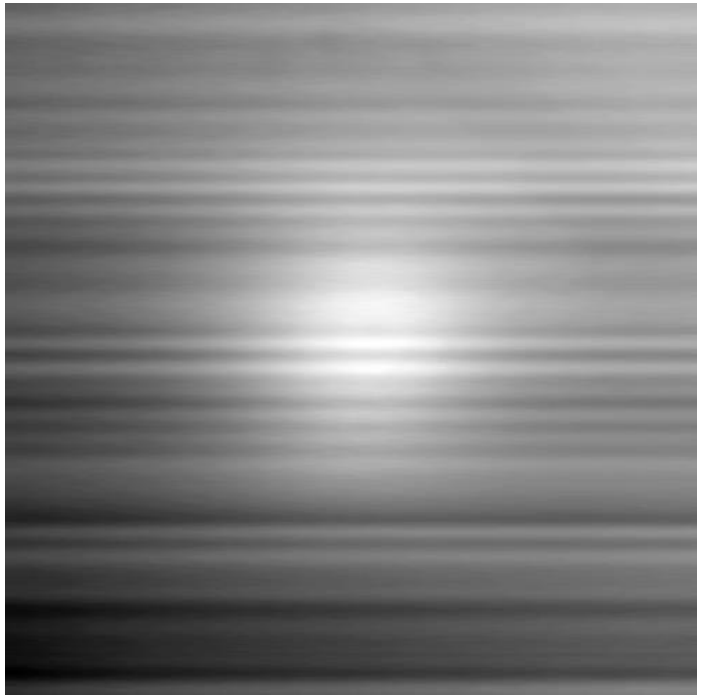
In the evaluation dataset,
the fraction of successful registrations
was increased from 75% to 93%

	# subjects	# registrations	# failed
Normal	10	60	1
Pathological (*)	7	42	6
Total	17	102	7

(*) NAION, Dry AMD, AMD w/ GA, DM no DR, PDR w/ DME

Quantitative Evaluation

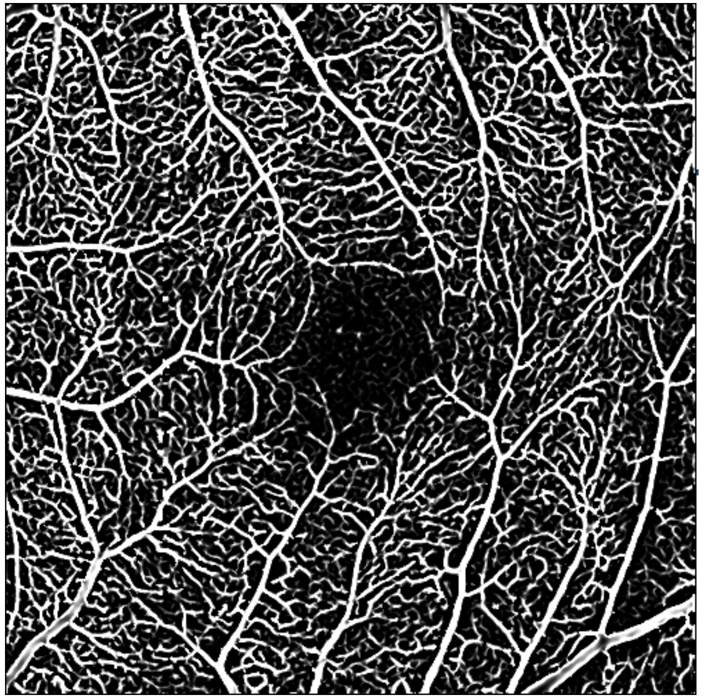
- Metrics related to clinically relevant features



Depth position of ILM

Vessel maps

Alignment Performance

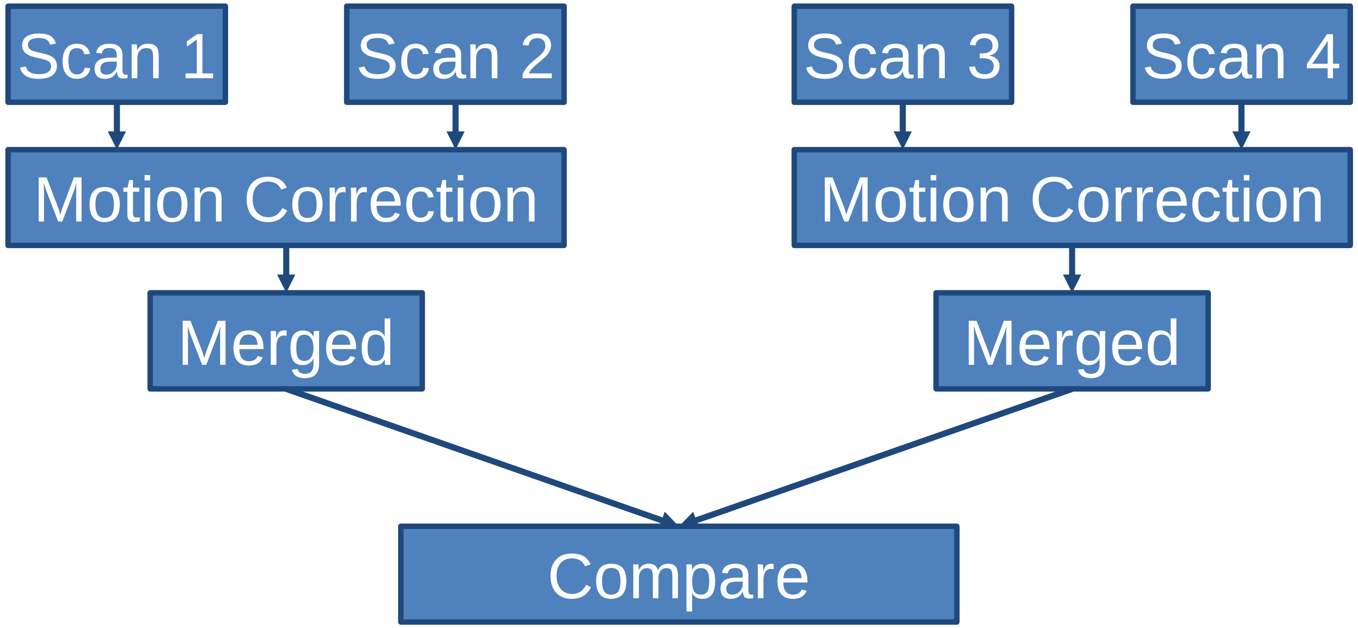


Map, scan 1 → Motion Correction

Map, scan 2 → Motion Correction

Compare

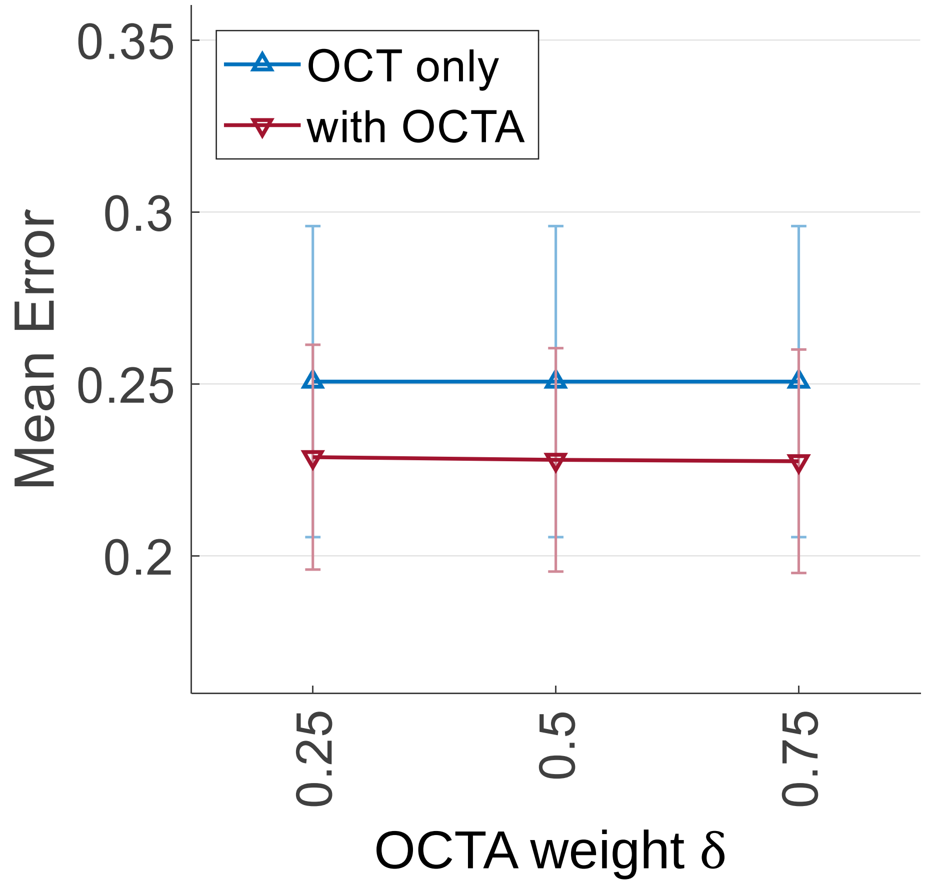
Motion Correction Performance



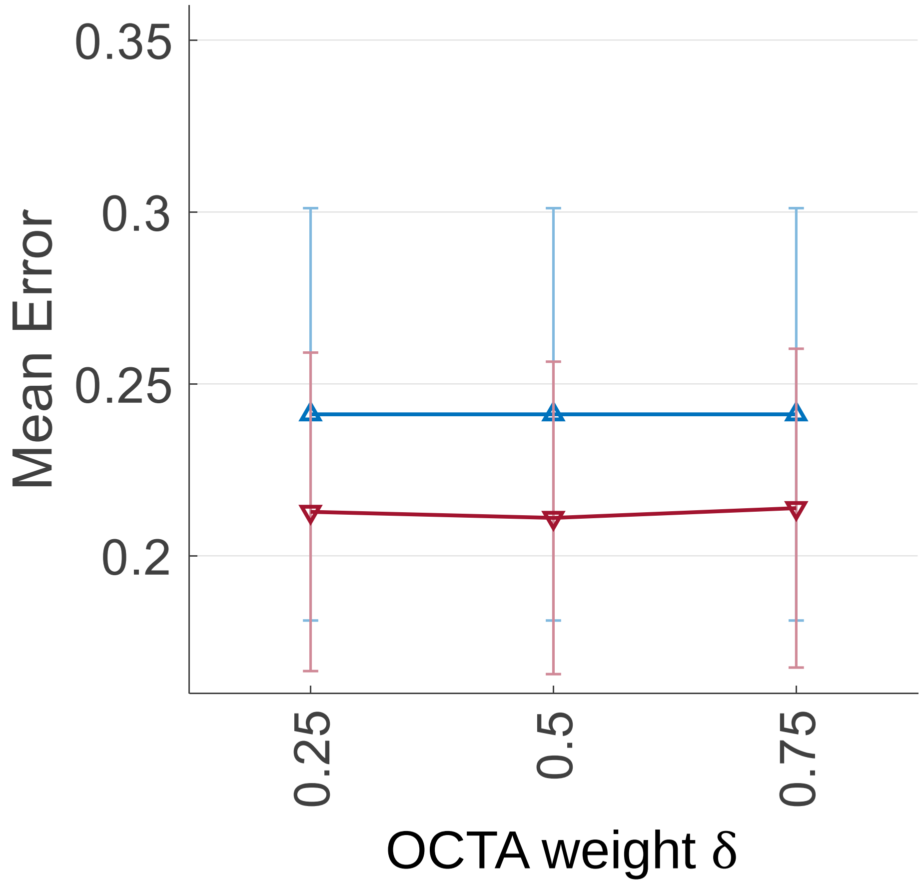
- Independent corrections
  - same eye, different motion
- Motion corrected volumes agree (they are *reproducible*)

Vessel Map Difference over OCTA Weight

Alignment performance

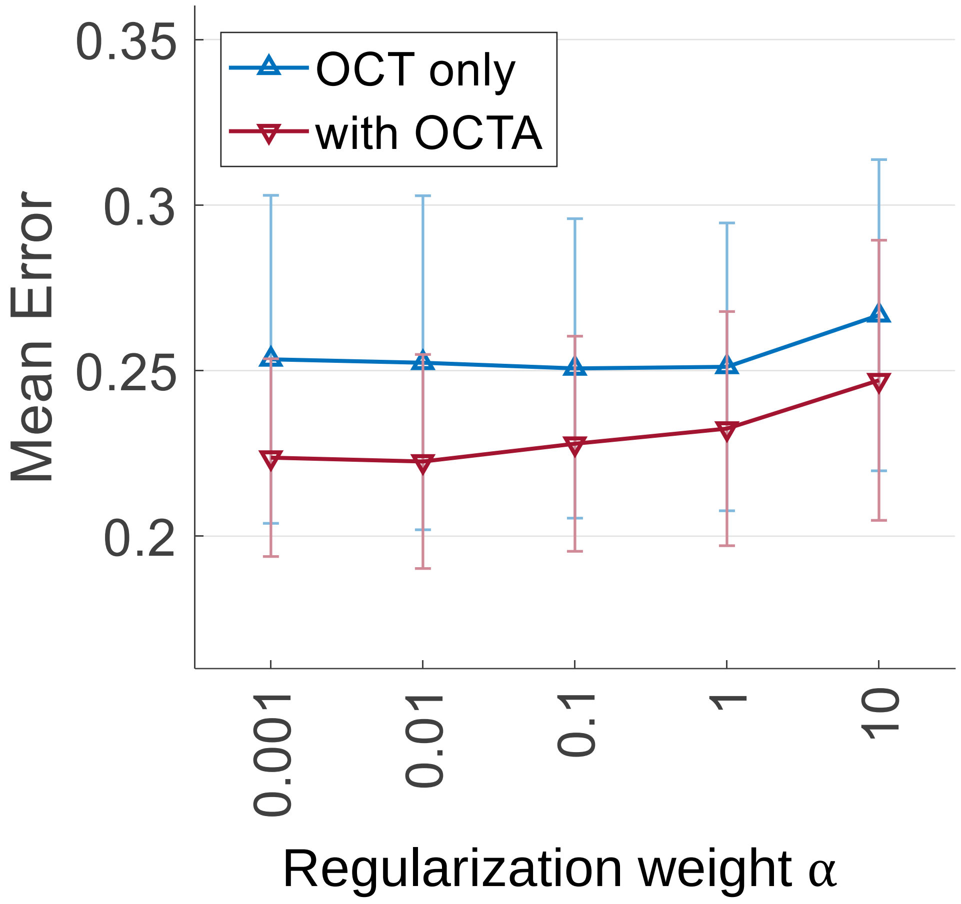


Motion correction performance

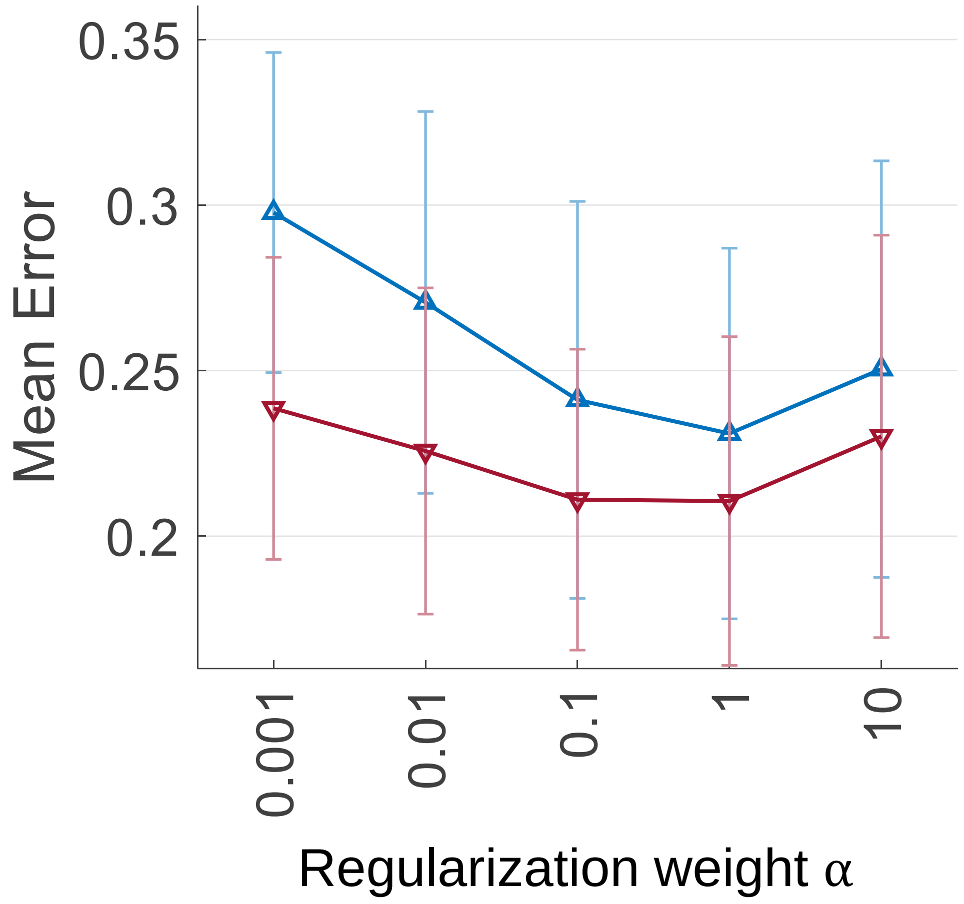


Vessel Map Difference over Regularization Weight

Alignment performance



Motion correction performance



Conclusions

- OCTA data can **improve**
  - **reliability** and
  - **accuracy** of motion correction.
- **En-face OCTA** is sufficient and can be **computed quickly.**
- **Motion correction evaluation** reveals that the **anisotropic nature** of OCT scanning **should be modeled.**

Collaborators

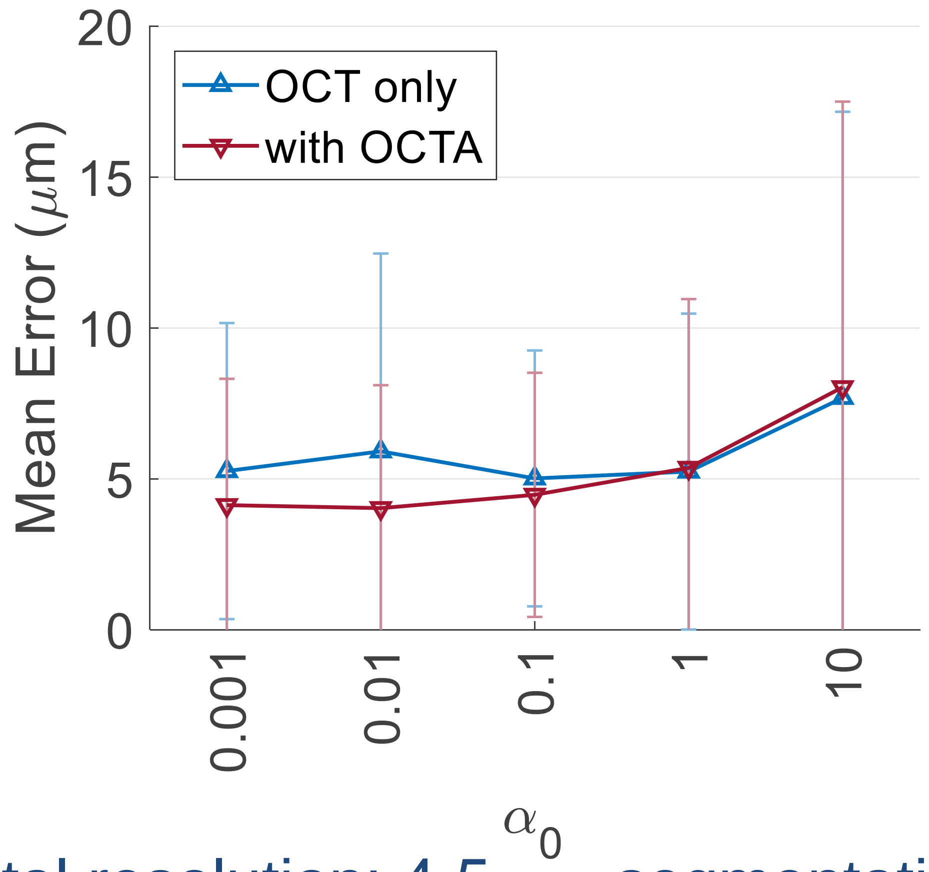
- Friedrich-Alexander-Universität
  - Joachim Hornegger
  - Lennart Husvogt
  - Martin Kraus
  - Andreas Maier
  - Julia Schottenhamml
- Massachussetts Institute of Technology
  - James Fujimoto
  - ByungKun Lee
  - Chen Lu
  - Eric Moult
  - Ben Potsaid
  - Patrick Yiu
- New England Eye Center
  - Yasin Alibhai
  - Caroline Baumal
  - Jay Duker
  - Eduardo Novais
  - Carl Rebhun
  - Nadia Waheed

Thank you for your attention.

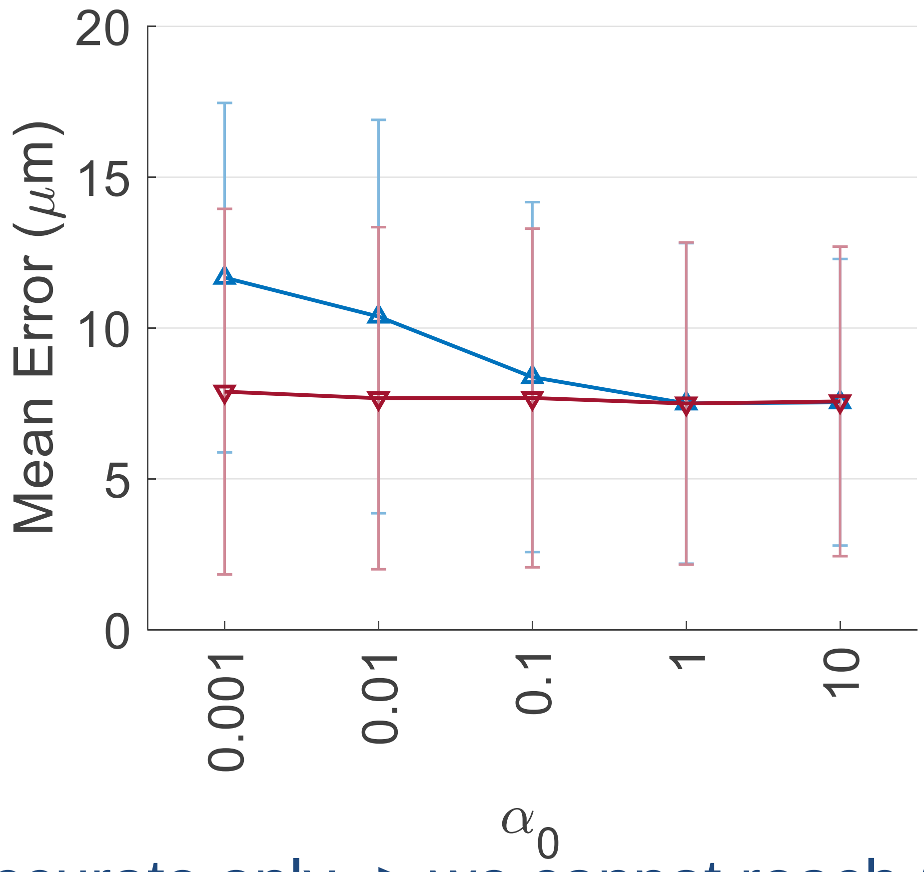
New England Eye Center

ILM depth over regularization weight

Registration Performance



Reproducibility Performance



Digital resolution: 4.5μm, segmentation pixel accurate only -> we cannot reach 0μm

Hardware vs. Software Motion Correction

Hardware

- Operates on lower frequency / lower resolution surrogate signal
- Drastically reduces gap size, small gaps may remain due to limited accuracy
- Single scan suffices

Software

- Operates on full OCT resolution
- Small gaps can remain if they were not scanned in any scan
- Delay due to computation time
- SNR improvement through averaging
- Device independent
- Can be applied & optimized retrospectively if all scans were stored

Combine both for best reliability & accuracy.

Comparison of scan patterns

Parallel scans

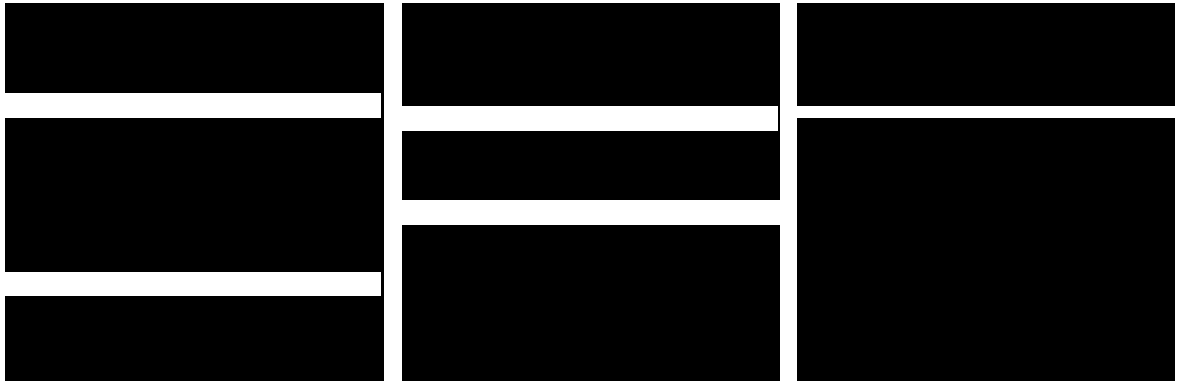
- No reference along slow scan axis, displacements can at best be averaged
- Trivial application to widefield scans
- Gap overlap unlikely
- If gaps remain, whole slices are missing, extent unknown

Orthogonal scans

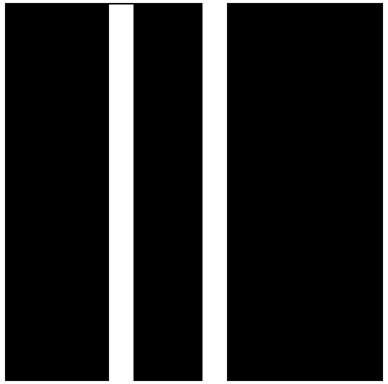
- Fast scans along both axes allow for accurate motion correction
- Non-trivial application to widefield scans
- When using two scans, gaps from different scans always have a known, small overlap

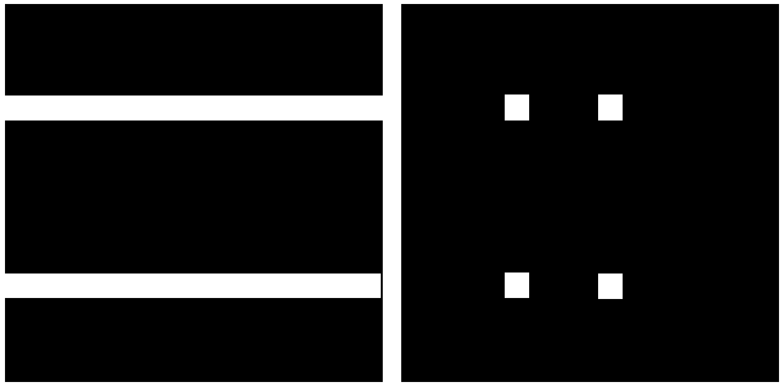
Comparison of remaining gaps

Parallel scans



Orthogonal scans





- Unknown extent in fast scan dir. due to missing reference
- A third scan combines the advantages