Recent Advances in Tissue Biomechanics Using Dynamic Optical Coherence Elastography

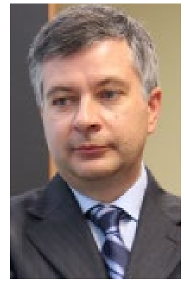
Presented by:

OSA Therapeutic Laser Applications Technical Group

Executive Committee

OSA Therapeutic Laser Applications Technical Group




Chair: Elina A. Vitol

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Committee Member: Yannis M. Paulus, Assistant Professor, University of Michigan

Committee Member: Guido Perrone, Associate Professor, Politecnico di Torino

Committee Member: Felix Fanjul-Velez, Associate Professor, University of Cantabria

Industry Liaison: Robbie Thomas, Photon Force, Ltd.

Social Media Liaison: Mariia Shutova, Texas A&M University

Where to find information about the group

OSA Therapeutic Laser Applications Technical Group

https://www.osa.org/en-us/get_involved/technical_groups/bmo/therapeutic

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Therapeutic Laser Applications (BA)

Get Involved

- Diversity & Inclusion
- Public Policy
- Chapters and Sections Map
- Technical Groups −
  - Bio-Medical Optics −
    - Microscopy and Optical Coherence Tomography (BM)
    - Molecular Probes and Nanobio-Optics (BP)
    - Optical Biosensors (BB)
    - Optical Trapping and Manipulation in Molecular and Cellular Biology (BT)
    - Therapeutic Laser Applications (BA)
    - Tissue Imaging and Spectroscopy (BS)
    - Photobiomodulation (BL)
  - Fabrication, Design & Instrumentation
  - Information Acquisition, Processing & Display

Therapeutic Laser Applications

This group focuses on the use of lasers in surgery or in other treatments of disease. This includes the use of lasers as surgical tools for tissue cutting, welding, and coagulation, as well as the use of optics to initiate cell-damaging photochemical reactions for the treatment of diseases such as cancer. In addition, optics, spectroscopy, and imaging provide unique tools that may allow real-time diagnostics of the efficacy of clinical procedures. For many of these applications, the development of optical tools for appropriate light delivery, especially for fiber-based or endoscopic delivery to tissues that are not directly accessible, is critical. In addition, this group emphasizes basic science studies of the mechanisms by which light can affect tissue in adverse or therapeutic ways.

Upcoming Technical Group Webinars

Photoacoustic Imaging of the Eye

Hosted By: Therapeutic Laser Applications Technical Group

24 October 2019, 10:00 AM - 11:00 AM

Register Now

Announcements

If you are a member of the Therapeutic Laser Applications Technical Group and have ideas for activities and initiatives to help engage this community, please share them with the chair, Elina Vitol.

View OSA Technical Group webinars on-demand at any time or register for any of our upcoming webinars online. Each webinar is an hour long and features a technical presentation on a topic selected by your OSA Technical Groups.

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in

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Work in Optics

We want you to join us!

- Select **Therapeutic Laser Applications** as one of 5 technical groups of interest at your OSA membership account page
- Attend our networking events, webinars and poster sessions
- Join us on LinkedIn and Facebook to keep in touch
- Look out for emails from the committee about group activities
- Interested in presenting your research? Have ideas for technical group events? Want to reach out to your fellow group members?
    - Contact us at elina.vitol@gmail.com or TGactivities@osa.org

Recent and upcoming webinars

Therapeutic Laser Applications Technical Group

24 October 2019

Photoacoustic imaging of the eye

Yannis M. Paulus, M.D., F.A.C.S., University of Michigan

Recording is available from OSA website

https://www.osa.org/en-us/get_involved/technical_groups/technical_group_webinars/#ondemand

21 January 2020, 11am EST*

Thermomechanical effect of infrared laser for cartilage regeneration

Registration will open in December

Yulia M. Alexandrovskaya, PhD

Institute of Photon Technologies, Federal Scientific Research Centre “Crystallography and Photonics” of the Russian Academy of Sciences (RAS)

Welcome to today's webinar!

OSA Therapeutic Laser Applications Technical Group

RECENT ADVANCES IN TISSUE BIOMECHANICS USING DYNAMIC OPTICAL COHERENCE ELASTOGRAPHY

Kirill V. Larin, Ph.D.
Professor, Department of Biomedical Engineering
University of Houston

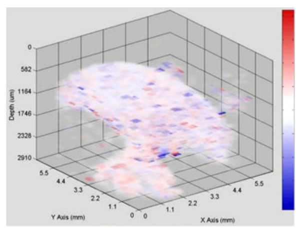
November 1, 2019

Recent Advances in Tissue Biomechanics Using Dynamic Optical Coherence Elastography

Kirill V. Larin

Professor
Fellow SPIE, Fellow OSA

University of Houston

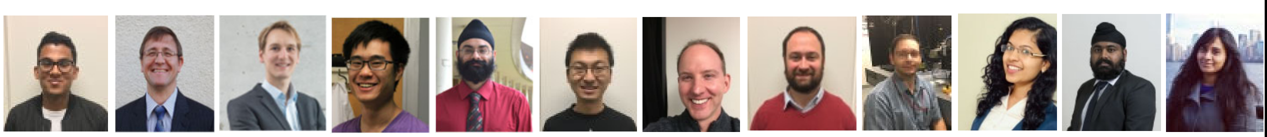


Biomedical Optics Laboratory

Major Projects in Biomedical Optics Lab

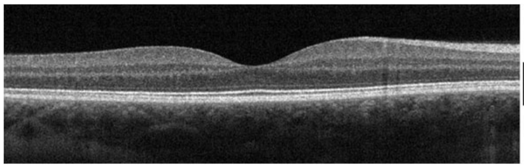
Optical
Elastography/Biomechanics

Developmental
Biology



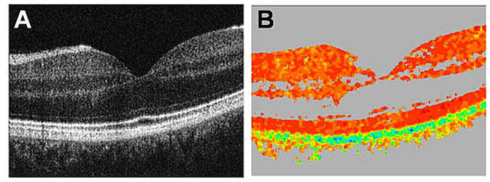
Major Breakthroughs in OCT
Functional and Contrast Enhanced Imaging

Morphological Imaging



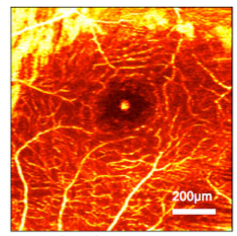
Introduced by Fujimoto et al in 1991

Polarization sensitive OCT



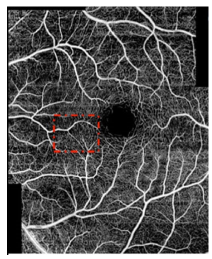
Hitzenberger, et al. *Optics Express*, 2001

Doppler OCT



Leitgeb, et al. *Optics Express*, 2003

OCT Angiography

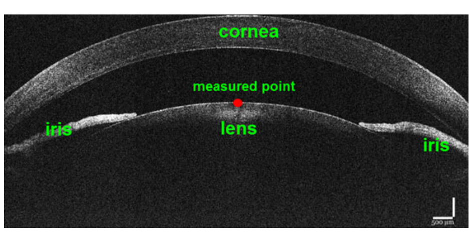


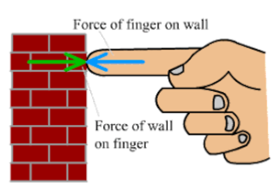
R. Wang Lab, UW

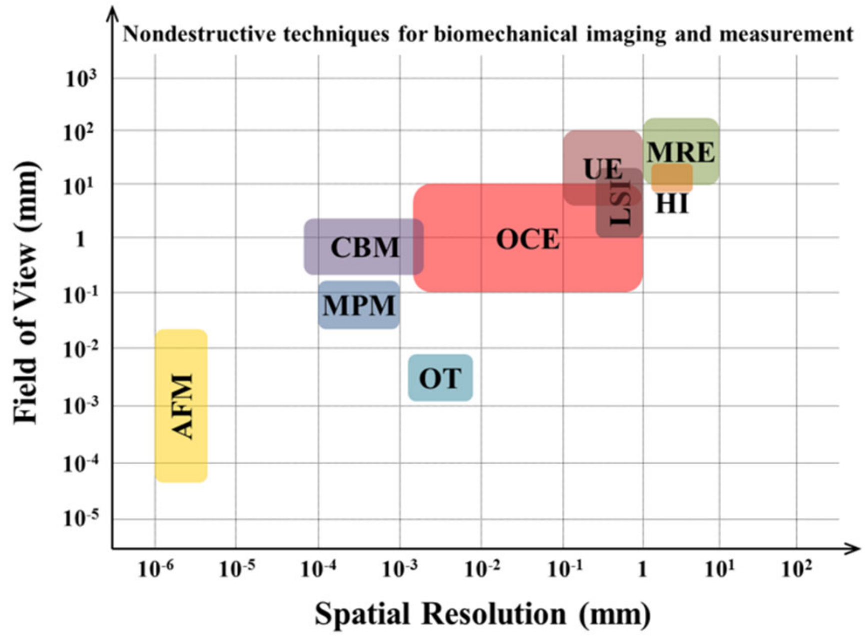
?

Optical Coherence Elastography:

OCT + Force







S. Wang and K. Larin, J of Biophotonics, (2015)

Optical Elastography and Tissue Biomechanics
Photonics West, 1 - 6 February 2020

Conference Chairs

- **Kirill V. Larin, Univ. of Houston (United States)**
- **Giuliano Scarcelli, Univ. of Maryland, College Park (United States)**

Program Committee

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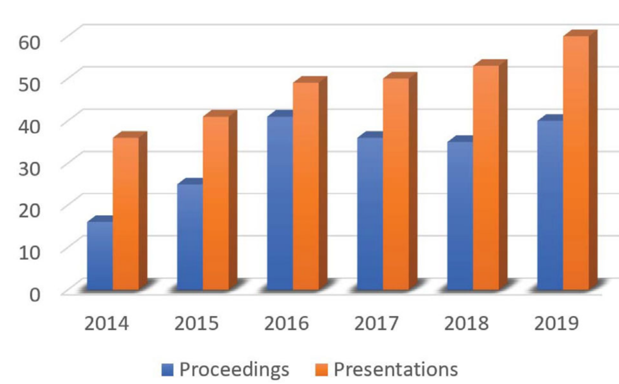
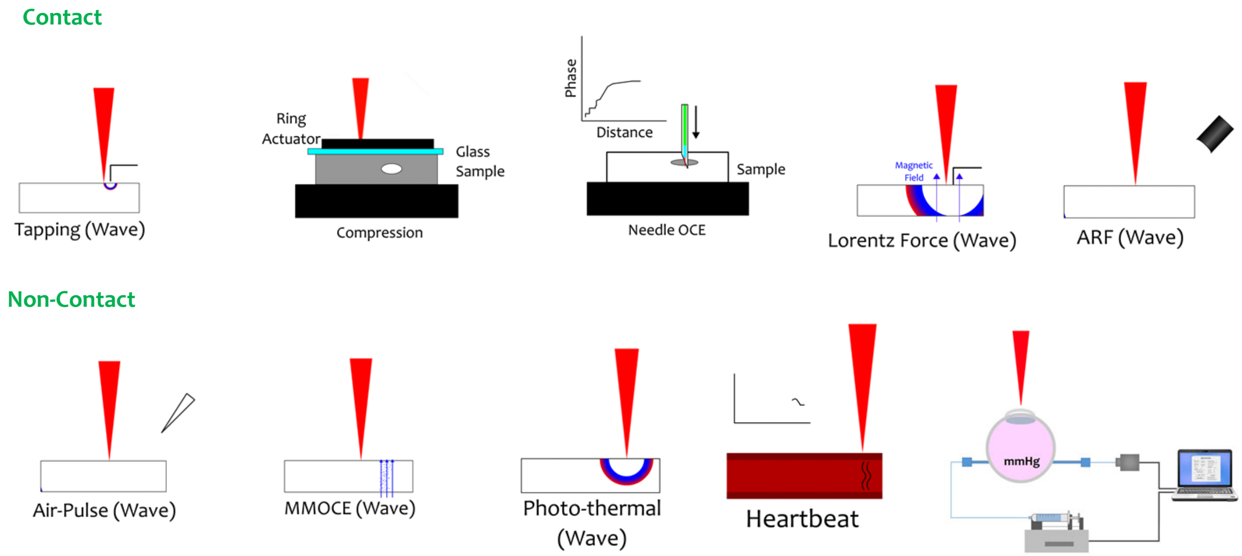


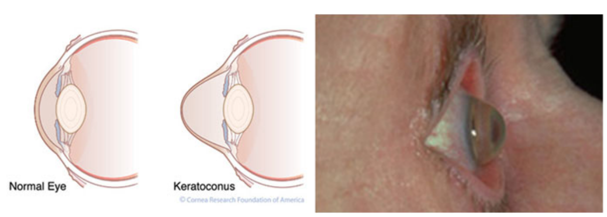
Excitation Methods in OCE



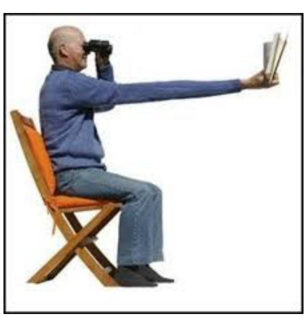
K. Larin and D. Sampson, Biomed Optics Express, 2017

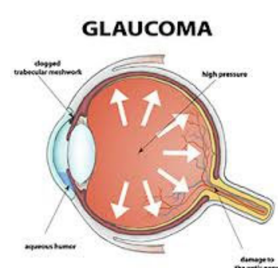
OCE in Ophthalmology

Keratoconus

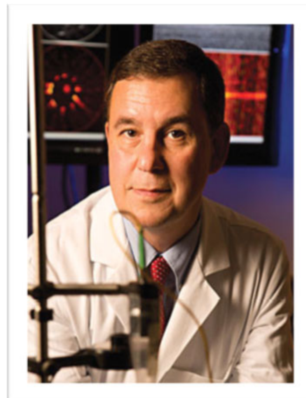


Presbyopia





Biomechanics of the Cornea

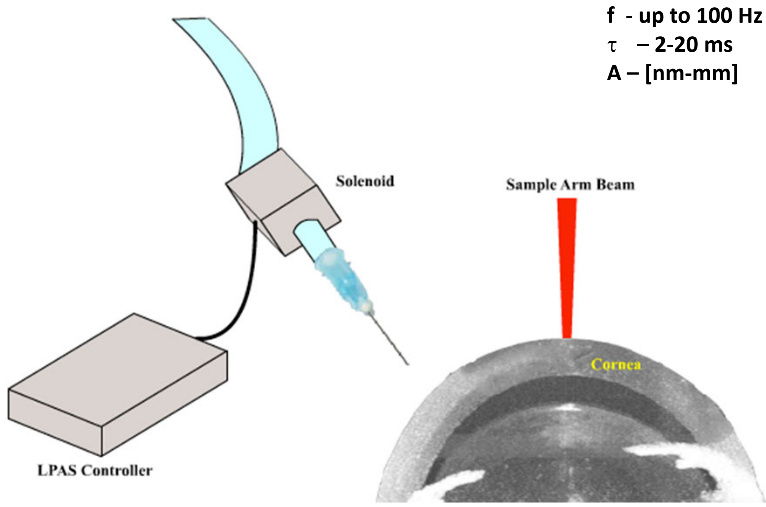


Michael Twa, Ph.D., O.D.
Professor, Dean of the College of Optometry,
University of Houston

Stanislav Emelianov, Ph.D.
Professor, Department of Biomedical Engineering,
Georgia Tech

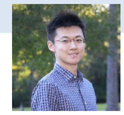
Excitation Method: Focused Air Puff

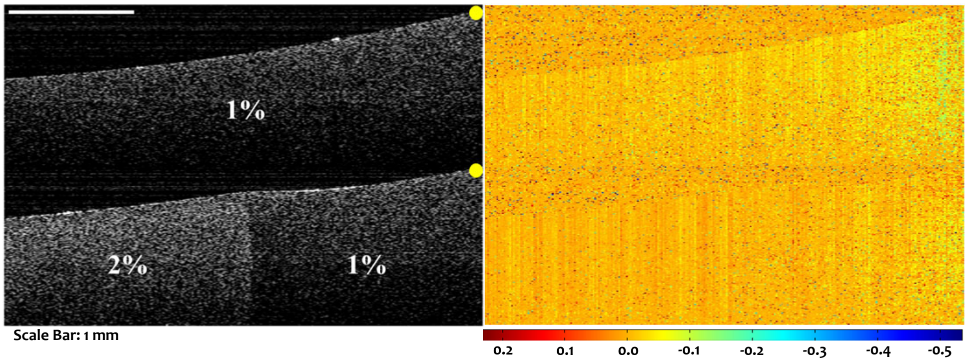
f - up to 100 Hz
τ – 2-20 ms
A – [nm-mm]



Wang et al: *Opt. Lett.*, 2012
Wang et al: *Laser Phys. Lett.*, 2013

Elastic Wave in Agar Phantoms

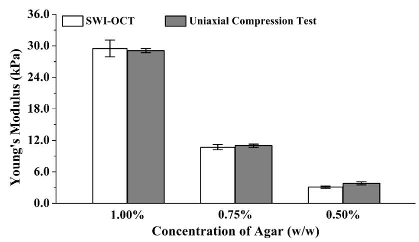




Scale Bar: 1 mm

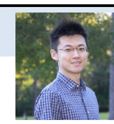
µm

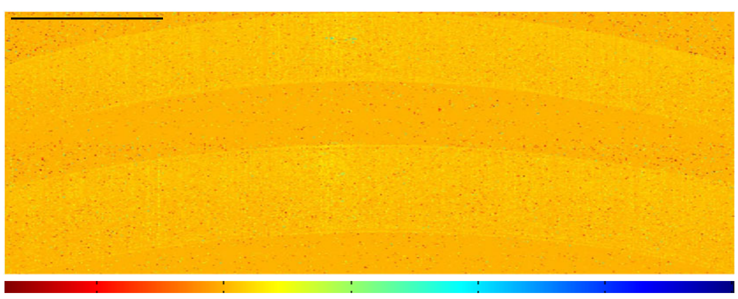
Actual Duration of Movie: 2.8 msec
Video Played at 2000X Slower



Wang et al: *Opt. Lett.*, 2012
Wang et al: *Laser Phys. Lett.*, 2013

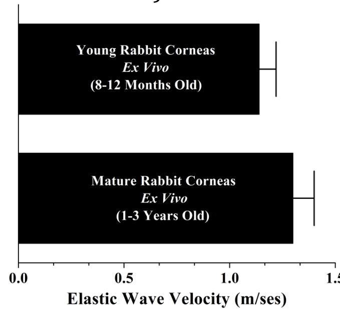
Imaging of Elastic Wave in Rabbit Corneas





µm

Scale Bar: 1 mm
Actual Duration of Movie: 6.2 msec
Video Played at 2000X Slower



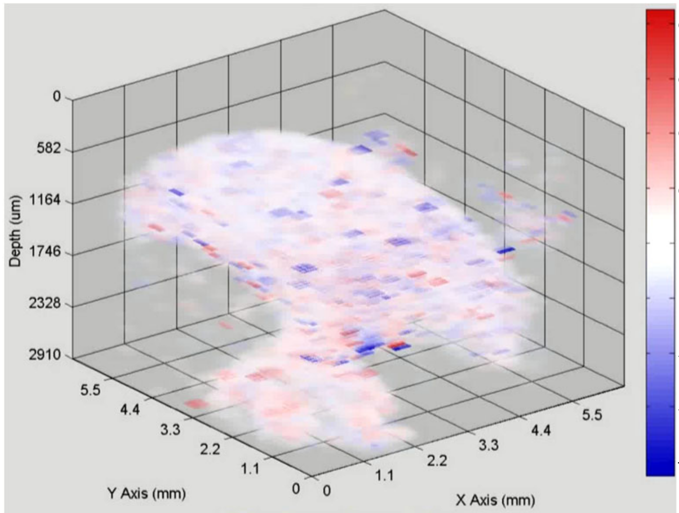
Group Velocity Quantification:

Young Rabbit Cornea: 1.14 $\pm$ 0.08 m/sec

Mature Rabbit Cornea: 1.30 $\pm$ 0.10 m/sec

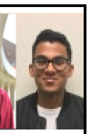
Wang et al: *Opt Lett*, 2014

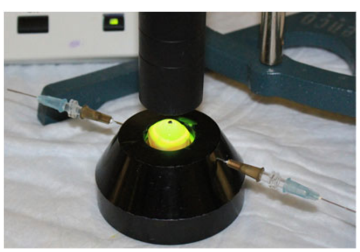
3D Elastic Wave Imaging

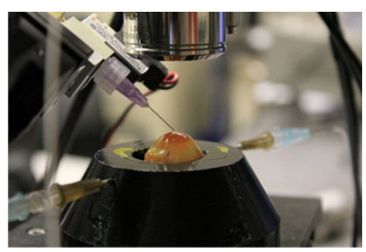


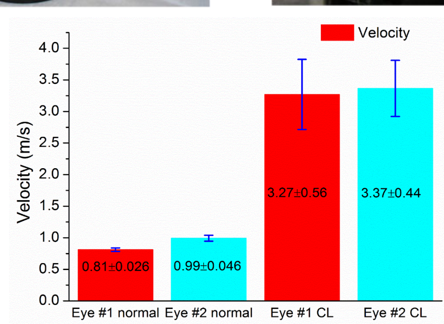
Singh et al: *IEEE JSTQE*, 2016

CXL



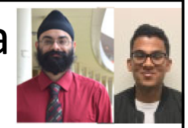




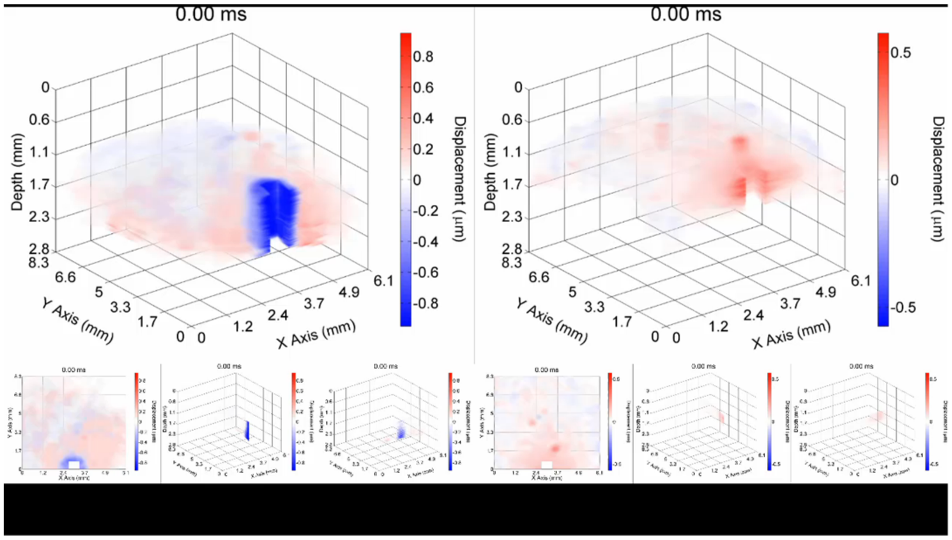


Vantipalli et al, *IOVS*, 2017

3D elastic wave propagation in cornea

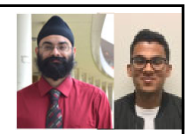


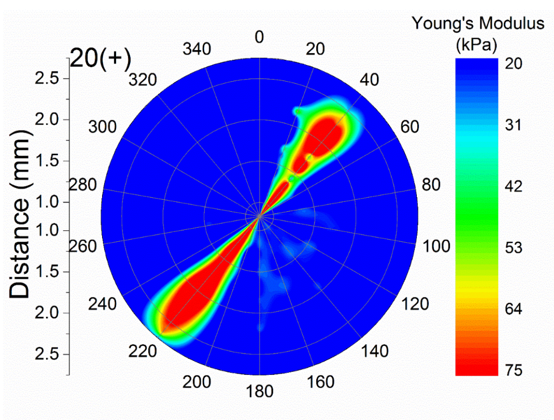
Untreated | CXL

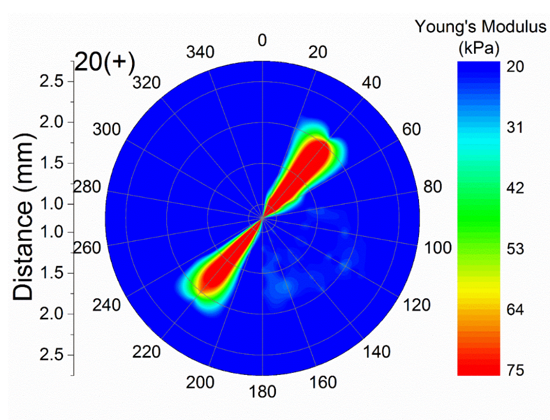


Singh et al: *IEEE JSTQE*, 22, 2016

Corneal Anisotropy

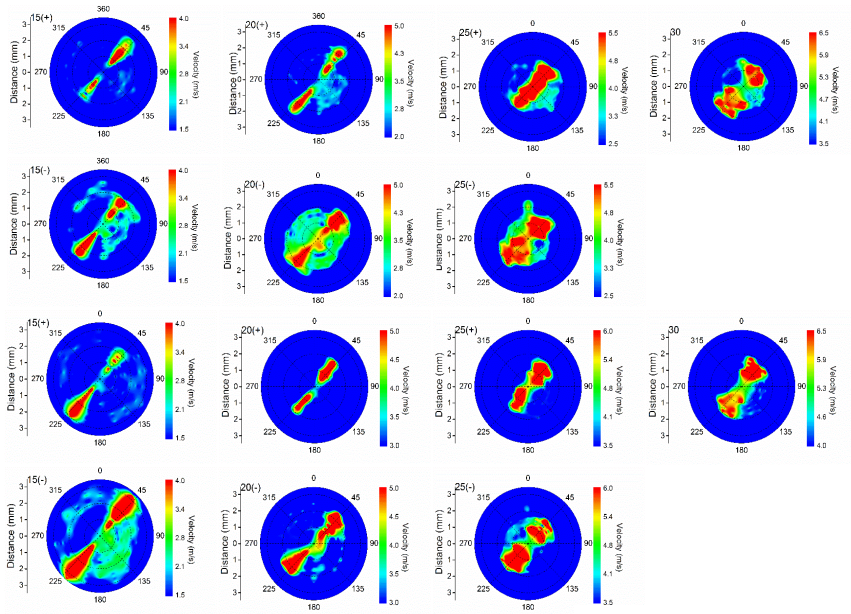






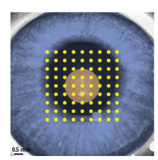
Singh et al: *J Refract Surg*, 2016
Singh et al: *Biomed Optics Exp*, 2017

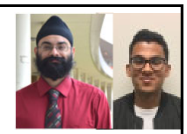
Corneal Anisotropy

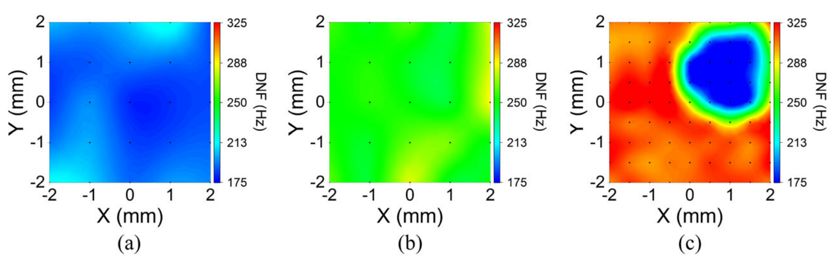


Singh et al: *J Refract Surg*, 2016
Singh et al: *Biomed Optics Exp*, 2017

Customized CLX



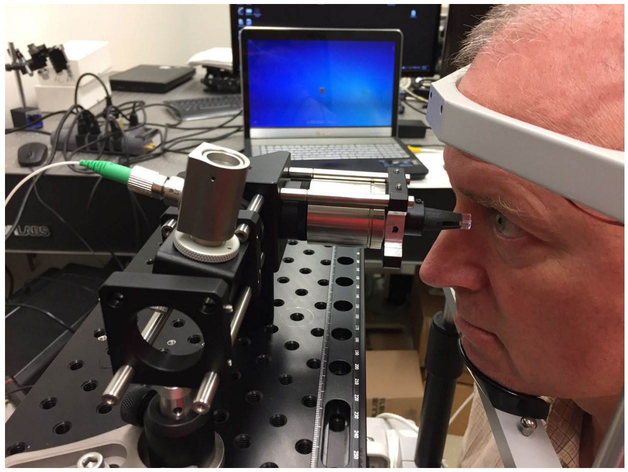




Next: corneal reshaping (*experimenting*)

Singh et al: *J Biomed Optics*, 2017

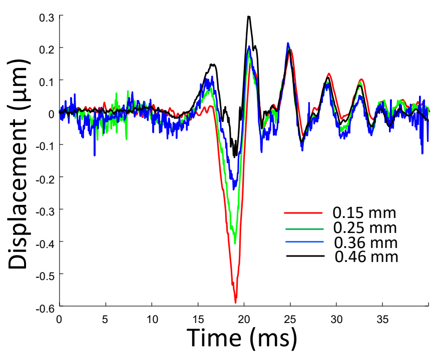
Pilot Human Studies

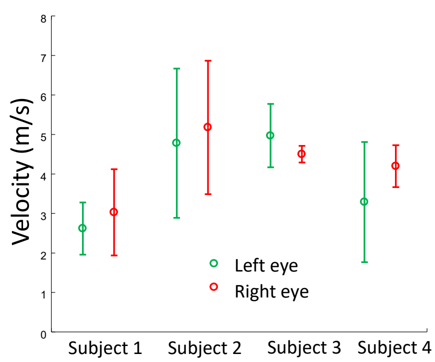


Twa et al, *IOVS, 2017*

Human Corneal OCE *in vivo*

n=11



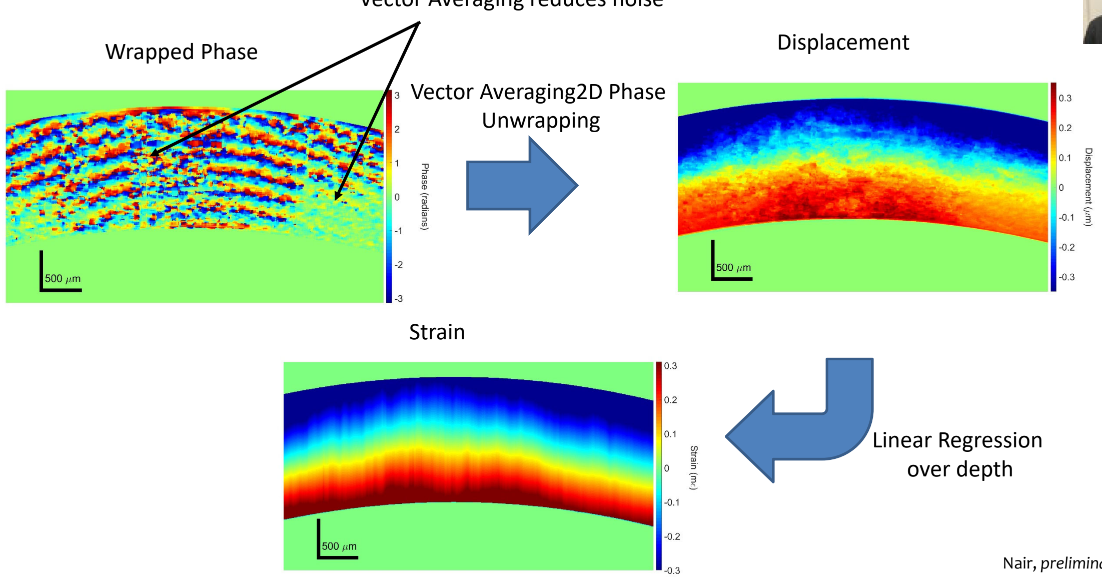


Twa et al, *presented at ARVO, 2019*

Can we assess corneal biomechanics without *any* external excitation?

Can we assess corneal biomechanics without *any* external excitation?

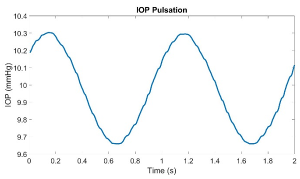
Heartbeat OCE

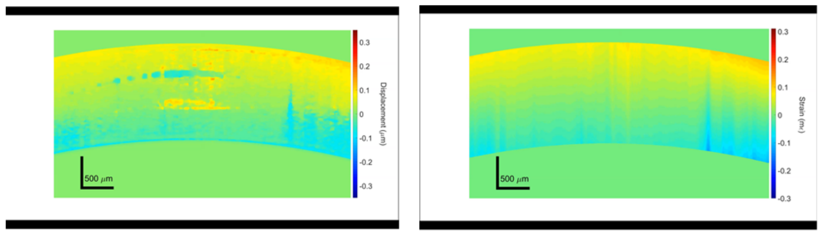


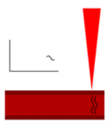
Nair, *preliminary data*

Can we assess corneal biomechanics without *any* external excitation?

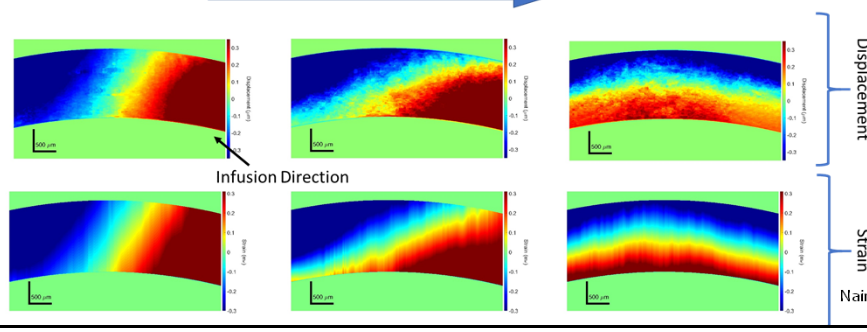
Heartbeat OCE







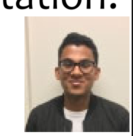
INFUSION → RELAXATION

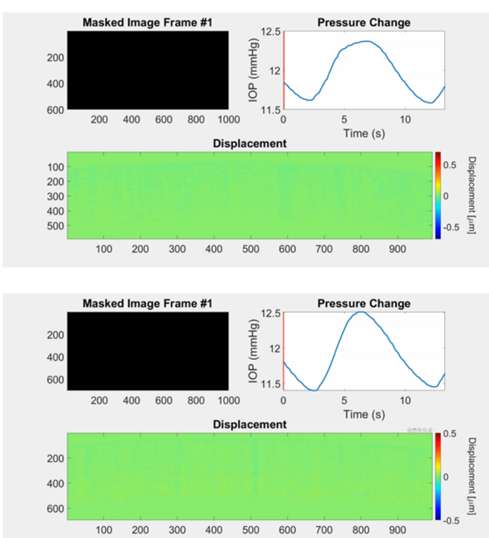


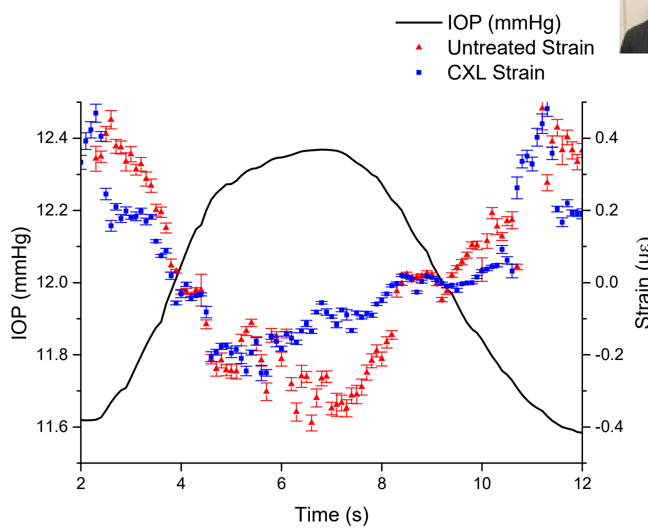
Nair, preliminary data

Can we assess corneal biomechanics without *any* external excitation?

Heartbeat OCE







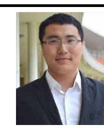
Nair, preliminary data

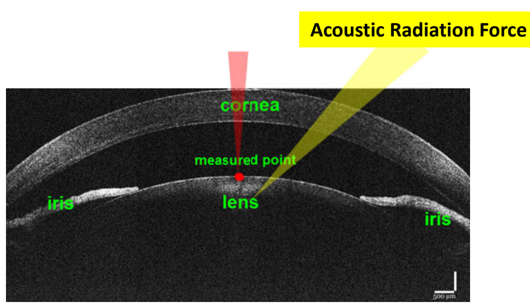
Biomechanics of the Lens

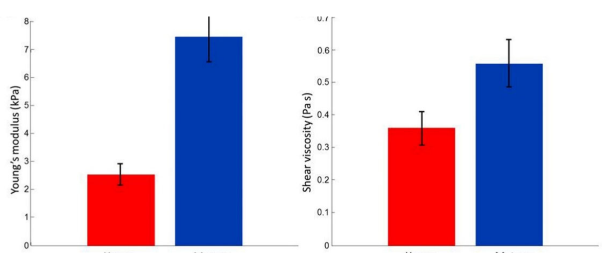
Giuliano Scarcelli, Ph.D.
Assistant Professor, Fischell Department of Bioengineering, University of Maryland

Fabrice Manns, Ph.D.
Professor, Department of Biomedical Engineering, University of Miami and Bascom Palmer Eye Institute

Crystalline Lens

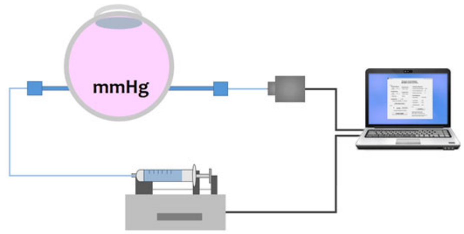


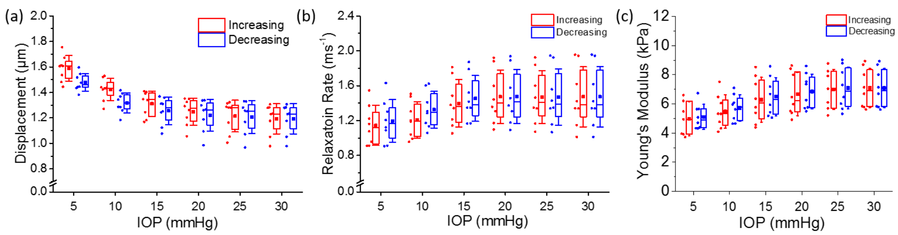




Wu, C., et. al. *Investigative ophthalmology & visual science*, 56(2), 2015

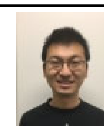
Crystalline Lens: function of IOP

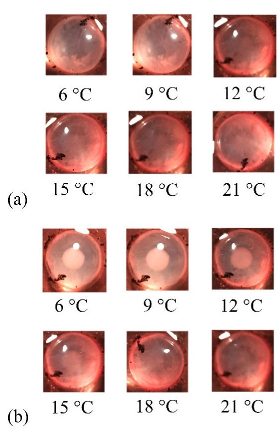


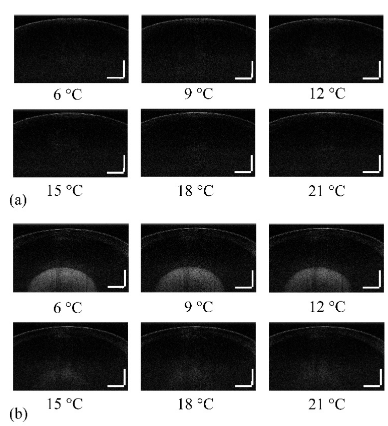


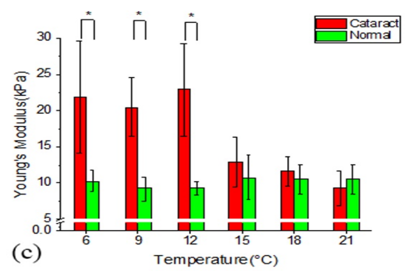
Wu, C., et. al. *Quantum Electron*, 2019

Crystalline Lens: function of cataract



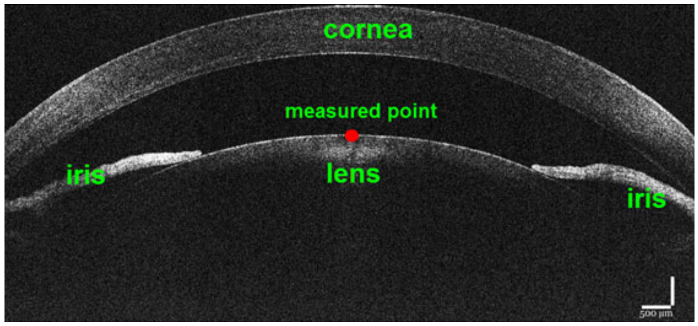




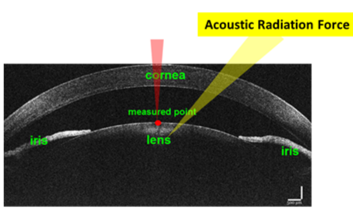


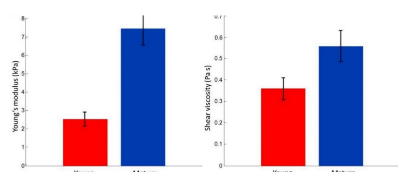
Zhang, H., et. al. *JBO*, 2019

Crystalline Lens: can we measure mechanical properties in 3D?



OCE:

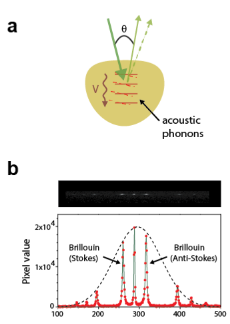


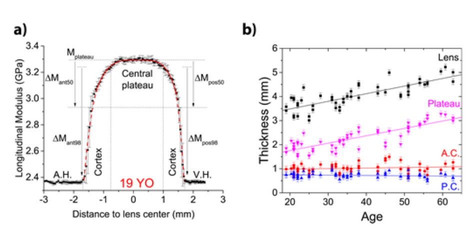


Wu, C., et. al. *Investigative ophthalmology & visual science*, 56(2), 2015

Pros: Quantitative
Cons: Lens surface only

Brillouin Spectroscopy:



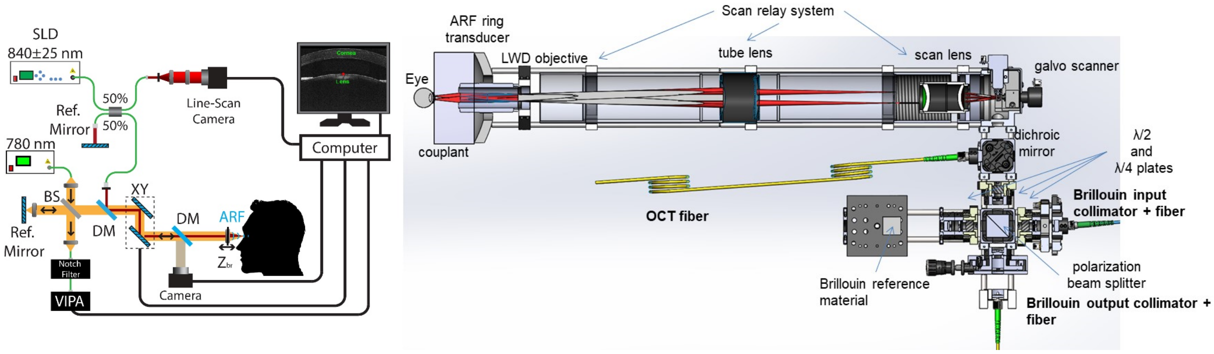


Scarcelli Lab, UMD

Pros: 3D ready
Cons: Qualitative

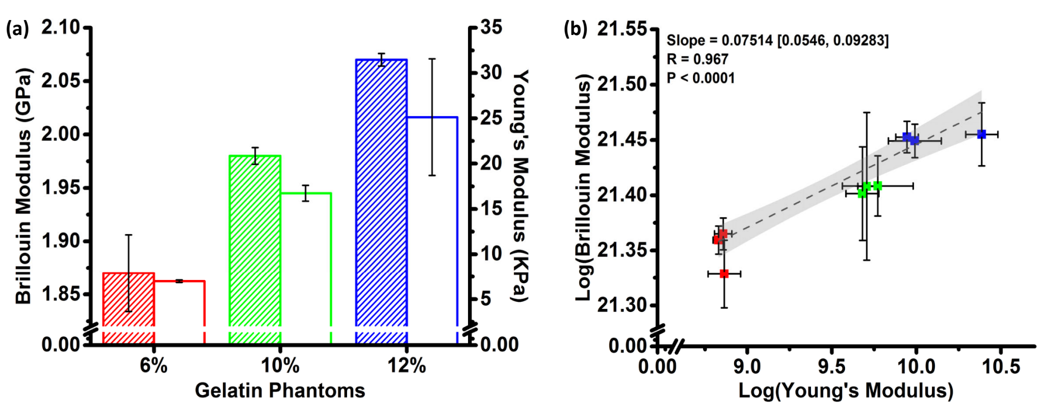
OCE + Brillouin Spectroscopy

For truly quantitative elastography of the Lens in 3D



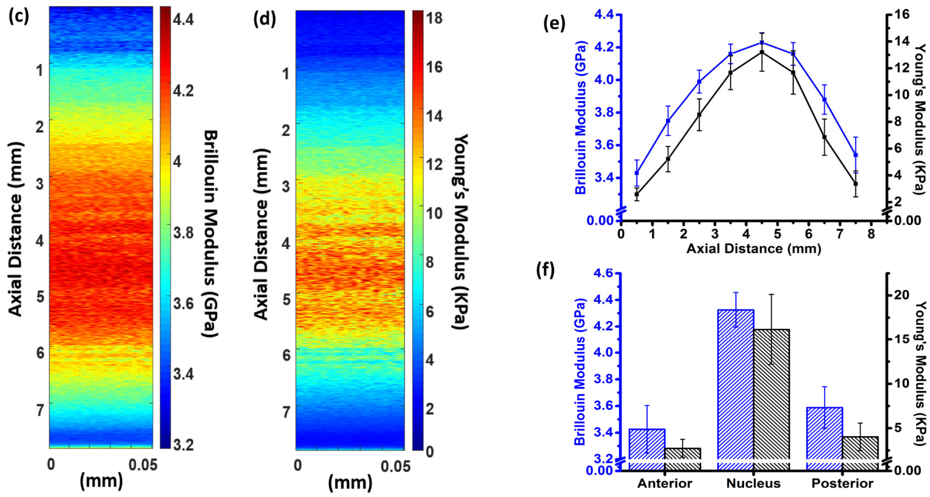
Can we ***quantify*** mechanical properties of the lens in 3D?

OCE + Brillouin Spectroscopy



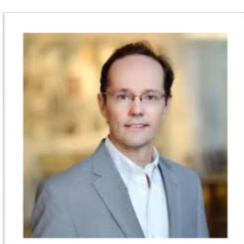
Ambekar et al (*in preparation*)

Can we ***quantify*** mechanical properties of the lens in 3D?
OCE + Brillouin Spectroscopy

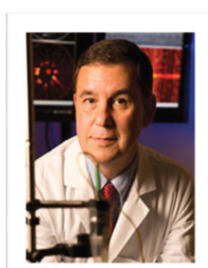


Ambekar et al (*in preparation*)

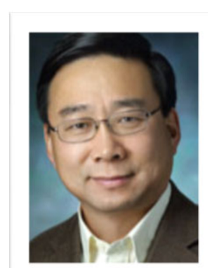
Biomechanics of the Cardiac Muscle



James Martin, M.D., Ph.D.
Professor, Department of Physiology and Biophysics,
Baylor College of Medicine

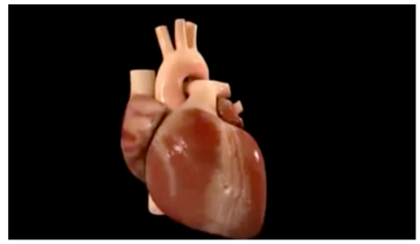


Stanislav Emelianov, Ph.D.
Professor, Department of Biomedical Engineering,
Georgia Tech



Xingde Li, Ph.D.
Professor, Department of Biomedical Engineering,
John Hopkins University

Mechanical Properties of Cardiac Muscle



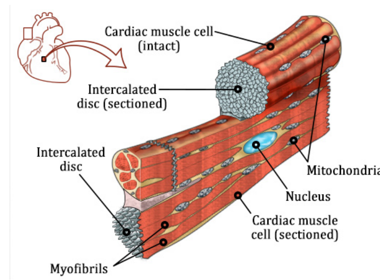
Myocardium and the beating of the heart

- Dynamic process: relaxation and contract;
- The elasticity of the cardiac muscle determines the normal function of the heart;
- Spatial heterogeneity: mechanical strength of the muscle fiber and between the muscle fiber.

Recovery of the heart after ischemic disease

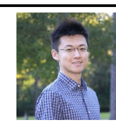
- Self-regeneration of cardiomyocytes.

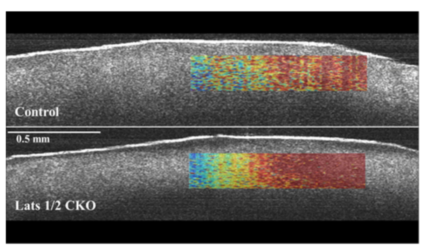
Stiffness of the cardiac muscle increases with age

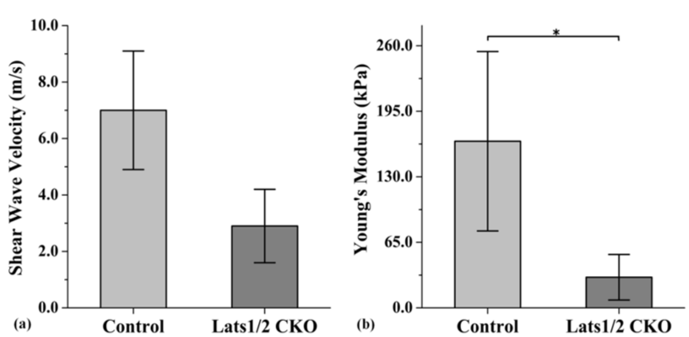


From Buzzle.com
http://www.buzzle.com/articles/cardiac-muscle-structure.html

Biomechanics of the Cardiac Muscle

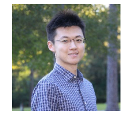


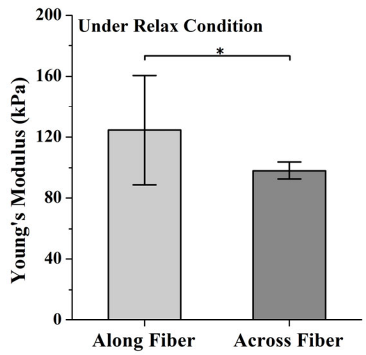


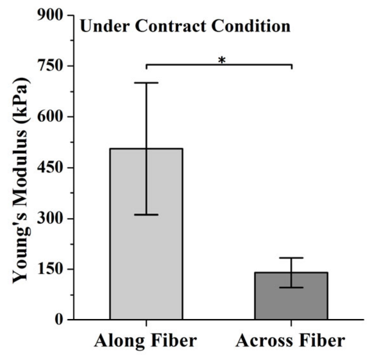


Wang et al: *Biomedical Optics Express*, 2014

Biomechanics of the Cardiac Muscle

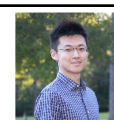


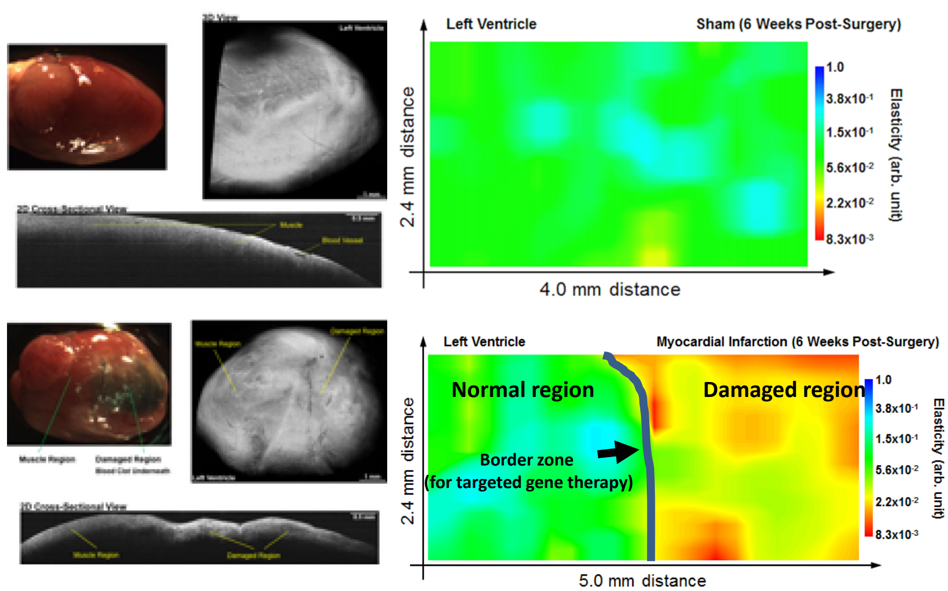




Wang, et al: *(unpublished)*

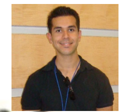
Biomechanics of the Cardiac Muscle during MI

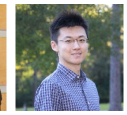


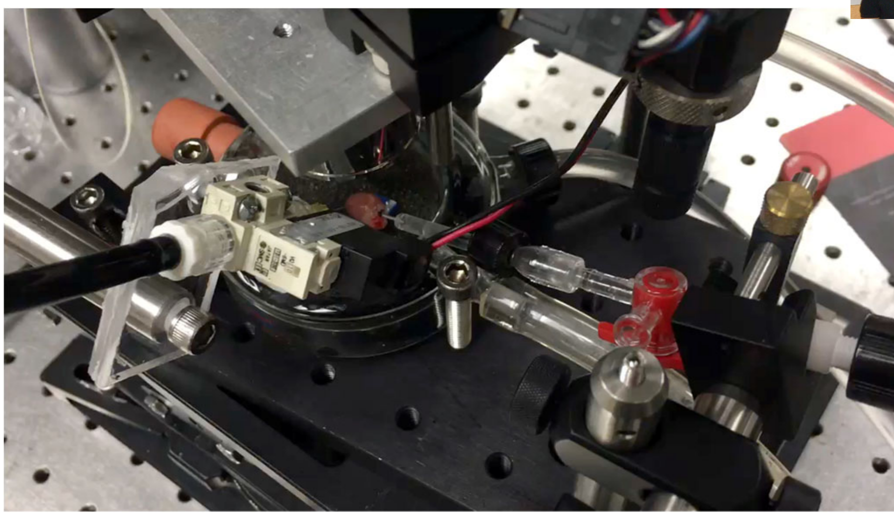


Wang, et al: *Biomed Opt Express, 2018*

Biomechanics of the Cardiac Muscle

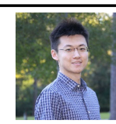


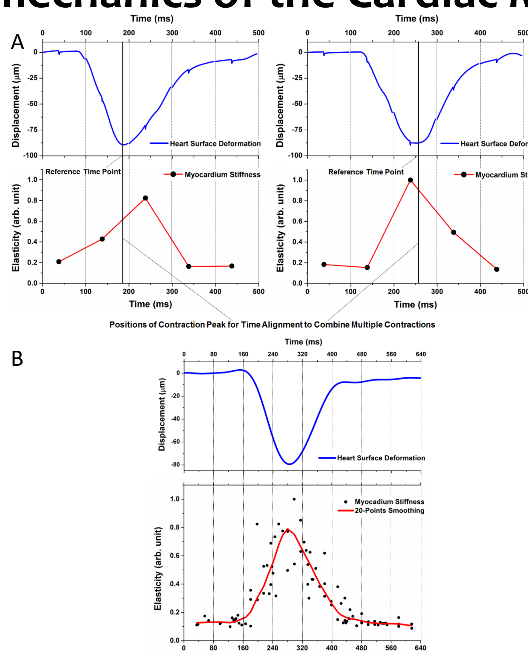




Lopez, Wang, et al, et al: *unpublished*

Biomechanics of the Cardiac Muscle



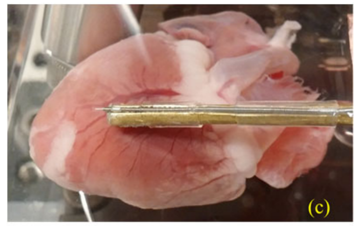


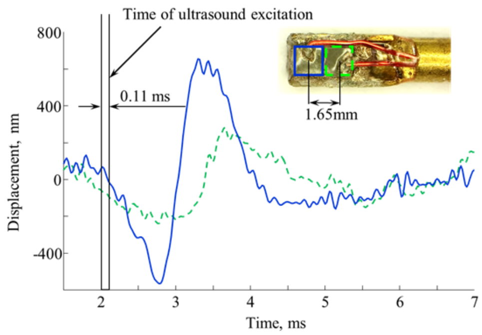
Wang, et al: *(unpublished)*

Biomechanics of the Cardiac Muscle: toward *in vivo*

(a)

(b)

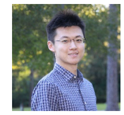




-> 37 kPa

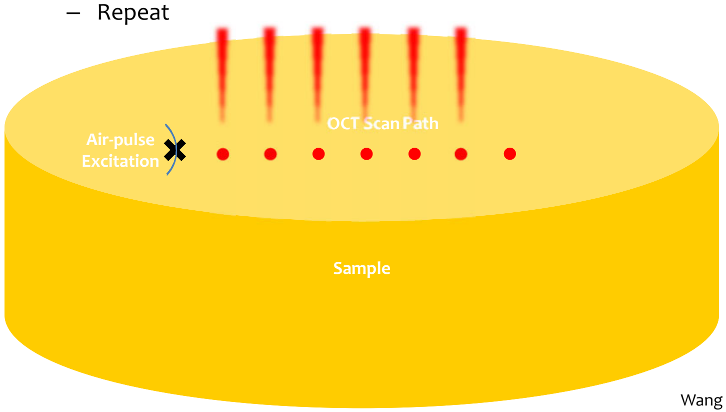
Karpiouk, et al: *J Biomed Optics, 2018*

Pushing limits of the technology

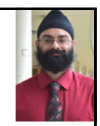


M-B mode OCE Imaging Methodology

- Synchronize successive M-mode images with focused air-pulse [1]
  - Excite, acquire M-mode image
  - Move to next position
  - Excite, acquire M-mode image
  - Repeat

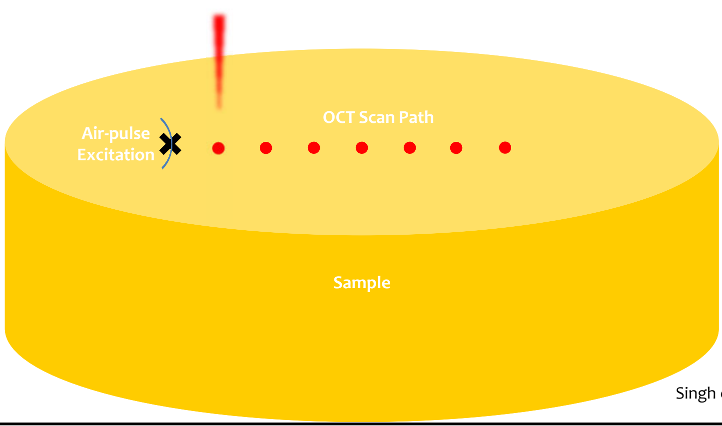


Wang et al: *Optics Lett*, 2014



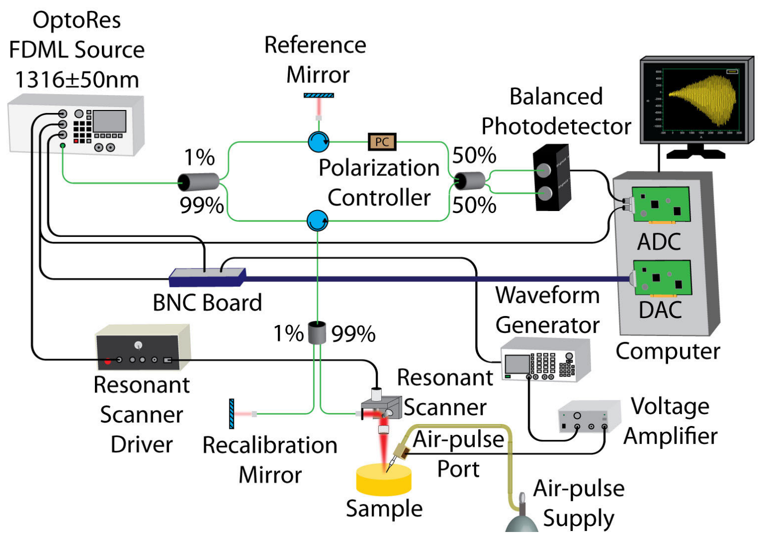
B-M mode OCE Imaging Methodology

- Fast B-mode imaging ***during*** wave propagation



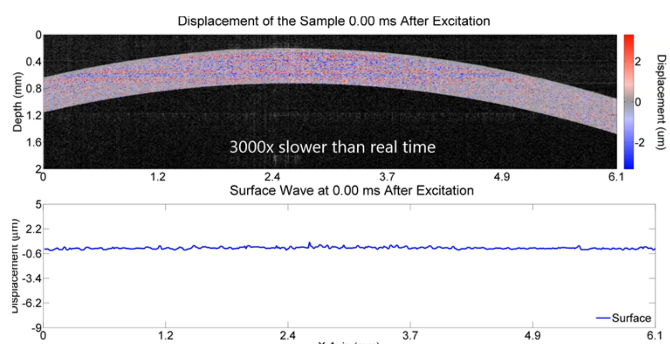
Singh et al: *Optics Lett*, 2015

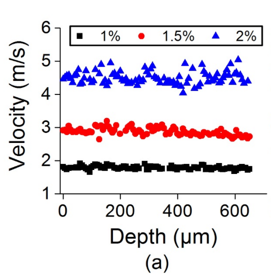
Real-Time OCE: 1.5 MHz A-scan rate SSOCT

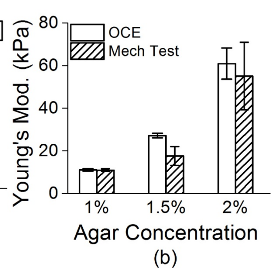


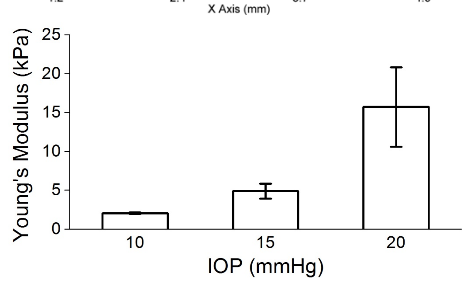
Singh et al: *Optics Lett*, 2015

Real-Time OCE: 1.5 MHz A-scan rate SSOCT





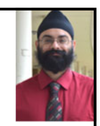


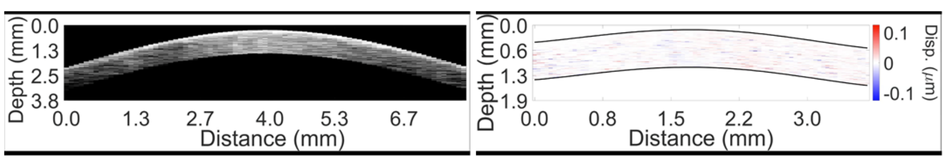


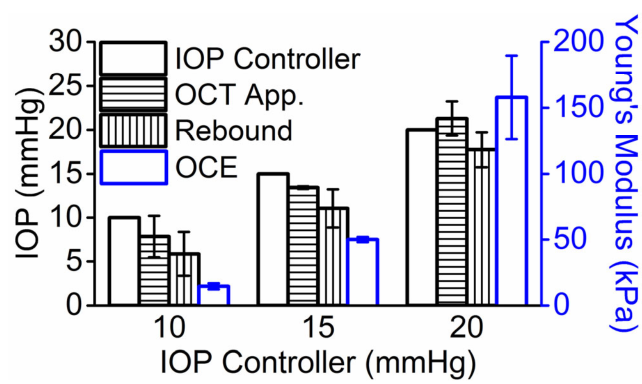
Singh et al: *Optics Lett*, 2015

Can we measure **IOP** and **corneal stiffness** using **ONE** instrument?

Intraocular Pressure and Cornea stiffness in ONE instrument
Applanation-OCE



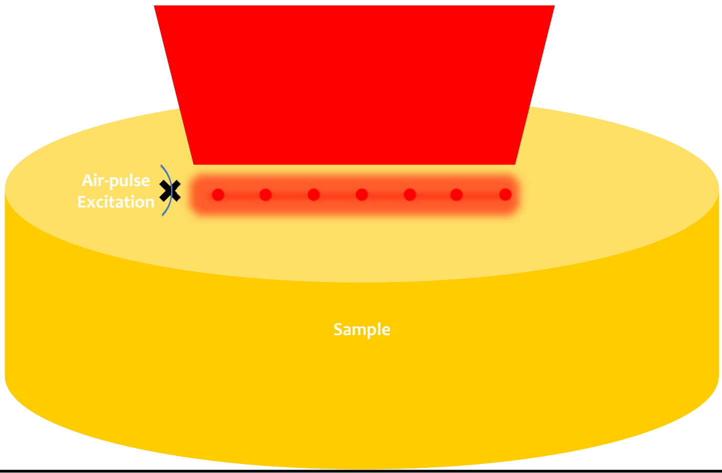




Singh et al: *J Biomed Opt*, 2017

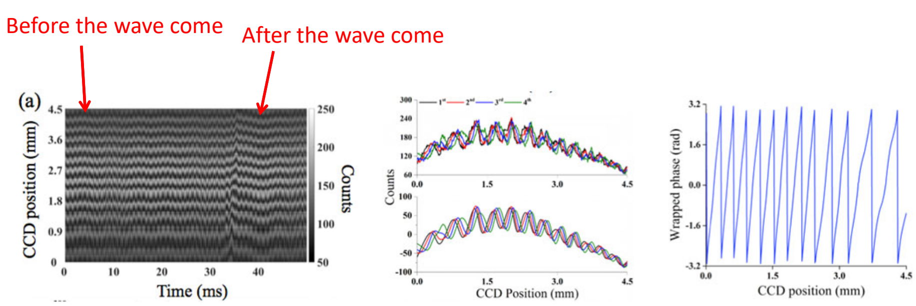
Line-Field OCE Imaging Methodology

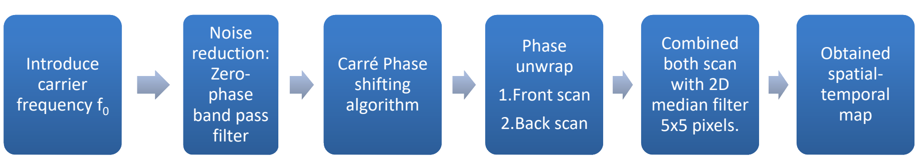
- Line imaging ***during*** wave propagation



Liu et al: *Biomed. Opt. Express*, 2017
Liu et al: *Biomed. Opt. Express*, 2016

Line-field OCT methodology



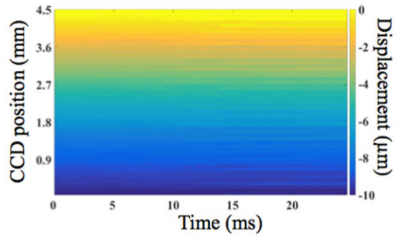


Equivalent to **72 MHz** acquisition rate – fastest demonstrated speed in elastography

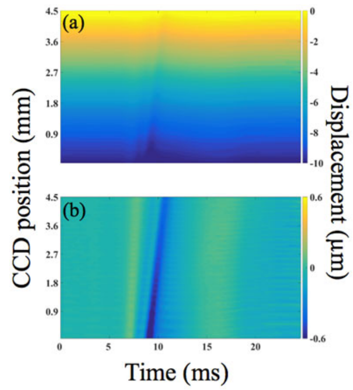
Liu et al: *Biomed. Opt. Express*, 7(8), 2016

Spatial-Temporal map of an agar phantom

Before the elastic wave



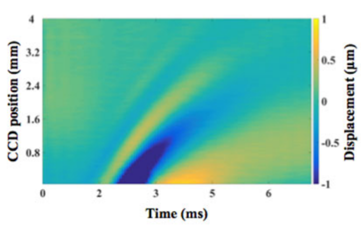
Capture of the elastic wave

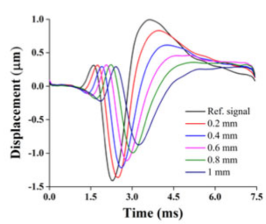


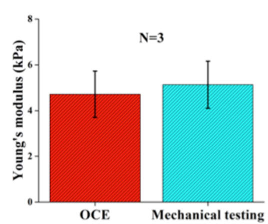
Liu et al: *Biomed. Opt. Express*, 7(8), 2016

Line-Field OCE

Captured elastic wave propagation in chicken breast (N=3)

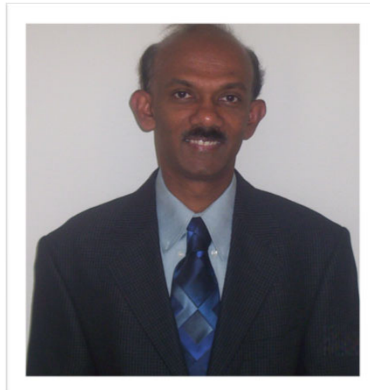






Liu et al: *Biomed. Opt. Express*, 7(8), 2016

The first clinical studies: Systemic Sclerosis



Shervin Assassi, M.D., M.S.
Associate Professor,
Rheumatology And Clinical
Immunogenetics,
UT Health

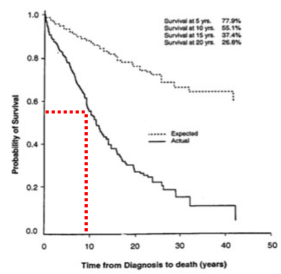
Chandra Mohan, M.D., Ph.D.
Professor, Department of
Biomedical Engineering,
University of Houston

Systemic Sclerosis

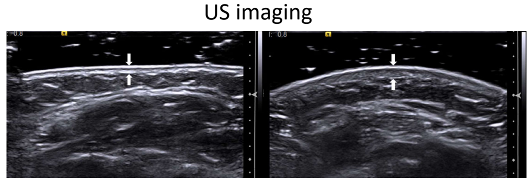
Systemic sclerosis (SSc) is a systemic connective tissue disease. Characteristics of systemic sclerosis include essential vasomotor disturbances; fibrosis; subsequent atrophy of the skin, subcutaneous tissue, muscles, and internal organs (eg, alimentary tract, lungs, heart, kidney, CNS); and immunologic disturbances accompany these findings.

Traditional systemic sclerosis examination

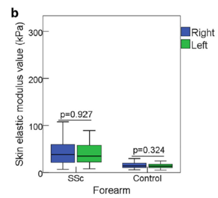
- 10-year survival rate: 58%
- Disease feature of SSc: Skin thickening
- Modified Rodnan score system (mRSS)
  - Limited sensitivity to subtle changes of the skin
  - Inter- and intra- observer variability (ICC:~0.76)
- Ultrasound imaging (US)
  - Dermal thickness detection
  - Acoustic radiation force impulse (ARFI)
    - Elastography assessment (Shear wave)
  - But, insufficient resolution for Imaging
    - Epidermal and dermal structures
      - especially dermal-epidermal junction.



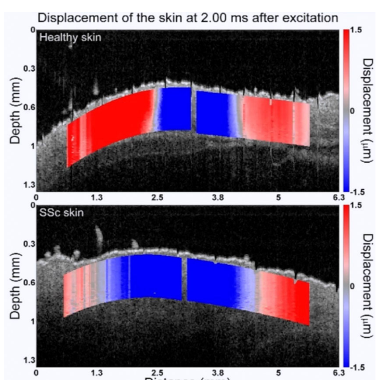
US imaging



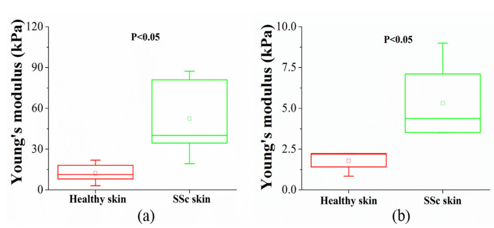
ARFI



Systemic Sclerosis – mice study



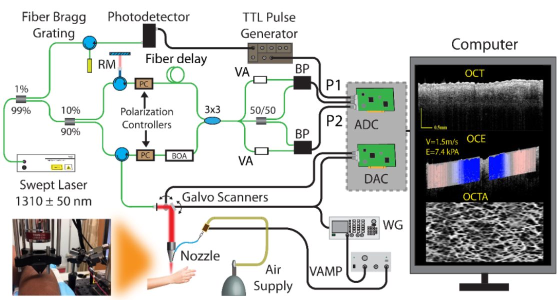
Elastic wave propagation in skin, as assessed by OCE in a typical healthy (top) and SSc (bottom) skin sample, measured at 2 ms after excitation in vivo

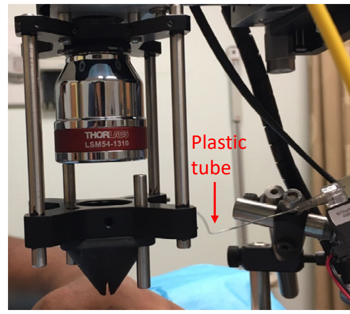


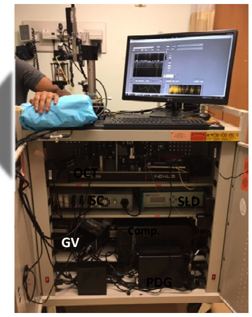
In vivo and in vitro OCE-assessment of skin involvement in the peripheral regions of SSc-affected skin. Plotted are the Young's modulus recorded in healthy skin and BLM-SSc afflicted skin at the periphery of the diseased region, from (a) in vitro and (b) in vivo OCE measurements (N = 4-9 mice per study group).

Du et al: *JBO*, 2016

Clinical OCE detection for SSc patients



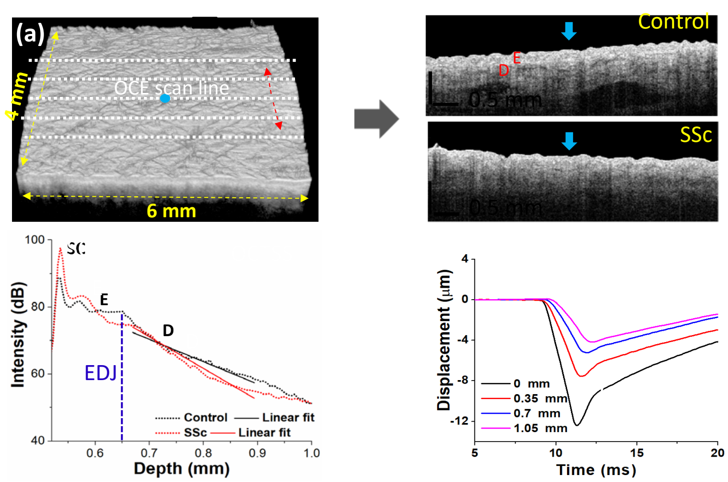




- Spectral domain OCT: 1310 ± 45 nm
- Line rate:70k Hz
- Pixel resolution: 8 um in air
- Acquisition time: 3D OCT scan + 5 OCE scan
  - 15 min with 5 min break
- Site specific mRSS
- Skin biopsy

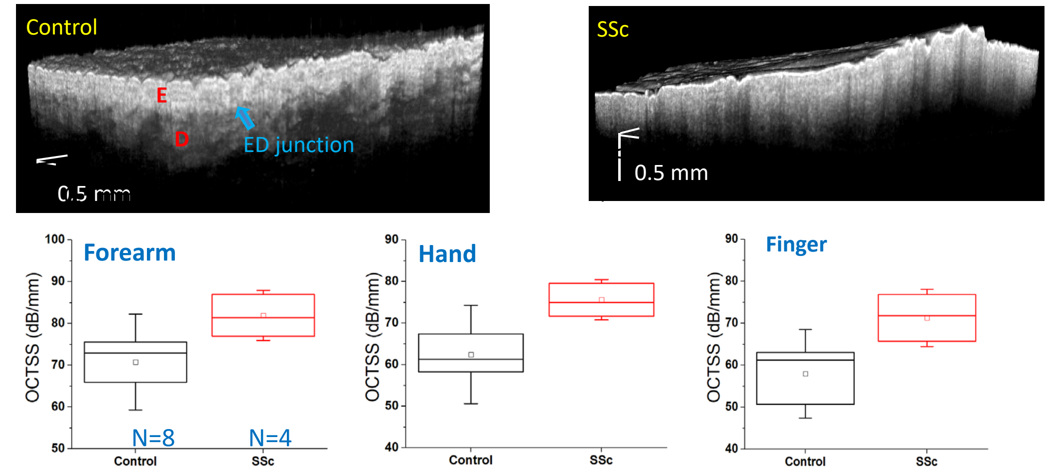
Liu et al: *J. Biophotonics*, (2019)

Experimental procedure



Liu et al: *J. Biophotonics*, 2019

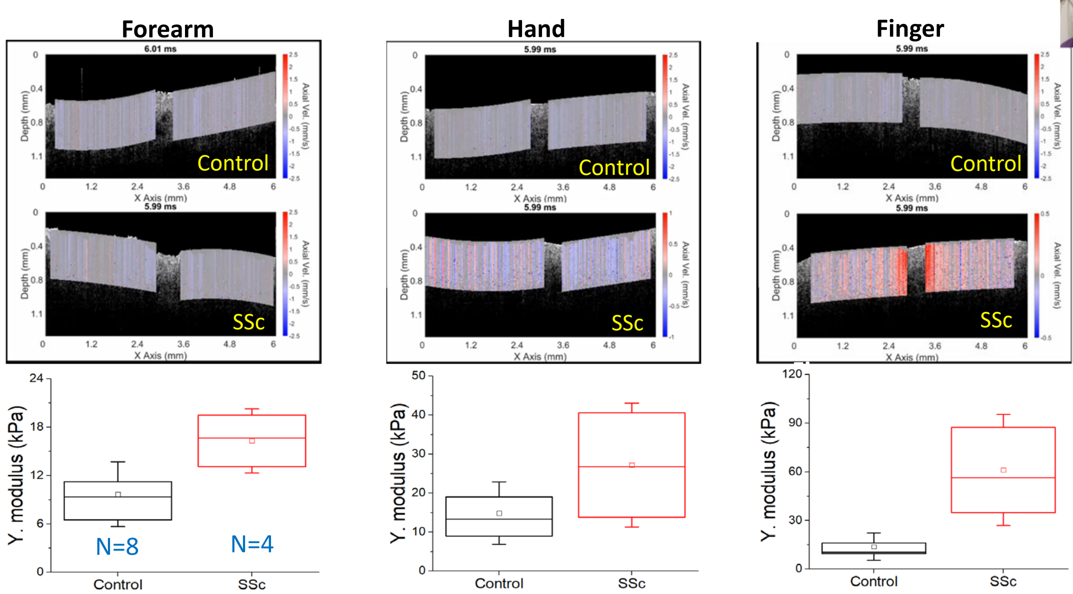
OCT analysis



P<0.05

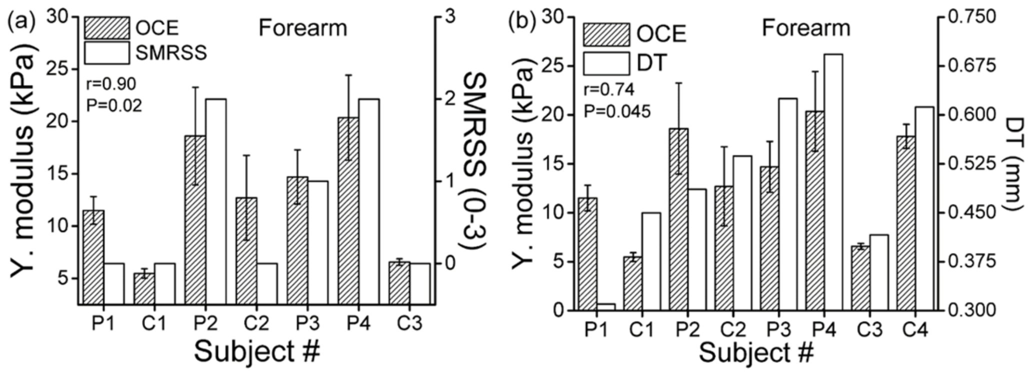
Liu et al: *J. Biophotonics*, 2019

OCE assessment



Liu et al: *J. Biophotonics*, 2019

Clinical Summary

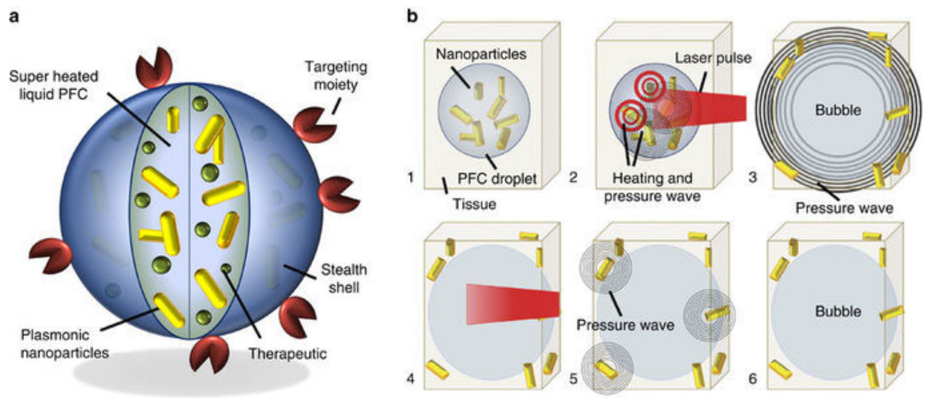


Liu et al: *J. Biophotonics, 2019*

“Nanobomb” Optical Coherence Elastography

Konstantin Sokolov, Ph.D.
Professor, Department of
Imaging Physics,
M.D. Anderson Cancer Center

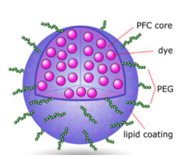
"Nanobombs"



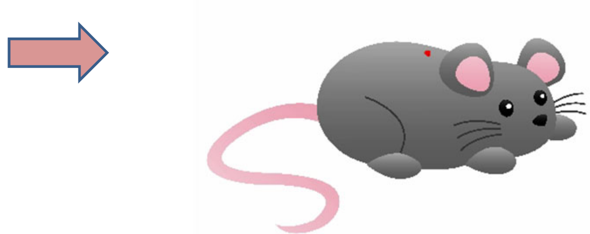
Emelianov, S., et al, *Nature Comm*, 2012

"Nanobomb" OCE

- Highly localized Targeting + High frequency response = nanobomb OCE
  - Dye-loaded perfluorocarbon (PFC) nanodroplets ("nanobombs")
    - Excited by 532 nm pulsed laser
    - Produce highly localized stress by the nanobomb explosion.
- Detected by line-field low coherent holography system

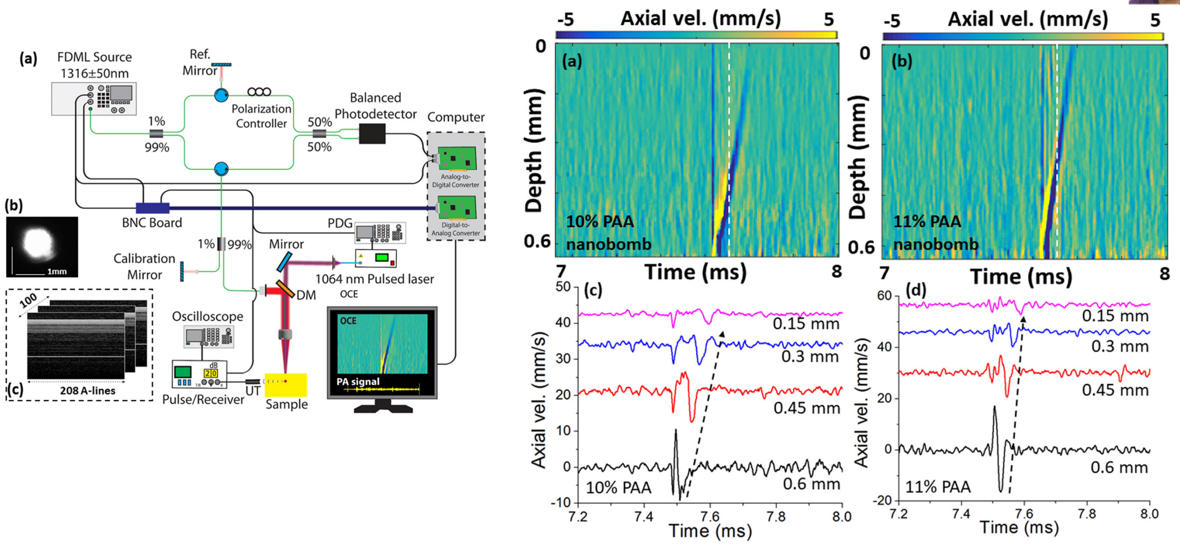


Schematic representation of nanobomb



C.-H. Liu et al., Biomed Opt Express 7 (2016)
C. H. Liu, et al., Opt Lett 43, 2006 (2018)

"Nanobomb" OCE



C. H. Liu, et al., Opt Lett (2019)

OCE: Summary and Conclusions

- OCE is a new emerging technique for tissue assessment: gives **biomechanical** contrast
- OCT structural images comes "for free"
- Allows 3D imaging and biomechanical assessment of various tissues
- Provides highly localized mechanical information of tissues with micrometer spatial resolution
- Holds a great promise for *in vivo* detection of various tissue diseases and quantitative evaluation of therapeutic interventions

Collaborators:

- **Irina Larina – BCM**
- **Michael Twa – UH Optometry**
- **Salavat Aglyamov – UH**
- **Stas Emelianov – G. Tech**
- **Fabrice Manns – U. Miami**
- **Konstantin Sokolov - MDACC**
- **Shervin Assassi– UTH**
- **Chandra Mohan– UH**
- Valery Tuchin – SSU
- Mary Dickinson – BCM
- Bruce Butler – UTHSC
- Michael Allon – HFC
- **Xingde Li, JHU**
- **James Martin– BCM**
- Rajesh Miranda– TAMU
- Mohamad Ghosn – Methodist
- Pradeep Sharma – UH
- Matthew Franchek – UH
- Richard Willson – UH
- Paul Ruchhoeft – UH
- Alexei Sobakin – UW, Madison
- Marlowe Eldridge – UW, Madison
- Raph Pollock – MDACC
- **Giuliano Scarcelli, UMD**
- **Richard Finnell, BCM**

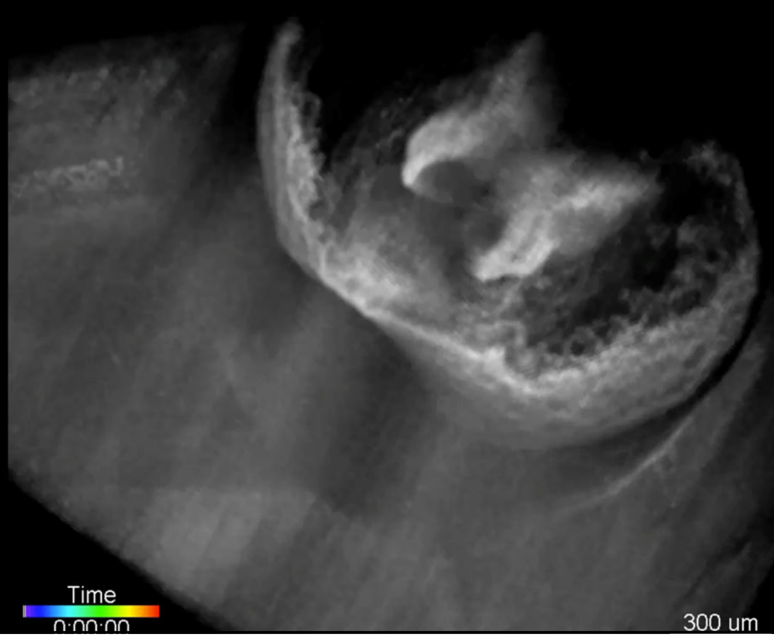
Current Funding:

NIH	2R01EY022362 (Larin, Twa)	(2010-2020)
	1R01HD086765 (Larin, Miranda)	(2016-2020)
	1R01HL130804 (Larin, Martin)	(2016-2020)
	1R01HD095520 (Larin, Scarcelli, Finnell)	(2018-2023)
	9R01HD096335 (Larina)	(2013-2023)
	1R01EB027099 (Larina)	(2019-2022)
	1R21CA231561 (Sokolov)	(2019-2021)
	1R01HL146745 (Mayerich)	(2019-2024)

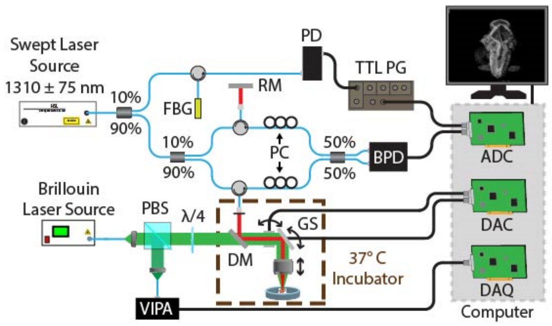
Graduate students and Postdoctoral positions are available:
Please inquire **klarin@uh.edu**

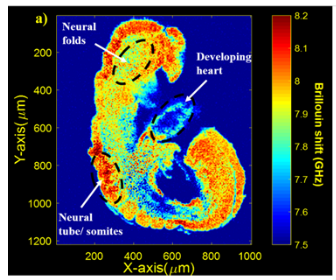
http://bol.egr.uh.edu/

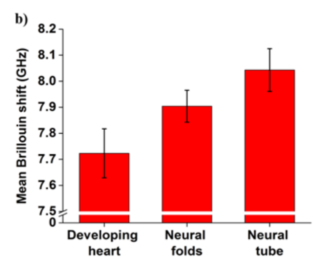
Can we map mechanical forces during development?



OCT + Brillouin Spectroscopy



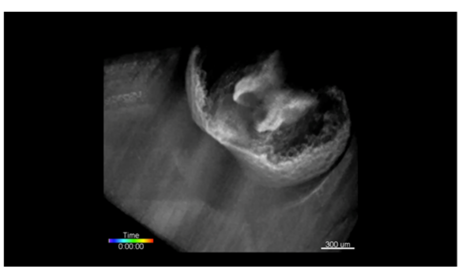




Raghunathan et al. J Biomed Opt. 2017
Zhang et al, Birth Defects Research, 2018

Future plans

In collaboration with Scarcelli and Finnell group



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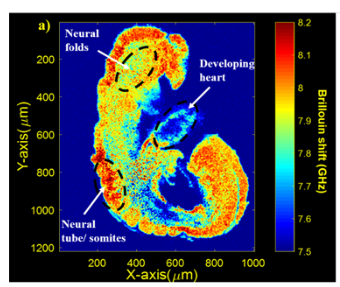
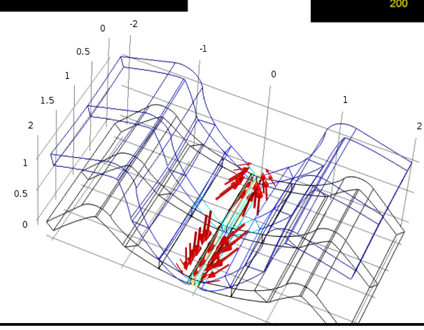
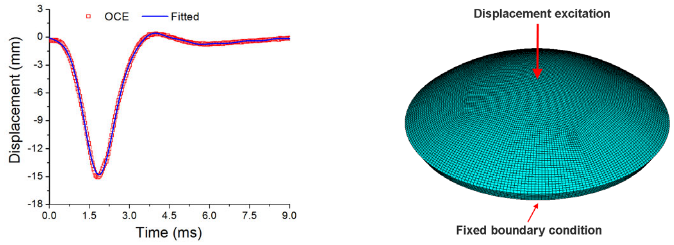




Effect of Corneal Curvature/Geometry

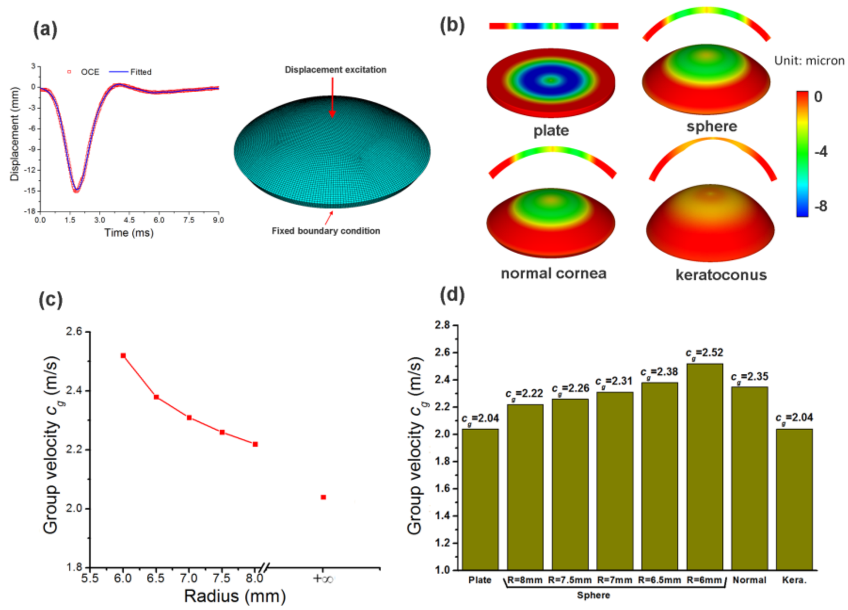


3D FEM modeling:

Young's modulus *E*=60 kPa, no viscosity
No aqueous humor effect (will be considered later)
Poisson's ratio *v*=0.49
Density ρ=1.06 kg/m³

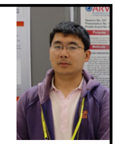
Han et al: Applied Phys Let , 2015

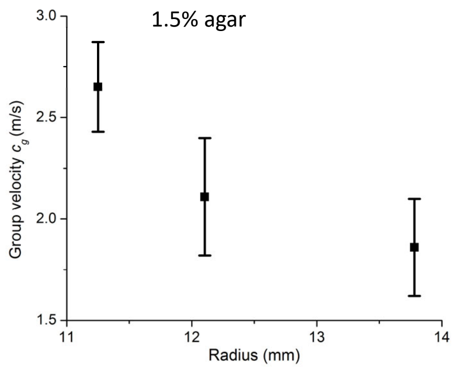
Effect of Corneal Curvature/Geometry

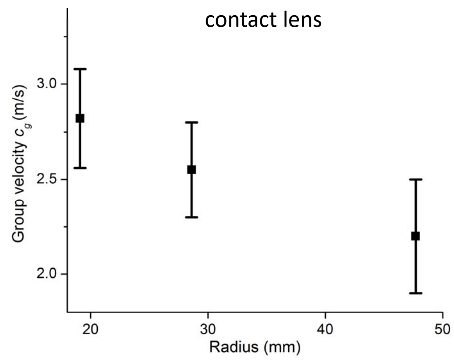


Han et al: Applied Phys Let , 2015

Effect of Corneal Curvature/Geometry: Experimental Data

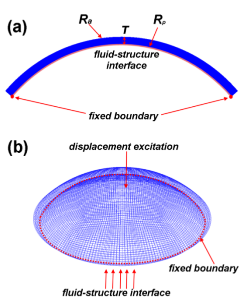


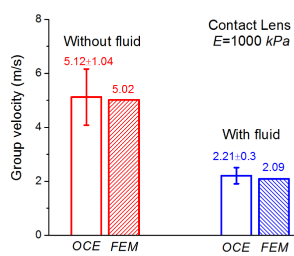


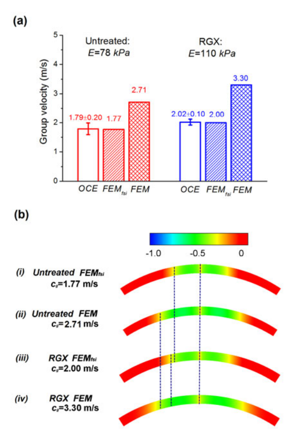


Han et al: Applied Phys Let , 2015

Fluid Effect







Han et al: Applied Phys Let , 2016

Quantifying Viscoelasticity

Lamb waves: modified Rayleigh-Lamb frequency equation

Modified RLFE: det(M)=0

$$M=\begin{bmatrix} (k^2+\beta^2)\sinh(\alpha d) & 2k\beta\sinh(\beta d) & (k^2+\beta^2)\cosh(\alpha d) & 2k\beta\cosh(\beta d) & 0 \\ 2k\alpha\cosh(\alpha d) & (k^2+\beta^2)\cosh(\beta d) & 2k\alpha\sinh(\alpha d) & (k^2+\beta^2)\sinh(\beta d) & 0 \\ -(k^2+\beta^2)\sinh(\alpha d) & -2k\beta\sinh(\beta d) & (k^2+\beta^2)\cosh(\alpha d) & 2k\beta\cosh(\beta d) & \frac{\rho_F\omega^2}{\mu_D} \\ 2k\alpha\cosh(\alpha d) & (k^2+\beta^2)\cosh(\beta d) & -2k\alpha\sinh(\alpha d) & -(k^2+\beta^2)\sinh(\beta d) & 0 \\ \alpha\cosh(\alpha d) & k\cosh(\beta d) & -\alpha\sinh(\alpha d) & -k\sinh(\beta d) & -\alpha_F \end{bmatrix}$$

$$k^2=\frac{\omega^2}{c_p^2} \quad \alpha^2=k^2-\frac{\omega^2}{c_1^2} \quad \beta^2=k^2-\frac{\omega^2}{c_1^2}$$

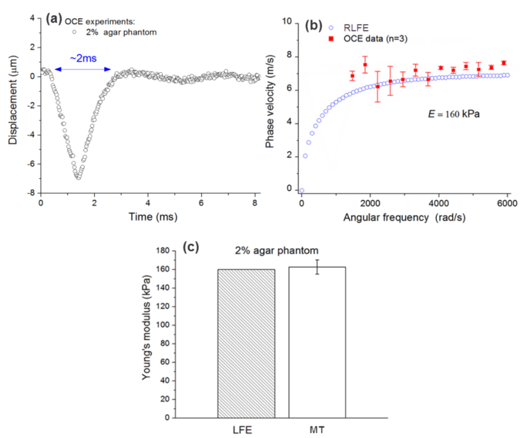
$$\mu_D=\mu+i\omega\eta \quad \alpha_F^2=k^2-\frac{\omega^2}{c_F^2} \quad c_2=\sqrt{\frac{\mu_D}{\rho}}$$

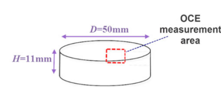
ω - Circular frequency
c_p - Phase velocity
ρ - Density
μ - Shear elastic modulus
η - Shear viscous modulus

c_1 - Speed of sound
$2d$ - Thickness
c_F - Speed of sound in fluid
ρ_F - Density of fluid

Han et al: *PMB, v. 60, 2015*

Quantifying Viscoelasticity (phantoms)



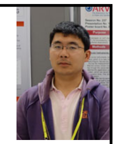


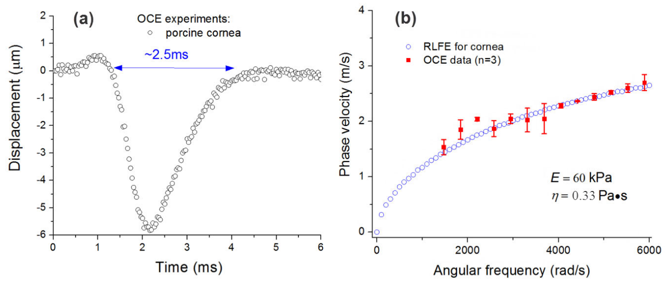
(a) Temporal displacement profile from 2% agar phantom
(b) OCE vs RFLE for 2% agar phantom
(c) Young's modulus of 2% agar phantom assessed by RLFE and mechanical testing (MT).

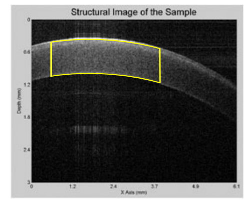
The Young's modulus of 2% phantom measured by OCE and fitted by RLFE is 160kPa, which was validated by uniaxial mechanical testing.

Han et al: *PMB, v. 60, 2015*

Quantifying Viscoelasticity (cornea)







(a) Temporal displacement profile from a porcine cornea
(b) OCE vs modified RLFE for porcine cornea (n=3)

For porcine cornea at IOP=20 mmHg, the Young's modulus was estimated as 60 kPa and shear viscosity as 0.33Pa•s.

Han et al: *PMB, v. 60, 2015*
Han et al: *JMBBM, v. 66, 2017*