

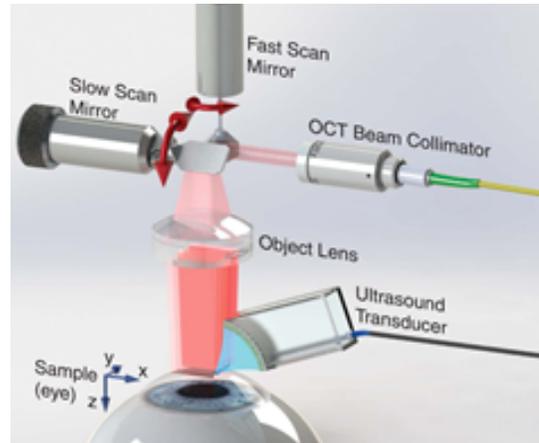
# How University of Washington is Developing a Novel Medical Device with OnScale

## OVERVIEW

In human physiology, it is often said that function follows structure. The human eye is no exception to this rule. Indeed, the eye's ability to collect and transfer visual information to the brain is intrinsically linked to its structural mechanics. Subtle changes in ocular biomechanics can greatly affect visual function, and ophthalmologists can measure these changes to diagnose disease or monitor treatments.

Unfortunately, quantitative methods for measuring the eye's mechanical properties are currently very limited.

Using an exciting imaging method called optical coherence elastography (OCE), Professors' Matthew O'Donnell and Ruikang Wang's groups from the Department of Bioengineering at the University of Washington hope to change this.



*We are developing a novel and truly non-contact OCE system to measure elasticity changes in the eye with sub-millimeter to micron resolution.*

Their goal is to develop a medical device that allows clinicians to detect changes in corneal elasticity and intraocular pressure, allowing them to identify disease and monitor therapeutic interventions. This work can then be extended to allow probing of other organs (such as skin) to treat skin burn victims, evaluate the aging process and monitor skin diseases. Such a device has the potential to greatly improve patient care by providing clinicians with the quantitative information they need to guide and optimize treatments.

## THE CHALLENGE

Elasticity imaging requires a physical stress to deform the tissue and a method to track the mechanical waves produced by that stress. The University of Washington group uses a technique called acoustic microtapping (A $\mu$ T) to generate broadband mechanical waves in the cornea. An air-coupled ultrasonic transducer delivers a temporally short "push" through the air to the corneal surface (completely non-contact), launching a surface acoustic wave. Using optical coherence tomography (OCT), the propagation of this wave can be tracked, and its behavior can be used to spatially map mechanical properties such as shear wave speed, shear modulus, or Young's modulus.

O'Donnell and Wang's team uses OnScale to explore the excitation and propagation of shear waves in simulated models of biological tissues. In particular, the geometric and material complexities of the cornea create unique challenges for reconstructing elastic moduli from the mechanical wave behavior. The results

of the team’s research are used to help better understand these challenges and to develop fundamentally new approaches to dynamic elastography.

## THE SOLUTION

To model elastic wave propagation in soft tissue, the team used OnScale to construct a two-dimensional finite element model that closely mirrors their experimental OCE system. Modeling elastic waves in soft tissue can be particularly challenging, as they are typically described as nearly-incompressible (Poisson’s ratio  $\nu \approx 0.499995$ ). The University of Washington team extensively tested their OnScale model to ensure that their solutions were not corrupted by hourglass modes, numerical dissipation, or numerical dispersion - all common errors that can arise in many commercially-available software packages.

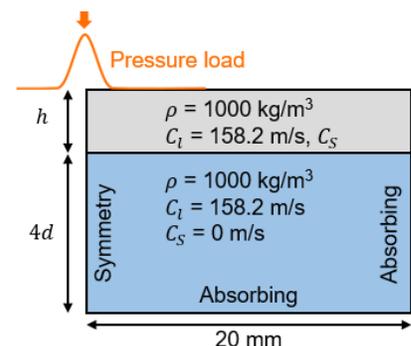
*This “stress-testing” has paid off, and the team obtained an extremely reliable numerical model with which they can rapidly test new ideas, explore elastic wave physics, and validate experimental results.*

## EXAMPLE

In a recent publication, “Does group velocity always reflect elastic modulus in shear wave elastography?”<sup>1</sup>, the team used OnScale to examine the effects of tissue boundaries and elastic wave bandwidth on OCE images. In many OCE studies, the group velocity of the elastic wave is used as a surrogate measurement for bulk shear wave speed. In thick-slab materials, this can be an accurate approximation. However, this is not true in the cornea, which can be described more accurately as a thin plate bounded on one side by air and on the other by water. This leads to a more complex wave field containing dispersive guided wave modes. As a result, group velocity estimates do not produce accurate images of the bulk shear wave speed. The University of Washington team was able to demonstrate that when group velocity is used to quantify elasticity, the accuracy is directly limited by the bandwidth of the mechanical wave.

### OnScale Model (Implemented by John Pitre Jr., University of Washington)

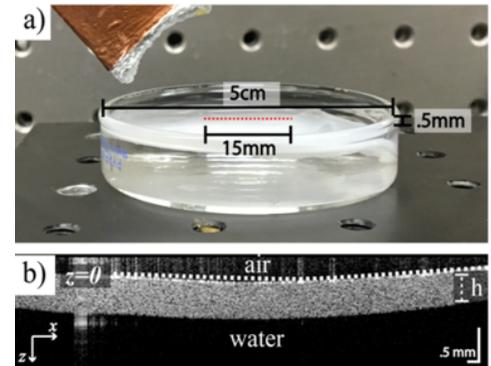
The bounded tissue model used in this study consisted of two layers of linear elastic materials. The top layer, which modeled the cornea, was a nearly-incompressible ( $\nu \approx 0.49995$ ) solid with thickness  $h = 0.5$  mm and shear wave speed  $C^S = 3.8$  m/s. The bottom layer modeled a bounding water domain, with a matched longitudinal wave speed and a shear wave speed of  $C^S = 0$  m/s. Elastic waves were excited by a spatio-temporally sharp pressure, or “push”, applied to the top boundary of the domain. The spatial push profile was Gaussian, while the temporal push profile was super-Gaussian. Both profiles were chosen to closely match the experimental push profiles created by the acoustic microtapping transducer, with a spatial width of  $500 \mu\text{m}$  and a temporal duration of  $100 \mu\text{s}$ .



Adapted from Ref. 1

## EXPERIMENTAL SETUP

For the study's OCE experiments, the team constructed a 0.5 mm thick tissue-mimicking phantom with a bulk shear wave speed of  $C^s = 3.8$  m/s. They then suspended a thin layer above a water bath to mimic the boundaries of the cornea. The acoustic microtapping transducer was positioned with its focus at the phantom surface, angled so as not to obstruct the OCT imaging beam. For each experiment, the transducer produced a 500  $\mu\text{m}$  wide spatially-Gaussian push for a duration of 100  $\mu\text{s}$ . A high-speed phase-sensitive OCT system was used to measure the velocity field produced by the elastic wave as it propagated through the phantom. To test the effect of limited signal bandwidth, the OCE velocity signals were filtered with varying cutoff frequencies. A group velocity estimation algorithm was then applied to the signals to produce elasticity images.



Reproduced from Ref. 1

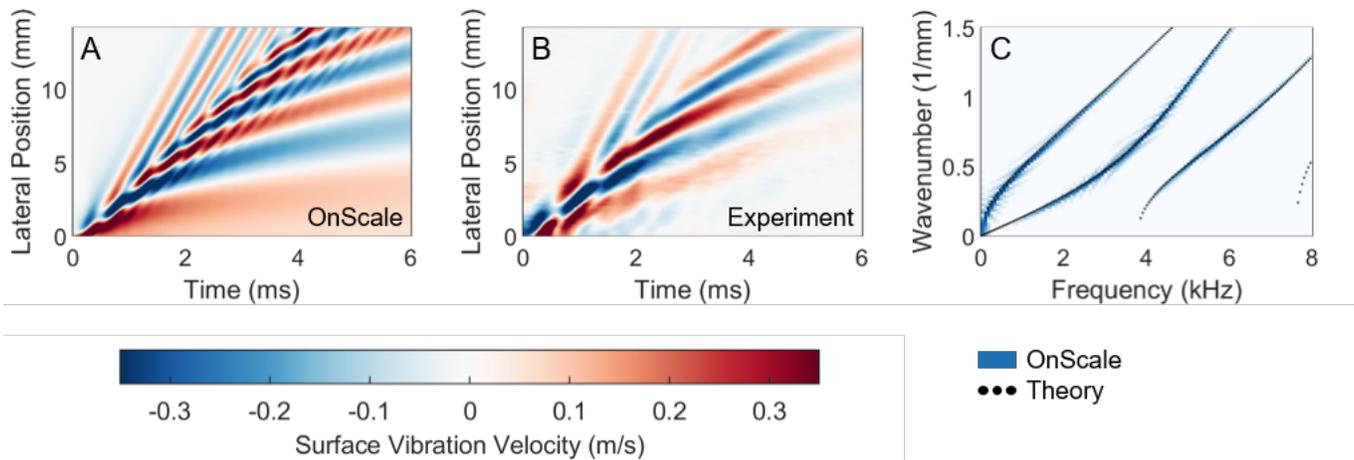
## RESULTS

*The OnScale model results closely matched the experimental OCE measurements. The OnScale model accurately captured the guided wave modes and even produced group velocity images with similar imaging artifacts.*

When the signal bandwidth was limited, both the experimental and numerical estimates of group velocity strongly underestimated the true shear wave speed. Lower signal bandwidths led to extremely inaccurate estimates of shear wave speed, with average errors of up to 60%, even in the absence of measurement noise. Thus, the signal bandwidth provides a fundamental limit on the accuracy of the group velocity estimate.

This result is important because the bandwidth of the elastic wave is intrinsically linked to the excitation method used to generate it. Air-puff excitation, a commonly-used alternative to acoustic microtapping, generates signals with bandwidths up to 400 Hz. This fundamentally limits the potential accuracy of these OCE elasticity estimates. In contrast, acoustic microtapping is capable of producing mechanical waves with frequency components up to 8 kHz, allowing it to more accurately probe tissue mechanical properties compared to other methods. Even so, these results point to the need for more advanced methods of elasticity reconstruction that are not as susceptible to geometric dispersion.

*O'Donnell and Wang's group continues to use their OnScale simulation to develop new methods that can overcome these challenges and help advance OCE toward clinical adoption.*



Numerical solutions (A) computed with OnScale and filtered to the experimental bandwidth accurately capture the guided wave modes observed in experimental OCE measurements of thin-layered tissue-mimicking phantoms (B), allowing OnScale to function as a “virtual workbench” for exploring new techniques to measure tissue elasticity. The accuracy of the OnScale solver in resolving the complicated guided wave field is beautifully illustrated by comparing the computed wavefield’s dispersive behavior to the theoretical solution (C).

## REFERENCES

1. Ivan Pelivanov, Liang Gao, John Pitre, Mitchell A. Kirby, Shaozhen Song, David Li, Tueng T. Shen, Ruikang K. Wang, Matthew O’Donnell, “Does group velocity always reflect elastic modulus in shear wave elastography?,” *J. Biomed. Opt.* 24(7), 076003 (2019), doi: 10.1117/1.JBO.24.7.076003.

## ABOUT ONSCALE

OnScale develops on-demand scalable engineering simulation software, empowering engineers to accelerate innovation across next-generation technologies such as MEMS, Semiconductor, 5G, Biomedicine, and Autonomous Vehicles. OnScale combines powerful multiphysics solver technology used and validated by Fortune 50 companies for over 30 years, with the limitless speed and flexibility of Cloud High Performance Computing (HPC). By removing the constraints of legacy simulation tools, OnScale allows engineers to dramatically reduce cost, risk and time to market for cutting edge technologies.