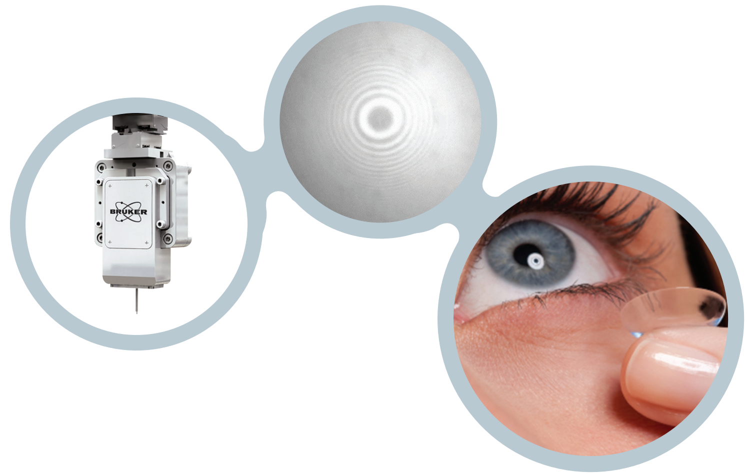

Application Note #1508

Indentation of Contact Lenses Using the Hysitron BioSoft In-Situ Indenter

The mechanical properties of a contact lens, such as stiffness, affect important characteristics, including comfort, ease of handling, and even the optical properties.[1] Low-modulus contact lenses are difficult to handle and provide insufficient movement during blinking, leading to poor tear exchange. High-modulus contact lenses can result in mechanically-induced complications, such as superior epithelial arcuate lesions (SEALs), contact lens–induced papillary conjunctivitis (CLPC), and mucin ball formation. Water content, hydraulic permeability, and viscoelastic behavior inherent to the hydrogel all factor into the mechanical response of a lens. Depth-sensing indentation offers a non-destructive, rapid, reliable, and quantitative method for characterizing the modulus of materials. However, traditional indentation instruments were designed for relatively stiff materials and are ill equipped for the unique challenges of characterizing soft matter. This application note shows how the Hysitron® BioSoft™ In-Situ Indenter, an instrument specifically designed for soft matter characterization, was successfully used to measure mechanical properties of two distinct types of contact lenses.

Figure 1. Hysitron BioSoft In-Situ Indenter performing testing while attached to an inverted microscope.

Introduction

The Hysitron BioSoft In-Situ Indenter is specifically designed for the quantitative characterization of soft matter. BioSoft's high-force sensitivity and extended displacement range provide reliable testing of materials throughout the MPa to kPa modulus range. The BioSoft system integrates with inverted optical microscopes to provide direct observation of initial surface contact. Optical surface detection during indentation allows for accurate determination of the initial contact point on an undisturbed surface, which is crucial for test repeatability on transparent, low-modulus materials. The BioSoft indenter operates in uniaxial force and/or displacement feedback control modes, allowing data to be directly analyzed utilizing various contact mechanics models. Bruker's BioScan™ software package provides an intuitive graphical user interface to streamline the testing process, while being flexible enough to accommodate a broad range of testing needs.

Experiment and Results

BioSoft was used to measure the mechanical response of three contact lenses made of different materials, two types of 2-hydroxyethyl methacrylate (HEMA)-based and one silicone-based hydrogel (SiHy). Lenses were mounted on a rigid convex surface and clamped from above with another concave surface as shown in Figure 2. A hole in the center of the top surface allowed a 1 mm diameter spherical probe to indent the contact lens. The entire apparatus was submerged in a commercially available saline contact lens solution during indentation. This was shown to be an easy and reliable method of mounting contact lenses for testing in a fully hydrated state.

During a depth-sensing indentation test, both the force and displacement of the indenter were continuously measured as a function of time. The resulting force-displacement curves were converted to effective elastic modulus using the standard Hertzian contact equation through the loading and hold segments of the measurement sequence;

Equation 1:

$$E(t) = \frac{3}{4\sqrt{R}} \frac{1-\upsilon^2}{h(t)^{\frac{3}{2}}} P(t)$$

where t is the time, R is the spherical probe's radius, h is the displacement, υ is the Poisson's ratio of the sample, and P is the load. A Poisson's ratio of 0.4 is assumed for both lens materials.

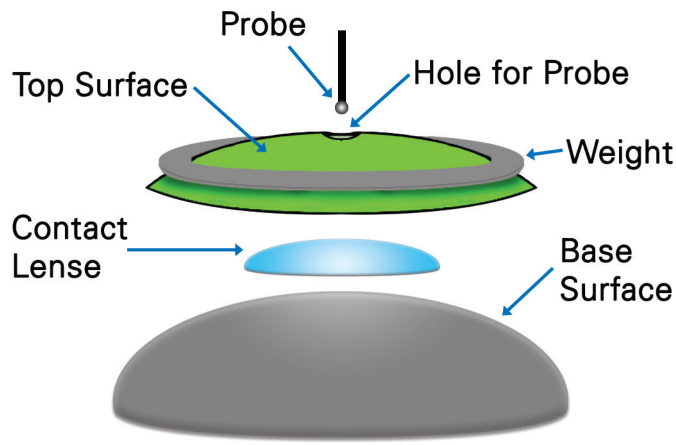

Figure 2. Mounting configuration for contact lenses. The apparatus was submerged in saline solution during testing.

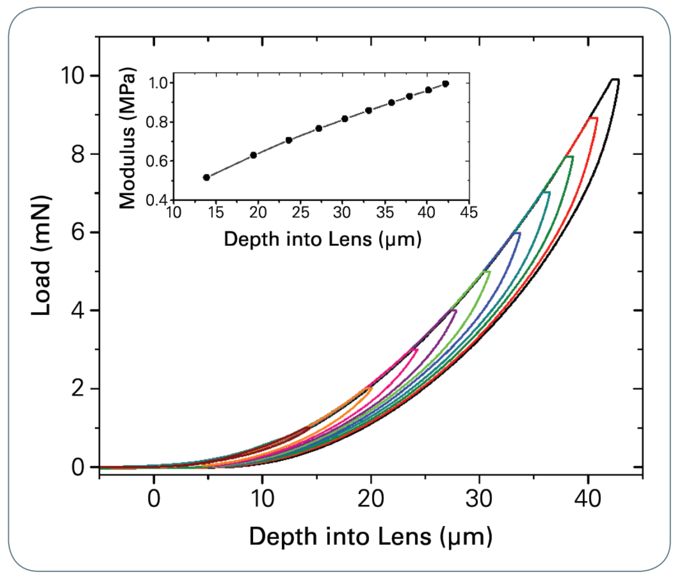

Figure 3. HEMA-based contact lens load vs. displacement for 500 µN/s loading to varying peak loads, showing excellent measurement repeatability. The inlay shows the effective elastic modulus increasing with depth.

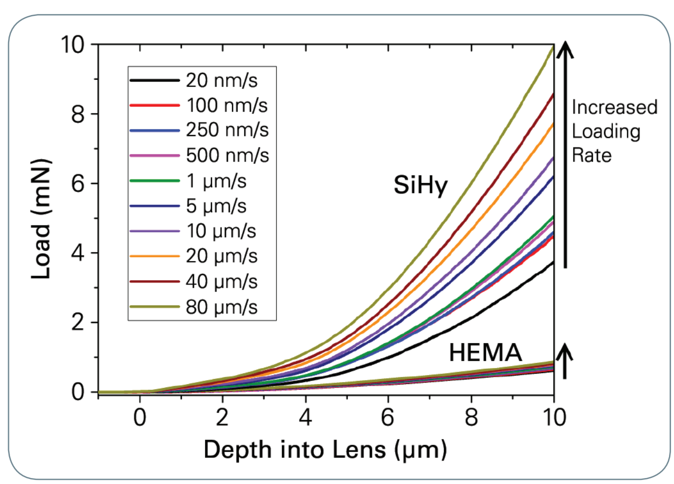

Figure 4. Load vs. displacement for contact lenses at varying loading rates showing increasing load with increasing loading rate due to hydrostatic pressure within the lens.

To assess measurement repeatability the first HEMA-based lens was loaded at 500 μN/s to varying peak loads. Indents were performed on the same location of the lens with a wait period of 10 minutes between tests to allow the lens to recover. The resulting load-displacement curves are shown in Figure 3. Excellent experimental repeatability was observed, as the loading segments of each test perfectly align. The inlay picture shows the modulus, calculated using Equation 1, increasing with depth into the lens. The depth effect is likely due to decreased polymer content or cross-linking near the surface. At deeper depths, the rigid substrate begins to constrain the elastic zone and restricts fluid flow resulting in an increase of the effective modulus.

The first HEMA- and SiHy-based lenses were indented to a peak depth of 10 μm at incremental displacement rates ranging from 20 nm/s to 80 μm/s. The rate of indentation has a significant effect on the response of contact lenses and other hydrogels.[2] The loading segment of these tests is shown in Figure 4. For both lenses, the required load increases with displacement rate, a result which can be explained by hydraulic effects. At higher speeds, the fluid within the hydrogel has less time to flow through pores within the hydrogel, increasing resistance to deformation.

For each displacement rate, the stress relaxation was measured by holding the peak displacement for 20 seconds and measuring the force decay. Stress relaxation occurs as fluid flows away from the contact zone through the porous polymer structure. As one would expect, the magnitude of load relaxation was greater following faster displacement rates as less time is given for fluid to move through pores within the hydrogel before the hold.

The loading can be converted to modulus using Equation 1 as shown in Figure 5. Measured moduli are in good accordance with reported values for similar contact lenses.[3,4] The modulus of the HEMA-based lens shows a large sensitivity to loading rate. The SiHy lens shows weak loading rate dependence at displacements less than ~4 μm, but increased sensitivity at greater depths, while the HEMA lens shows a strong dependence at even small depths.

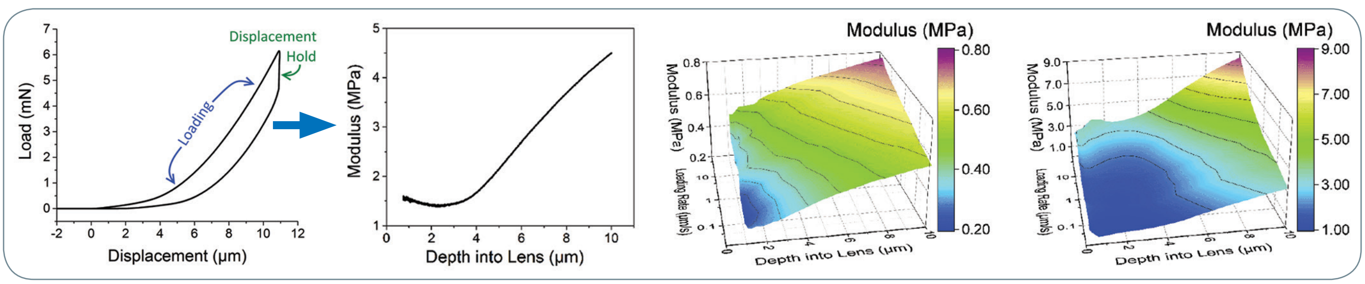

Figure 5. The loading segment of each indentation was converted to effective elastic modulus using the Hertz equation. Using multiple tests, a map of the modulus as a function of displacement rate and depth into the lens was generated for the HEMA (left) and SiHy lenses (right).

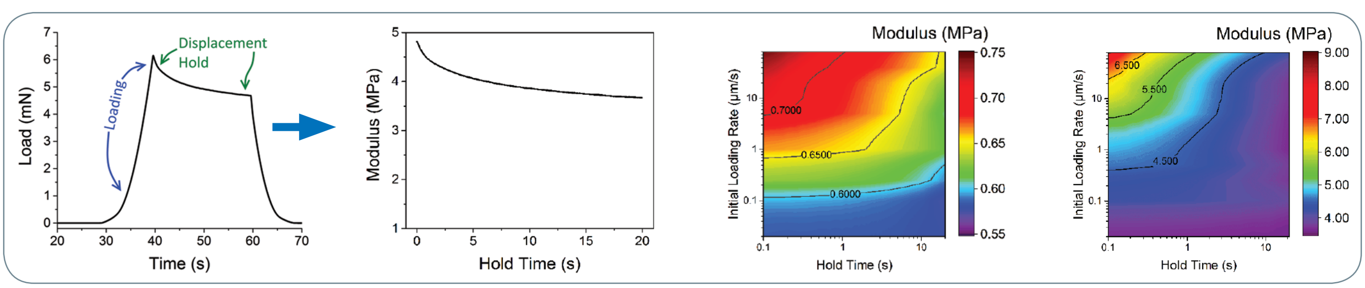

Figure 6. The stress relaxation segment of each indentation was converted to effective elastic modulus using the Hertz equation. Using multiple tests, a map of the modulus as a function of displacement rate and depth into the lens was generated for the HEMA (left) and SiHy lenses (right).

The stress relaxation segment of the test can be converted to modulus, as shown in Figure 6. During the stress relaxation, the SiHy lens relaxed quicker than the HEMA lens, reaching equilibrium after 20 seconds regardless of displacement rate. For the SiHy lens, at the slowest loading rate of 20 nm/s, most of the stress relaxation occurred during the loading, and almost zero relaxation occurred during the hold.

The second HEMA lens was indented to shallow depths less than 1.5 μm. Indents were performed at 200 nm/s. The resulting load displacement curves are shown in Figure 7. A Hertzian fit was applied to the curves yielding an elastic modulus of 365.1±4.8 kPa.

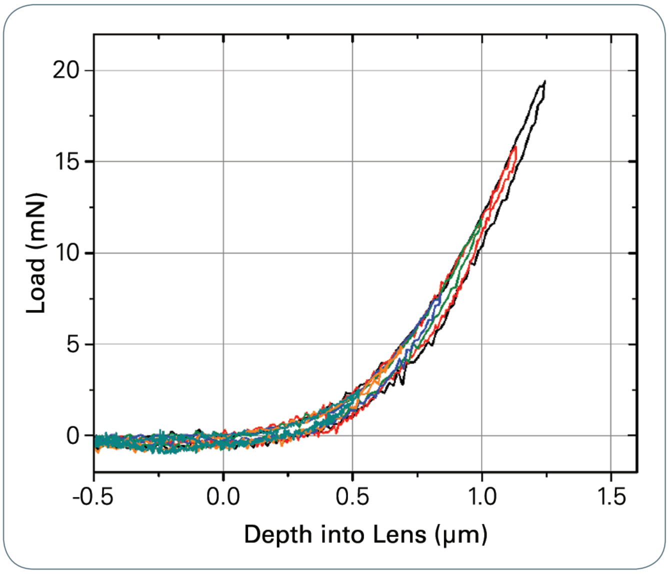

Figure 7. Load vs. displacement for a HEMA contact lens to varying peak loads.

Conclusions

The Hysitron BioSoft In-Situ Indenter provides an accurate and reliable means for quantitatively characterizing the modulus of low-stiffness materials used in the manufacture of contact lenses. Excellent test-to-test repeatability was demonstrated owing to the BioSoft's accurate surface detection capabilities, high-force sensitivity, and extended displacement range. HEMA and SiHy lenses showed significant differences in measured effective modulus as a function of loading rate, displacement into the contact lens surface, and relaxation time.

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