Measurement of the refractive index dispersion curve for contact lenses

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Refractive Index Measurement System For Contact Lens in a Natural Hydrated State

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ABSTRACT

Accurate refractive index of the contact lenses is one of the most important parameters needed to properly evaluate the lens performance. Measurements of the refractive power and other optical properties of the lenses are typically conducted in solution and converted to in-air performance. Such an approach is very sensitive to errors in the refractive indices of both the lens and the solution.

A number of different approaches have been undertaken by the manufacturers to overcome this difficulty. Efforts to accurately measure the phase refractive index a contact lens directly have for the most part been unsuccessful due to a curved shape of the lens and lens material properties. In this paper we describe a different approach of obtaining a group index dispersion curve with high accuracy of 0.003 or better, and discuss practical implications.

We have conducted measurements of the group refractive index (GRI) of hydrogel contact lenses at different wavelengths, from 530 to 670 nm, using time-domain low-coherence interferometer (LCI), based on the super-continuum light source (SCLS). The technique is being developed to overcome sources of error in the current measurement technique.

Keywords: low-coherence interferometry, refractive index, Etafilcon A, soft contact lens, super-continuum light

INTRODUCTION

The current accepted measurement technique for material phase refractive index (PRI) is the Abbe refractometer. In this instrument, a sample is sandwiched between two prisms and illuminated with a source. The incident light is refracted at the sample/prism interface, and the divergent critical angle determined. With knowledge of the prism refractive index and the measured angle, Snell's Law is the used to calculate the sample refractive index.

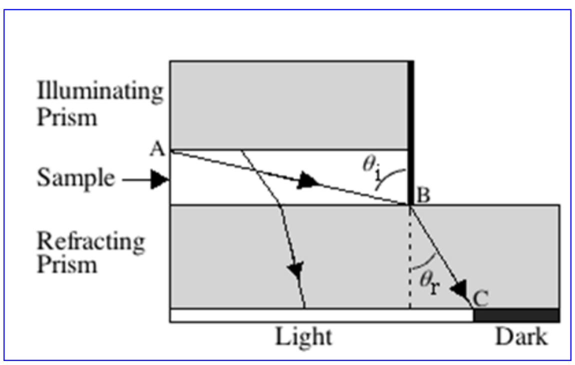

Figure 1. Abbe Refractometer [1]

The measurement is typically performed at 589 nm (Sodium D line) and requires conversion if a different wavelength is used in the optical performance measurements. The measurement of phase refractive index utilizing the Abbe refractometer is also prone to errors due to the contact lens shape (thin meniscus), thickness (~0.070 mm to 0.300 mm), and material compression - the lens is squeezed between the two prism faces, driving out water content. While this is the common and accepted measurement technique for PRI in contact lens manufacturing, it is prone to errors.

The refractive index is used to assess the optical performance of the contact lens. Ideally, the contact lens should be evaluated in its intended operational environment, i.e. while worn on the eye. In addition to the increased technical

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complexity of measuring a medical device worn by a patient, such approach is extremely expensive and time-consuming, and cannot be implemented at the production facility. The alternative approach of measuring the contact lens suspended in-air is impractical due to the evaporation and dehydration of the lens.

The industry standard is to measure the optical performance of the contact lens as it is resting inside a saline-filled cuvette. The measured transmitted wavefront of the lens, along with the lens thickness, base curve, lens PRI and solution PRI are used to calculate the in-air performance. The conversion equation strongly depends on the refractive indices of the lens and the refractive index of the solution. Because these refractive indices are close in value, any small measurement errors (when compared to the absolute value of the refractive indices) become large.

Therefore, accurate measurements of the refractive indices become very critical in this evaluation process. Any false positive or false negative pass criteria during the quality control evaluation process result in low customer satisfaction and associated significant financial and resource losses. It is not a surprise that the contact lens manufacturers therefore pursue better and more accurate measurement technologies to aid their pursuit of higher quality medical devices.

Due to the difficulty in measuring the phase refractive index (PRI) directly, an alternative can be taken, which is based on measuring the group refractive index (GRI). The PRI and GRI are related via a well-known equation:

$$n_{\mathrm{g}} = n - \lambda_0 \frac{\mathrm{d}n}{\mathrm{d}\lambda_0}, \tag{1}$$

where $n_g$is the GRI, n is the PRI, and λ_0 is the wavelength at which the GRI is calculated [2]. See Figure 2 for an example of PRI and GRI dispersion curves for BK-7 glass.

Normally, it is the GRI that is calculated from knowing the dispersion curve for the PRI. Calculating the PRI from GRI is not as straightforward, since any direct integration is associated with an undefined constant leading to an infinite number of solutions. A model is being developed, based on [3], which will be to obtain PRI from the measurements of the GRI dispersion curve. The details of this model will be published elsewhere. In this manuscript we describe the technique for accurate measurements of the GRI at different wavelengths.

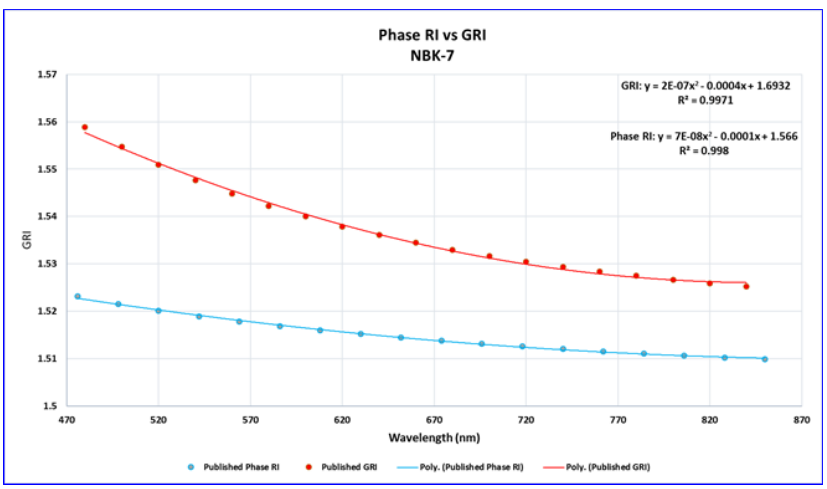

Figure 2. Published phase vs group refractive index of NBK-7. [4]

GRI MEASUREMENT APPROACH

The measurement setup is based on the multiwavelength low-coherence interferometer (Figure 3). The light from the super-continuum light source (1) passes through a tunable filter (2), a polarized beam-splitter (4) and an achromatic quarter wave-plate (5), and is split into two paths by a 50/50 beamsplitter (8). One half of the beam is focused into the cuvette containing the contact lens submersed in a saline solution (11), while the other half is reflected by a mirror mounted onto a translation stage (10). The light, reflected by the mirror and by the cuvette, is recombined by the beamsplitter and detected by the balanced detector (7). A separate laser-based interferometer (12,13,14) is used to measure the displacement of the translation stage (10) in real time.

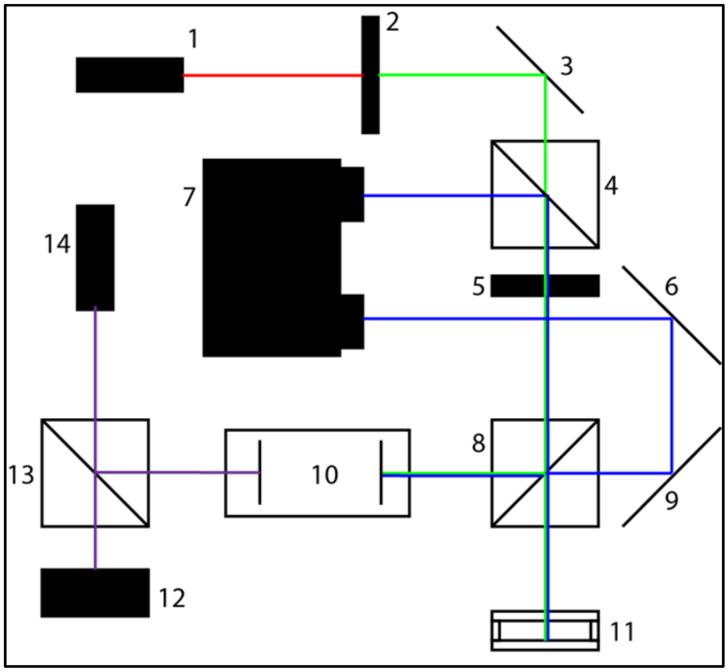

Figure 3. GRI measurement setup, based on low-coherence interferometer [5].

The low-coherence interferometer (LCI) is used to measure the optical distances (a product of physical thickness and the GRI) between reflecting interfaces of the measurement sample, i.e. the cuvette and the contact lens. Three steps are required to accurately measure the GRI of the saline solution and the lens at each wavelength, selected by the tunable filter:

Step 1: Measure optical thicknesses of the saline-filled cuvette and the contact lens.
Step 2: Remove the contact lens, and measure the optical thickness of the cuvette with just the solution.
Step 3: Evacuate the solution from the cuvette, and measure its optical thickness of the empty cuvette.

The GRI is then calculated from these measure values using the following equation:

$$n_l = n_a \frac{S}{C} \frac{L}{S - S_1 - S_2}, \quad (1)$$

where n_l is the lens GRI, n_a is the air GRI, S is the optical thickness of the cuvette with solution only, S_1, S_2 are optical thicknesses of the solution above and below the contact lens, C is the optical thickness of empty cuvette, and L is the optical thickness of the lens.

RESULTS

Most of the work conducted during the measurements was aimed at characterizing measurement uncertainties, their sources and effects on the GRI. These errors included temperature influences, lens settling and stabilization times after loading, external vibration, balanced detector channel equalization with wavelength, and SCLS spectral stability. Controlling these errors allows us to obtain the measurement repeatability in optical distances on the order of 200 nm or better, and therefore achieve the measurement repeatability of GRI repeatability of approximately 0.0004 across all wavelengths. Measurement repeatability is defined as the standard deviation of 20 repeat measures. Figure 4 shows the example of the measurements for the parameters used in Equation 2.

Measurement 2 ,CWL= 540nm.					
	S	S_1	L	S_2	C
Std Dev	0.084	0.164	0.126	0.181	0.097
Average	6984.305	1049.572	281.583	5667.28	5146.487

Figure 4. Example of the measurement results for the optical distances used for GRI calculation (Equation2)

We have observed good repeatability across all wavelengths for standard materials (DI water and fused silica), for which published GRI data is readily available. The measured group dispersion curve matches the published data down to a ~0.001 offset (Figures 5 and 6).

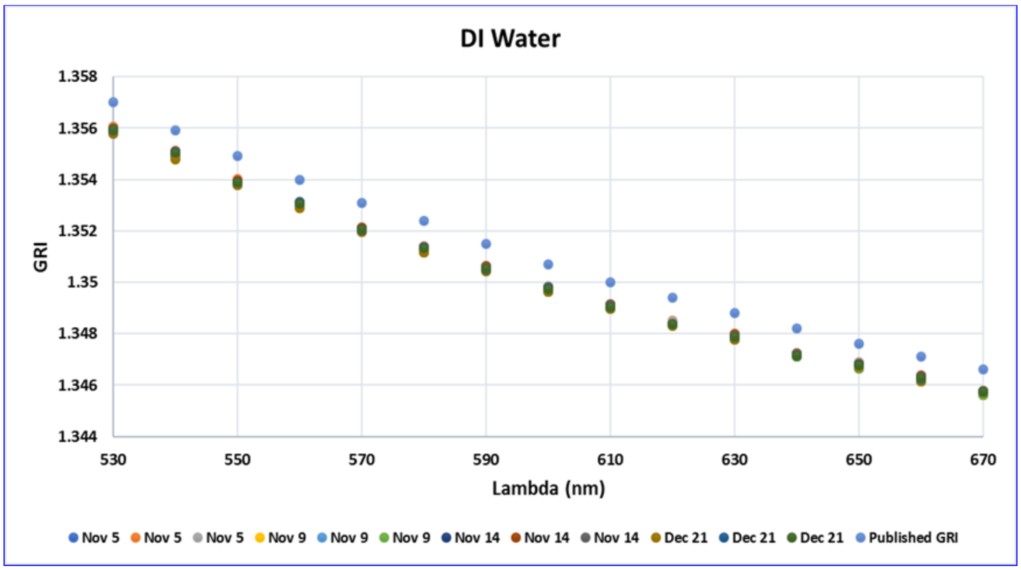

Figure 5. Measured and published GRI data for DI water.

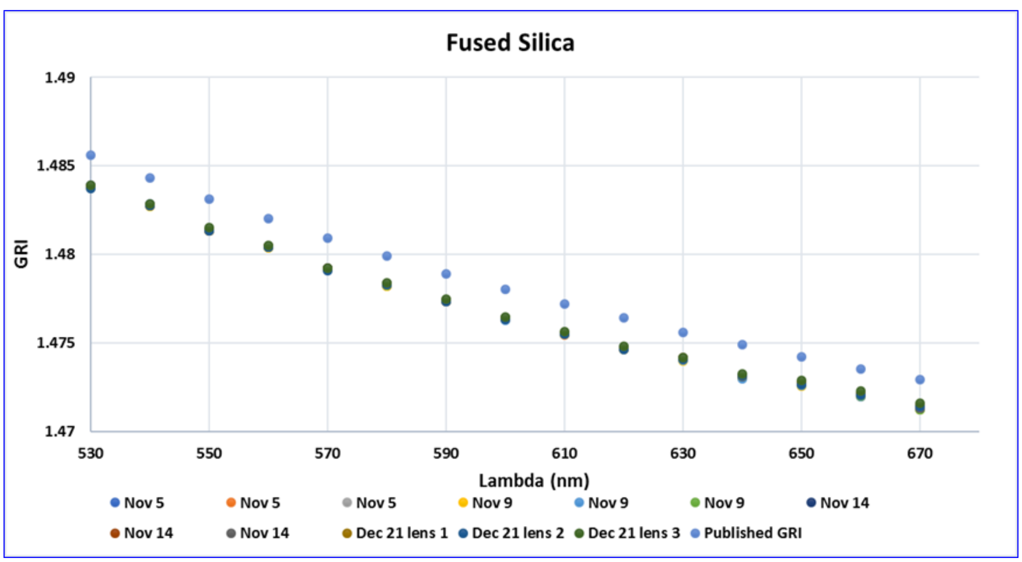

Figure 6 Fused Silica GRI Dispersion Curve, Multiple Measurements vs Published

Figures 7 and 8 show the GRI consistency between different JJVC Etafilcon A contact lenses. It demonstrates the importance of measuring and using the accurate GRI not only for each batch of lenses, but ideally even for each lens.

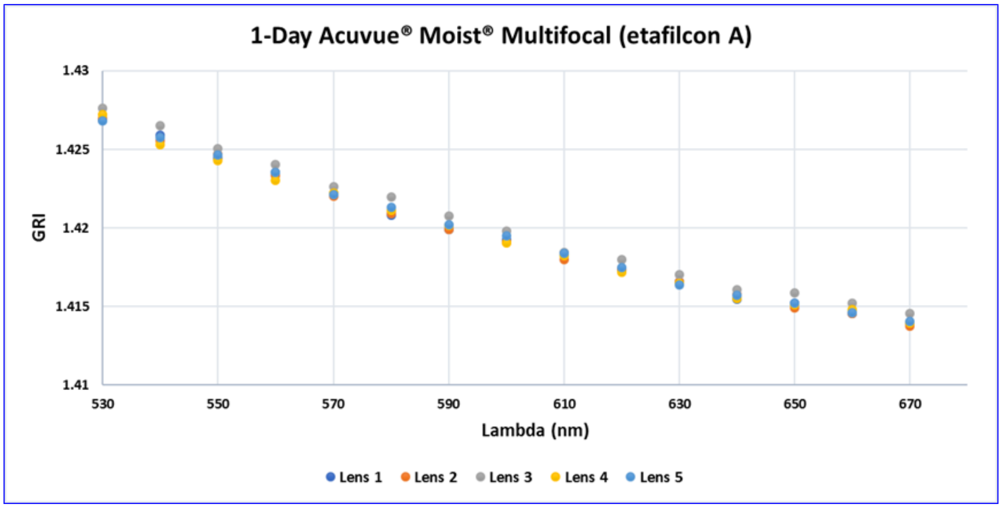

Figure 7 1-Day Acuvue® Moist Multifocal® GRI Dispersion Curve, Multiple Lenses

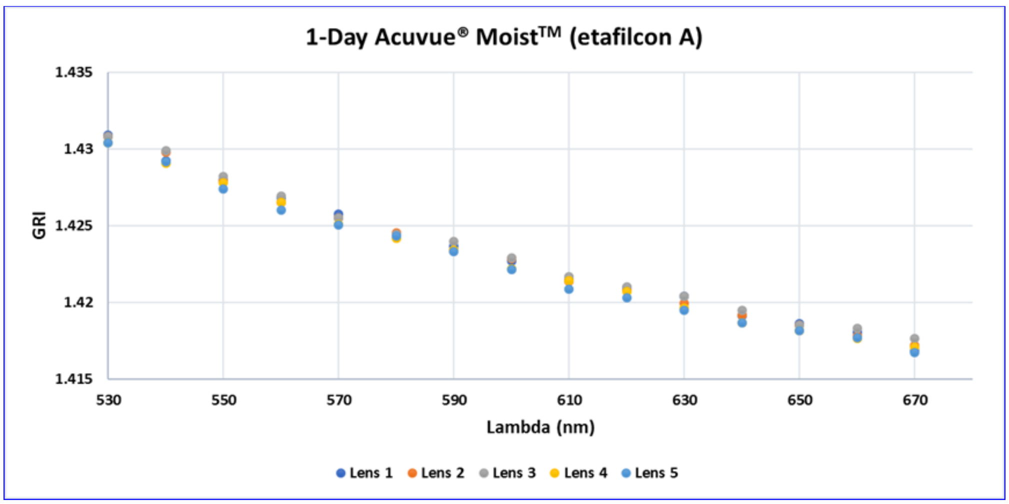

Figure 8 1-Day Acuvue® Moist™ GRI Dispersion Curve, Multiple Lenses

Figure 9 provides an example conversion between group and phase index for etafilcon A. Current capability allows material differentiation and determination of post-manufacturing stabilization. Raw material boundary conditions can be detected as well.

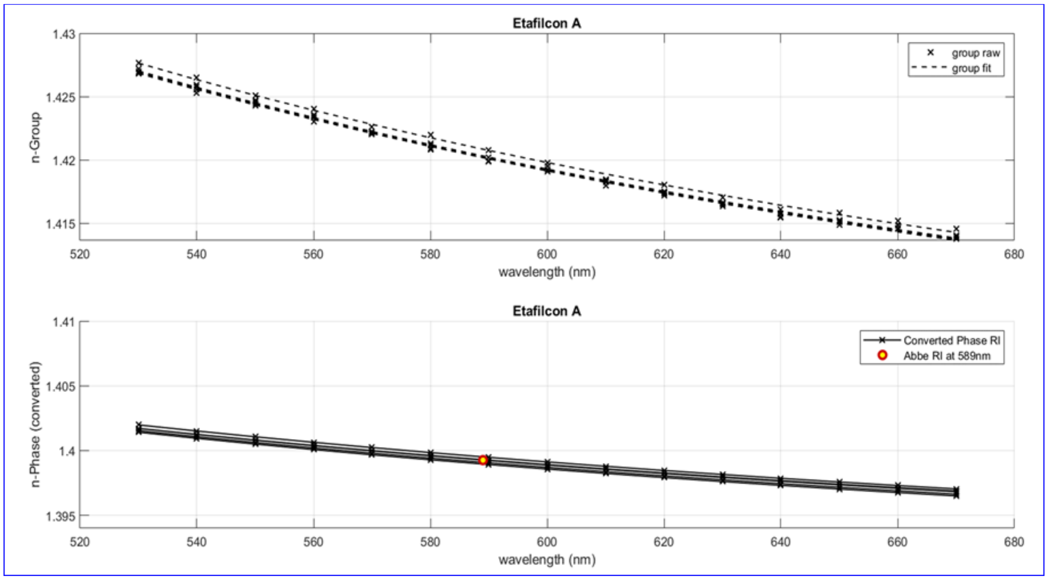

Figure 9 Etafilcon A GRI vs Phase RI Dispersion Curve After Modeling

The conversion accuracy, however, depends on a constant proposed in the model and is not a value that can be directly derived from the GRI or GRI dispersion curve itself. Work is being done to collect a larger data set of known materials to determine if a constant (or constants) can be developed based the estimated phase refractive index of an unknown contact lens material. This is bolstered by the observation that the collected GRI dispersion curves all behave in a very similar manner, if a 2nd order polynomial is fit to either contact lens materials or to the conventional well characterized optical materials. The fit is almost identical, only shifted along the y-axis, see Figure 10. Even with an estimated constant for the conversion, phase RI values are currently being modeled to better than 0.003.

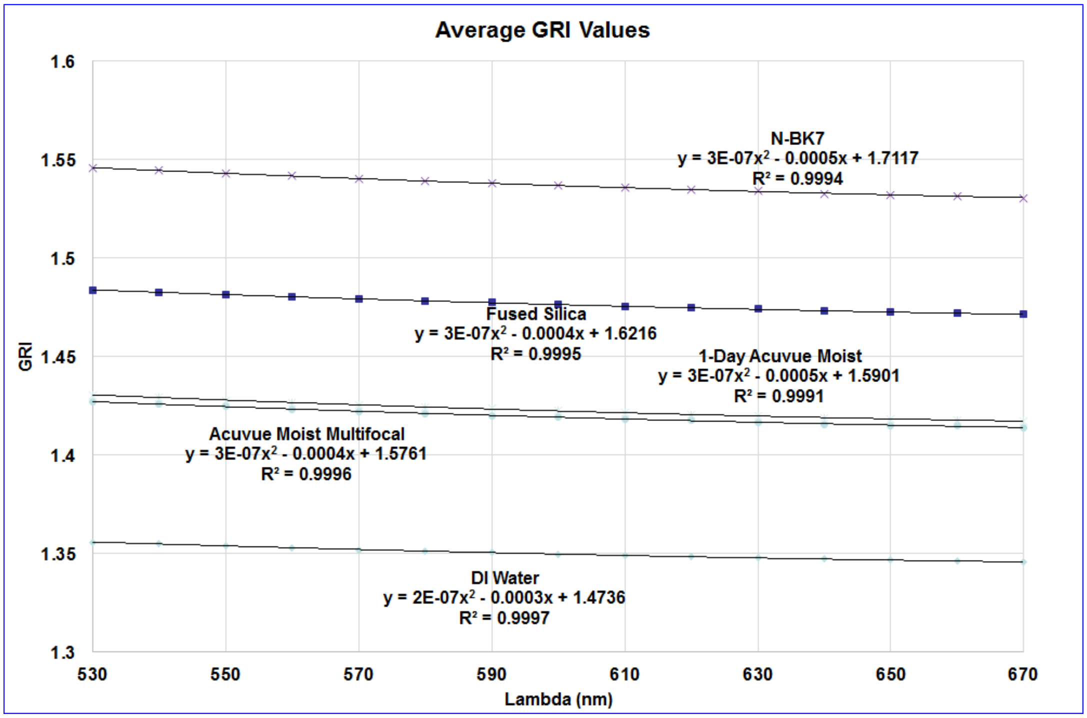

Figure 10 Dispersion Curves of Multiple Materials Comparison

NEXT STEPS

Work is continuing to further develop a model based on the actual measured group refractive index data for well characterized materials (DI water, fused silica, N-BK7) and soft contact lenses. Improvements to the measurement instrument will also lead to the reduction in the number of the measurement sequence steps, to the decrease in lens stabilization times prior to measurement, and help characterize model sensitivity to GRI dispersion fits.

CONCLUSION

The proposed measurement GRI measurement equipment and technique will allow material phase RI characterization at visible wavelengths with high accuracy of 0.003 or better.

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