Multimodal characterization of contact lenses

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ABSTRACT

A table top instrument has been designed, constructed and tested to characterize all of the primary optical and physical properties of contact lenses. Measured optical properties include base power, cylinder power, cylindrical axis, prism, refractive index and wavefront aberrations. Measured physical properties include center thickness, lens diameter and lens sagittal depth. The instrument combines a Shack-Hartmann wavefront sensor (SHWS), a machine vision sensor, and a low coherence light interferometer (LCI) all coaxially aligned into a single tabletop unit. The unit includes a cuvette, mounted in a translatable sample chamber for holding the contact lens under test, and it can be configured to measure wet or dry contact lenses. During operation, the vision sensor measures the diameter of the lens, and locates the center of the lens. The lens is then aligned for other measurements. The vision sensor can also measure various alignment marks on the lens, as well as identify any alpha numerical features, which can be used to associate the lens orientation with the measured aberrations. The LCI measures the center thickness, sagittal depth and index of refraction of the contact lens. The base radius of curvature is then calculated using these measured parameters. The SHWS measures the lenses prescription power, including spherical, cylinder, prism, and higher order wavefront aberrations. NIST traceable calibration artifacts are used to calibrate the SHWS, machine vision and LCI modalities. Repeatability measurements on a contact lens in a saline solution are presented.

Keywords: refractive index, low-coherence interferometry, wavefront sensing, contact lens metrology

1. INTRODUCTION

Ophthalmic lens manufacturers deal with a number of measurement parameters that they need to know in order to create high quality lenses. Important physical parameters of contact lenses include base curve, lens diameter, center thickness, and curvature. The base curve is the radius of curvature of the sphere of the concave back surface of the contact lens and is typically in the range of 8.0 - 10.0 mm. This base curve should match the wearer's cornea for comfort, to facilitate tear exchange and oxygen transmission. The diameter of the contact lens is the size of the outer rim of the lens and the proper diameter is important for fitting to the wearer's cornea, to minimize irritation and to result in appropriate centration of the lens. The central thickness of the lens is also important for proper fitting and in controlling the optical power of the lens. The primary purpose of a contact lens is to correct a patient's vision by adding the appropriate optical power to make the patient emmetropic. The optical performance parameters of the contact lens including power and aberrations are also important. One such parameter, spherical aberration, is important for comfort and satisfaction of the patient, as it is defines the quality of the image that is seen by the wearer of the contact lens and it is often added to presbyopia correcting lenses.

The ClearWave^{TM} Contact Lens Aberrometer is a commercially available system designed to measure the optical properties of contact lenses. It integrates a Shack-Hartmann wavefront sensor with a collimated light source, a contact lens sample holder, and a motorized automatic collimating system. It is optimized for the measurement of contact lenses over the standard power range manufactured by the world's top contact lens suppliers. The Optigauge^{TM} is also a commercially available system and is used to measure contact lens center thickness.

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2. INSTRUMENTATION OVERVIEW

A prototype combination instrument for multimodal characterization of contact lenses was constructed by combining the functionality of a dual low-coherence all-fiber interferometer, a vision sensor and a wavefront aberrometer into one benchtop unit. The instrument was constructed by modifying a Clearwave^{TM} Contact Lens Aberrometer to accept an optical probe coupled to an OptiGauge^{TM}, both manufactured by Lumetrics, Inc. Figure 1 shows an image of the commercially available Clearwave^{TM} Contact Lens Aberrometer on the left (A) and the modified instrument with optical probe attached on the left (B). A schematic of the combined instrument is shown in Figure 2 which will be used to explain the principle of operation.

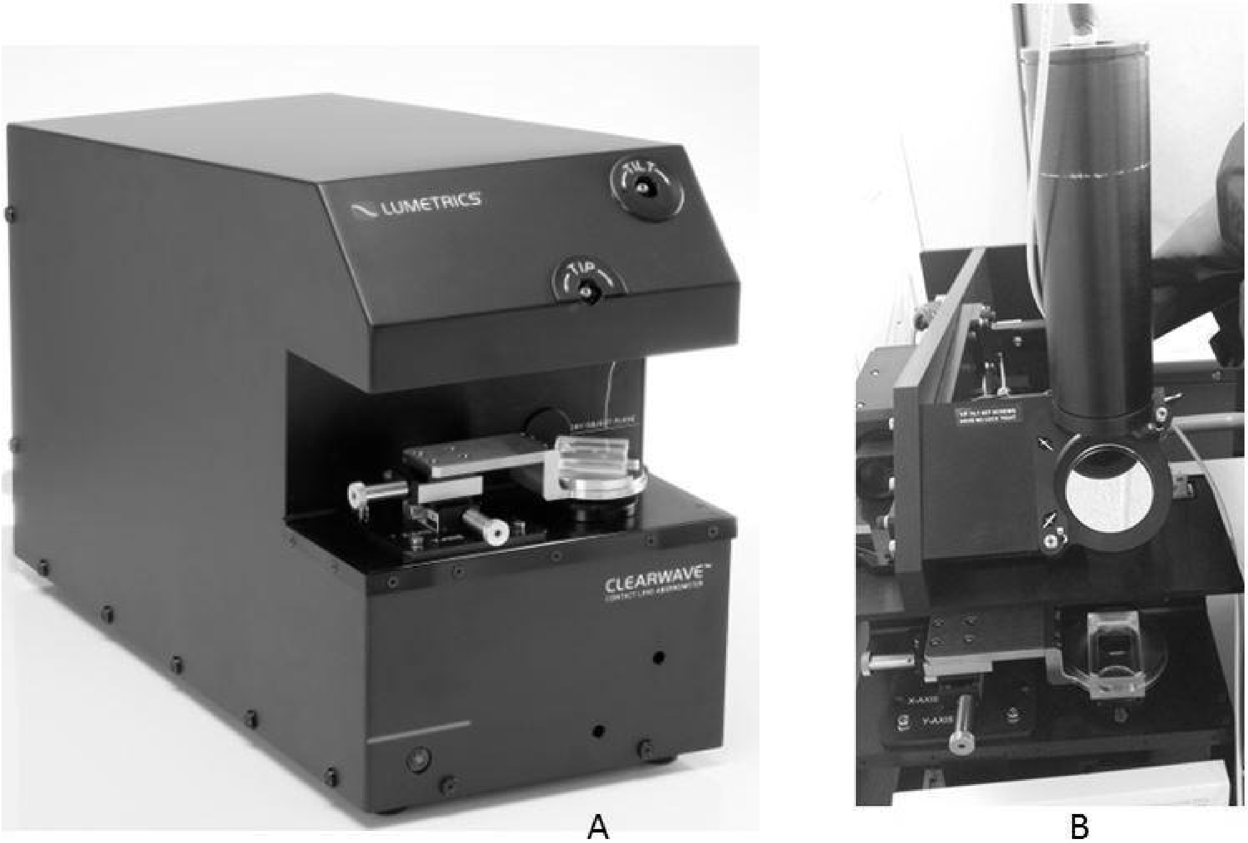

Figure 1. The Clearwave^{TM} Contact Lens Aberrometer instrument is shown on the left side (A) and the modified instrument with the optical probe set up and aligned is shown on the right side (B).

Green Light from a point LED light source (LS) shown at the top of Figure 2 is collimated using a lens mounted a distance away from the point source equal to the focal length of the lens. The collimated light from a green light source (LS) is incident on a Shack Hartmann wavefront sensor (SHWS) shown at the bottom of Figure 2. The vertical lines are drawn to show the width of the illumination beam emanating from the light source (LS). After collimation, the light beam is first transmitted through a dichroic beam splitter (hot mirror), which allows infrared light from a low coherence interferometer (LCI) to be combined with the collimated light beam. The LCI beam is aligned so that it is centered with respect to the SHWS. It is noted that in the example prototype instrument shown in Figure 1, the position of the LCI probe and the point LED light source (LS) are reversed as compared to the configuration shown in Figure 2 and a cold mirror is used instead of a hot mirror. The collimated light beam then passes through a 1" diameter open aperture of a

XYθ stage which is installed in the instrument. The XYθ stage is constructed having a cuvette holder with ledges adjacent to an open aperture and is configured to hold a measurement cuvette loaded with the contact lens under test. The X and Y positions and angular orientation of the cuvette can be adjusted to ensure that the lens is centered during center thickness and wavefront measurements. When the lens is mounted into the cuvette collimated light from light source LS passes through the contact lens and then passes through a beam splitter (BS) located above the SHWS. The beam splitter (BS) is located below the XYθ stage and it functions to split the collimated light into two beams, one going to the SHWS and the other going to a vision camera. The lens in front of the vision camera is used to focus the light onto the imager surface. The present imaging demagnification factor of the lens is 5.58x.

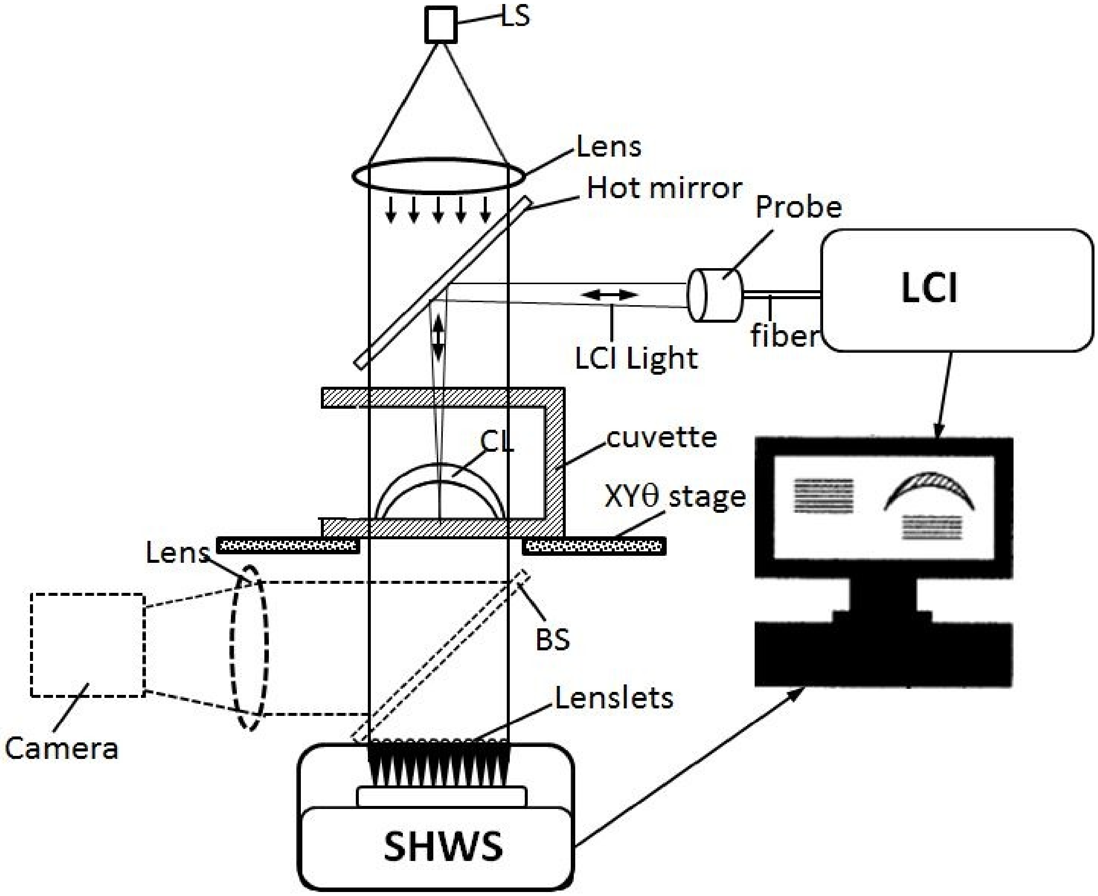

Figure 2. Schematic showing the optical layout of an example prototype instrument to perform multimodal characterization of contact lenses.

3. Measurement Detail and Results

The following is the measurement procedure for the multimodal characterization of contact lenses. First the lens is placed in a cuvette filled with saline solution and is mounted into the cuvette holder of the instrument. The lens is observed with the vision camera and the diameter and location of the center of the lens is measured using custom developed software. The lens is then concurrently centered with respect to the low coherence interferometer beam and the SHWS using the XY stages holding the cuvette. The center thickness and sagittal depth of the lens are then measured using the Optigauge^{TM} LCI. The lens index of refraction can also be determined with the LCI as described previously[5]. The lens base curve is then calculated from the measured diameter and sagittal depth measurements. The base curve data, diameter, center thickness data and lens index of refraction are then used as inputs for the Clearwave^{TM}. The wavefront deviations of light passing through the lens are then analyzed using the Clearwave^{TM} SHWS and the lens power and aberrations of the lens are determined as described previously[1-4].

3.1 Lens Diameter Measurements

The vision imaging camera is a Firewire monochrome camera (Imaging Source model DMK21AF04) utilizing a ¼" Sony CCD having 640 x 480 pixels for measuring the lens in the cuvette. The pixel size of the imager is 5.6 μm square and the imaging optics results in a magnification at the image plane of 31.250 μm per camera pixel. After the lens is mounted into the instrument measurement chamber the vision camera captures and displays live video images of the lens mounted in the instrument. The analysis software uses a combination of Canny edge detection together with circle fitting and masking to find the lens diameter.

The X and Y axis transport stages are adjusted until the full lens appears in the camera image. Figure 3 shows images of an example lens before (A) and after centering (B). The large white spot in camera image A on the left is the image of the LCI light beam which is in focus at the location of the lens and is beyond focus at the focal plane of the camera. The small white dots in the image are artifact images of green LED light reflecting back from the lenslets on the wavefront sensor and back from the bottom of the cuvette and then into the camera imager. Once the camera is viewing the entire lens as shown in Figure 3A, the user initiates the measurement. The software automatically calculates the diameter and center location of the lens and shows the outline of the outer diameter as a red circle and the center location as a green dot. In the current implementation of the instrument, the user then manually adjusts the position of the X and Y stages to center the low coherence light source over the center green dot as shown in Figure 3B. When the LCI light source overlaps the center position of the lens, as shown in Figure 3B, the software measures the center thickness and the sagittal depth of the lens.

3.2 Center Thickness, Sagittal Depth and Refractive Index Measurements

The LCI utilized in the instrument is based on a commercially available dual low-coherence all-fiber interferometer (OptiGauge^{TM}, Lumetrics, Inc.). Low coherence light from a superluminescent light emitting diode (SLED), having a center wavelength of 1310 nm and a bandwidth of about 50 nm is sent through an optical fiber and then through an optical probe which is used to focus light on the sample which in this case is a contact lens mounted in a cuvette filled with saline solution. Light reflecting off of each optical interface of the sample passes back through the optical probe, back through the optical fiber and then enters into the all-fiber dual Michelson interferometer.

The LCI measurement geometry is shown in Figure 4 for a contact lens mounted in a cuvette filled with saline solution. The physical distance from the inner wall of the cuvette top to the inner wall of the cuvette bottom is d_o. The saline solution has an index of refraction n_s. The LCI measurements are performed with the lens being centered over the optical probe of the LCI. The lens has physical thickness t_l and the optical thickness $n_l t_l$ is measured where n_l is the refractive index of the lens. The physical sagittal depth or sag of the lens is defined as S and the optical distance $n_s S$ is measured. Once the measurements are performed as shown in Figure 4, the lens can be removed from the cuvette without moving the cuvette so that $n_s d_o$ can be measured at the same location. The solution is then removed from the cuvette without moving the cuvette to measure d_o directly using the known refractive index of air. Figure 5 shows a sample LCI scan of the lens shown in Figure 3 measured at the location shown in Figure 3B. Further details of the measurement procedure to measure index of refraction and center thickness are described in reference 5 along with the appropriate relationships.

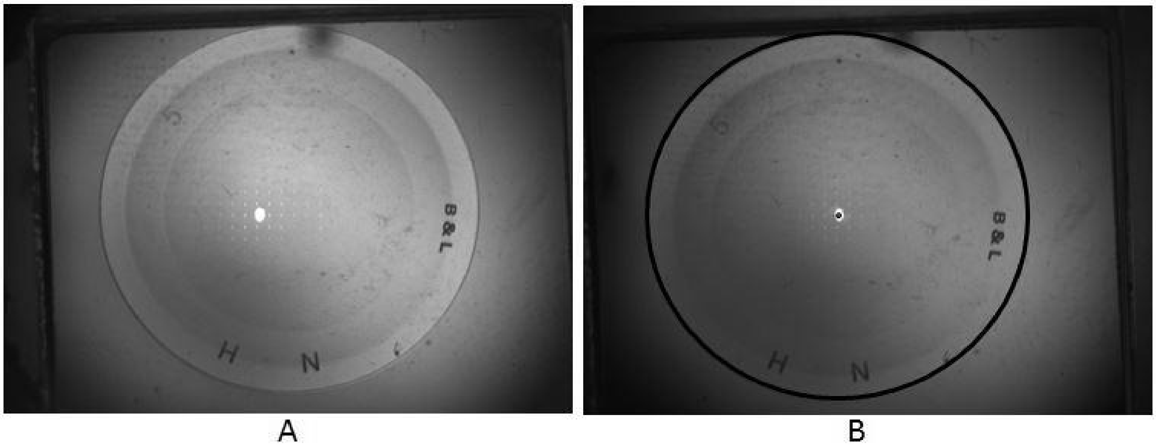

Figure 3. The vision camera view of a lens, when (A) the cuvette has been placed into the measurement position, and (B) when the lens has been aligned with the measurement beam.

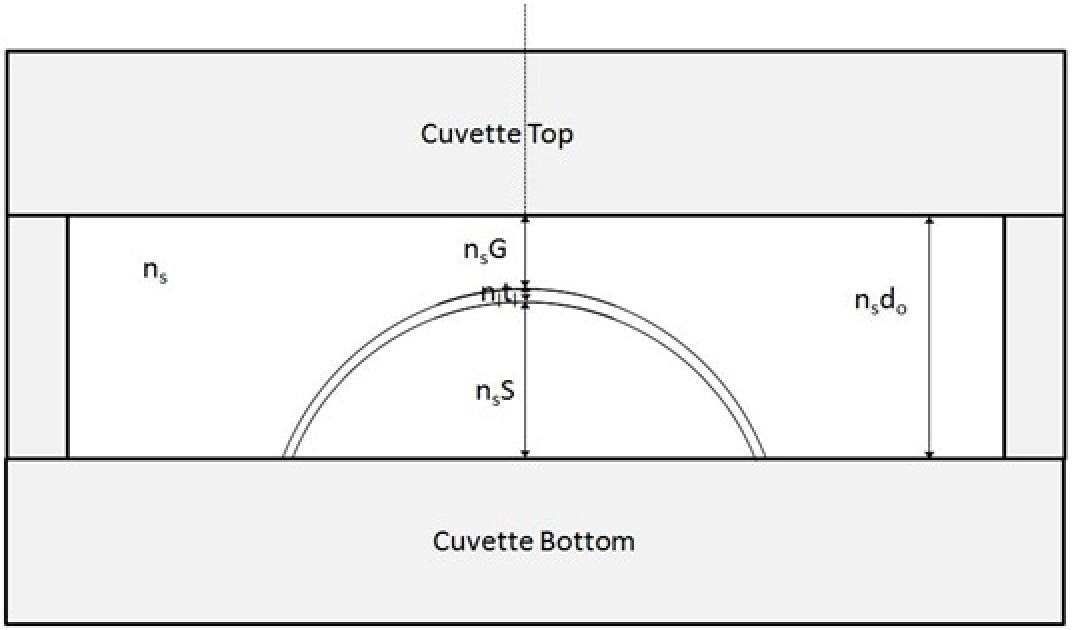

Figure 4. Geometry for measurement of a contact lens mounted in a cuvette containing saline solution and the LCI parameters being measured.

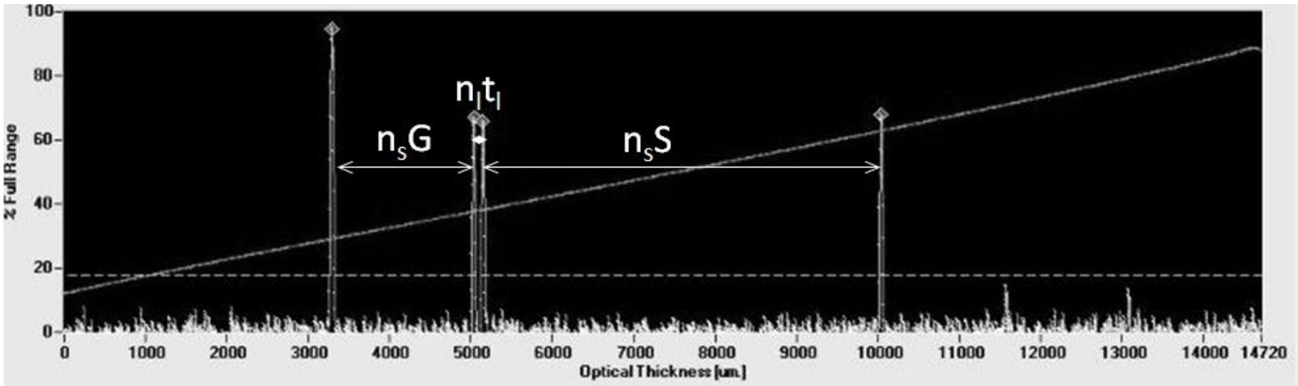

Figure 5. LCI scan signal of the lens shown in Figure 3 measured at the location shown in Figure 3B.

3.3 Base Curve Calculations

The base curve BC of the lens can be calculated from the measured sagittal depth S and the measured lens diameter using the geometry shown in Figure 6. The base curve BC is given by the relationship

$$BC = (D^2 + 4S^2)/8S.$$

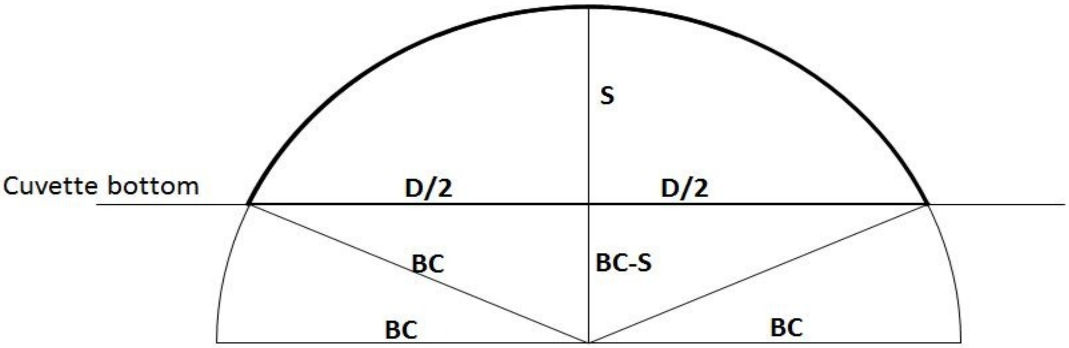

Figure 6. Measurement Geometry for calculating the base curve BC of the lens from measured diameter and sagittal depth.

Table 1 shows data for 10 repetitive loadings of the same lens mounted in a cuvette as shown in Figure 3. The index of refraction of the lens and the saline index were measured during the first measurement and were performed by the three step measurement procedure described in reference 5. The measured lens index of refraction at 1310 nm was 1.4050 and the measured saline solution index of refraction at 1310 nm was 1.3402. Each value of G, t_l and S shown in Table 1 is an average of ten repeats of 3-second averages of data obtained at a 50 Hz measurement rate. The values of the index of refraction for the lens and saline solution calculated during the first measurement sequence were used for calculating the top gap G, lens thickness t_l and lens sagittal depth S shown in the table for measurements 2 - 10. In between each measurement set, the cuvette containing the lens was removed from the platform and replaced in the mount and recentered before obtaining each individual set of measurements. Table 2 shows the statistics for these repeat measurements. It is noted that temperature was not monitored during these initial measurements.

Table 1. LCI sagittal depth and lens thickness together with vision diameter and base curve calculations for 10 repetitive measurement of the lens shown in Figure 3.

Top Gap G (μm)	**Lens thickness t_l (μm)**	**Lens Sag S (μm)**	**Lens Diameter D (mm)**	**Lens Base Curve BC (mm)**
1374.340	80.214	3615.680	14.123	8.703
1374.320	80.234	3615.653	14.123	8.704
1374.305	80.234	3615.682	14.125	8.705
1374.376	80.205	3615.653	14.119	8.700
1374.573	80.215	3615.475	14.120	8.701
1374.709	80.211	3615.345	14.118	8.699
1373.987	80.195	3615.813	14.115	8.695
1373.830	80.236	3615.818	14.107	8.688
1373.544	80.179	3616.248	14.093	8.673
1371.018	80.183	3618.865	14.064	8.642

Table 2. Statistics for the data shown in Table 1.

	Top Gap G (μm)	**Lens thickness t_l (μm)**	**Lens Sag S (μm)**	**Lens Diameter D (mm)**	**Lens Base Curve BC (mm)**
mean	1373.900	80.211	3616.023	14.105	8.691
stdev	1.070	0.021	1.026	0.020	0.020
max	1374.709	80.236	3618.865	14.120	8.705
min	1371.018	80.179	3615.345	14.064	8.642
range	3.691	0.057	3.520	0.056	0.064

Figure 7 shows the calculated base curve as a function of measured lens diameter. Note that the lens diameter and sagittal depth can be measured at the same time, and therefore allow for studying the settling time of a lens after it is placed into saline solution. Also the effect of temperature on these parameters can be investigated.

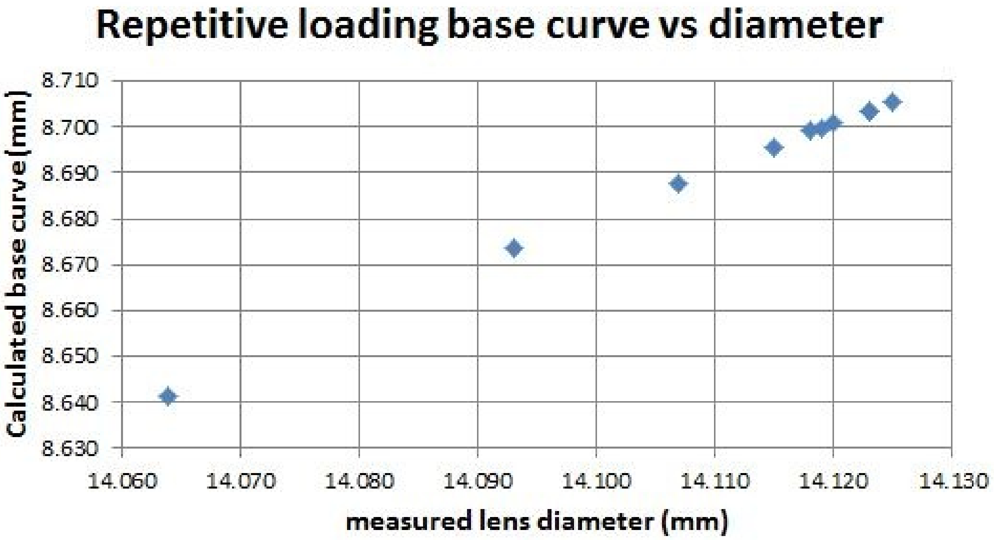

Figure 7. Calculated base curve versus measured lens diameter for the repeat loading measurements shown in Table 1.

3.4 Wavefront Sensor Data and analysis

ClearWave^{TM} data is output to an excel spreadsheet compatible file. Table 3 shows partial data from the file, which has been re-formatted to improve the readability. The analysis diameter is defined by the operator. The Shack-Hartmann wavefront analysis application uses a least-squared fit method to calculate the Zernike coefficients for the transmitted wavefront of the contact lens under test over the defined analysis diameter. All contact lens optical parameters are calculated from the Zernike coefficients and the results of the ClearWave^{TM} analysis routine. Table 3 is organized to show the input values on the left, the calculated parameters in the center and the Zernike polynomial coefficients measured on the right.

Table 3: Partial measurement data obtained from ClearWave™

Inputs	**Value**	**Outputs**	**Value**	**Zernike Coefficients**	**Value, µm**
Analysis Diameter	5 mm	**Lens power**	-3.6088 D	**Z(1,-1)**	-1.7064
Lens diameter	14.123 mm	**Cylinder power**	-0.0471 D	**Z(1,1)**	4.1093
Lens Thickness	80.214 µm	**Cylinder Axis**	43.1 deg	**Z(2,-2)**	0.0298
Base curve radius	8.703 mm	**Coma**	0.1774 D	**Z(2,0)**	-3.3934
Refractive index, saline	1.3402	**Spherical equiv. power**	-3.6324 D	**Z(2,2)**	0.0019
Refractive index, lens	1.4050	**Prism power**	0.356 D	**Z(3,-3)**	-0.0013
Temperature	23.86 ^{o}C	**Prism Axis**	157.4 deg	**Z(3,-1)**	0.0261
		Longitudinal spherical aber.	2.0265 D	**Z(3,1)**	-0.1578
		Higher order error	0.0323 µm	**Z(3,3)**	0.0249
				Z(4,-4)	0.0100
				Z(4,-2)	-0.0111
				Z(4,0)	-0.2360
				Z(4,2)	0.0035
				Z(4,4)	-0.0136

4. CONCLUSIONS

A prototype instrument has been developed for multimodal characterization of contact lenses. The instrument combines a vision camera, which measures the diameter and location of the center of the lens, together with a low coherence interferometer to measure the center thickness and sagittal depth of the lens, and a wavefront sensor, which uses the input from the interferometer and vision camera to calculate the optical performance parameters of the contact lens. The interferometer can also be used to measure the index of refraction of the lens and kinetics of changes in thickness, sagittal depth and index during hydration in saline solution. Temperature effects on the physical and optical properties of the lens can also be investigated. The combination instrument provides the capability to measure all of the important optical parameter of a contact lens at the same time using a single instrument.

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