Research Article

Individual IOL Surface Topography Analysis by the WaveMaster Reflex UV

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Purpose. In order to establish inspection routines for individual intraocular lenses (IOLs), their surfaces have to be measured separately. Currently available measurement devices lack this functionality. The purpose of this study is to evaluate a new topography measurement device based on wavefront analysis for measuring individual regular and freeform IOL surfaces, the “WaveMaster Reflex UV” (Trioptics, Wedel, Germany).

Methods. Measurements were performed on IOLs with increasingly complex surface geometries: spherical surfaces, surfaces modelled by higher-order Zernike terms, and freeform surfaces from biometrical patient data. Two independent parameters were measured: the sample's radius of curvature (ROC) and its residual (difference of sample topography and its best-fit sphere). We used a quantitative analysis method by calculating the residuals’ root-mean-square (RMS) and peak-to-Valley (P2V) values.

Results. The sample's best-fit ROC differences increased with the sample's complexity. The sample's differences of RMS values were 80 nm for spherical surfaces, 97 nm for higher-order samples, and 21 nm for freeform surfaces. Graphical representations of both measurement and design topographies were recorded and compared.

Conclusion. The measurements of spherical surfaces expectedly resulted in better values than those of freeform surfaces. Overall, the wavefront analysing method proves to be an effective method for evaluating individual IOL surfaces.

1. Introduction

Cataract surgery has been the most frequent surgical procedure for the last decades. Its primary goal was to restore the patient’s vision. Currently, the patient’s satisfaction and the restoration of the target refraction are of heightened interest. This leads to extensive research on more sophisticated lens surfaces which can eliminate even higher-order aberrations of the patient’s optical system. With the aim of maximal improvement of the patient’s visual performance, the latest developments focus on IOLs with customized freeform surface geometries which compensate corneal aberrations [1–3]. They are produced by a nonpolishing lathing process which offers new challenges for postprocessing lens quality inspection.

To our knowledge, there is no system available for scanning individual IOL surfaces. Currently, the quality inspection of conventional IOLs is done directly in the production chain by interferometry, deflectometry, or wavefront sensors. Interferometry devices compare signals from the sample’s surface and focus mainly on spherical surfaces. They are considered the golden standard for optical lens surface inspection. Their limited dynamic range, however, limits their application to basic lens geometries, such as rotationally symmetric or aspheric IOL surfaces. More complex surfaces require sophisticated measures to stay within their limited dynamic range [4, 5]. Deflectometric devices evaluate an IOL surface by projecting a pattern (e.g., lines, chessboard patterns) and analyse its deformation in a camera image [5, 6]. Most setups work in reflection mode with wavelengths in the visible range. Therefore, light is partly reflected off the front surface, while a major part of light is transmitted and reflected off the back side. Both signals are simultaneously received at the detector and interfere with each other. This leads to artefacts and disturbs the measurement. As the IOL is supposed to be implanted after having passed inspection, exposing it to fluids or wax to suppress the back surface reflections is unacceptable. Topography measurements by
wavefront sensors are affected by the same issues because
current wavefront sensors operate in the visible spectrum.

In order to measure individual surfaces under sterile
conditions, we introduce a new device for measuring indi-

dual IOL surface topographies: The WaveMaster Reflex UV
(Trioptics, Wedel, Germany). Like its predecessors, the Wave-
Master IOL and the WaveMaster Pro Reflex, it operates by a
Shack-Hartmann sensor (SHS) setup [7]. Both predecessors
are, however, not designed for measuring the IOL topography
but rather its visual performance. They operate with radiation
in the visible range. Therefore, signals from the IOL back side
are always overlapped with front surface signals. One can,
though, suppress those signals by blackening the back side
of the IOL, but this would desterilize the IOL. The novelty
of the WaveMaster Reflex UV is its operation in the near-
UV range of 365 nm. The radiation in this wavelength is
greatly absorbed inside the IOL material, so that undesired
UV back reflexes are suppressed. The novel achievement of using
near-UV radiation in an SHS-based IOL topography scanner
enables the sterile measurement of individual IOL surface
topographies.

The aim of this paper is to demonstrate the applicability
of the new WaveMaster Reflex UV in the field of measuring
individual IOL surface topographies.

2. Materials and Methods

The measurements were performed in a lab environment at a
temperature of 22 °C.

All measured IOLs are made from Contamac blanks [8].
We perform measurements on three kinds of surface topogra-
phies The first group contains spherical surface geometries
with radii of curvature (ROCs) between 6 mm and 20 mm.

The second group consists of six samples with surface
geometries representing a superposition of higher-order
aberrations: Zernike coefficients of coma, astigmatism, tre-
foil, and tetrafoil are added to a spherical surface with a base
ROC of 11.5 mm to model higher-order aberrations [15]:

\[
Z(x, y) = Z_{\text{Sphere}}(x, y) + Z_{\text{Coma}}(x, y) + Z_{\text{Tetrafoil}}(x, y)
\]

\[
Z_{\text{Sphere}}(x, y) = \sqrt{11.5^2 - (x^2 - y^2)},
\]

\[
Z_{\text{Coma}}(x, y) = K \cdot ((-2) \cdot mx + 3 \cdot mx \cdot (mx^2 + my^2)),
\]

\[
Z_{\text{Tetrafoil}}(x, y) = -K \cdot (x^4 - 6 \cdot x^2 \cdot y^2 + y^4),
\]

\[
mx = x \cdot \cos(\Phi) - y \cdot \sin(\Phi),
\]

\[
my = x \cdot \sin(\Phi) - y \cdot \cos(\Phi).
\]

The six surfaces are calculated according to the following set
of parameters:

Sample 1: \( \Phi = 0^\circ; K = 0.0001 \);
Sample 2: \( \Phi = 0^\circ; K = 0.0003 \);
Sample 3: \( \Phi = 0^\circ; K = 0.0005 \);
Sample 4: \( \Phi = 180^\circ; K = 0.0001 \);
Sample 5: \( \Phi = 180^\circ; K = 0.0002 \);
Sample 6: \( \Phi = 180^\circ; K = 0.0003 \).

They are referred to as “higher-order samples.”

The third group holds two customized lenses derived
from biometric patient data [1–3]. A general quadric surface
is described by the following equation:

\[
S(x, y, z) = Ax^2 + By^2 + Cz^2 + 2Dxy + 2Eyz + 2Fzx + 2Gx + 2Hy + 2Iz + K = 0.
\]

Alternatively, the surface can be described in matrix nomen-
clature by

\[
S = \begin{bmatrix}
A & D & F & G \\
D & B & E & H \\
F & E & C & I \\
G & H & I & K
\end{bmatrix}.
\]

The coefficients of the two surfaces under investigation are

Sample 1:

\[
\begin{bmatrix}
1 & -0.094 & -0.065 & 0.025 \\
-0.094 & 1.135 & 0.101 & -0.039 \\
-0.065 & 0.101 & -2.897 & 7.660 \\
0.025 & -0.039 & 7.660 & -5.211
\end{bmatrix}.
\]

Sample 2:

\[
\begin{bmatrix}
1 & -0.028 & -0.131 & 0.060 \\
-0.028 & 0.992 & -0.272 & 0.007 \\
-0.131 & -0.272 & -7.195 & 11.259 \\
0.060 & 0.007 & 11.259 & -4.541
\end{bmatrix}.
\]

This group is labelled “freeform samples.”

The WaveMaster Reflex UV is an SHS-based IOL topogra-
phy scanner in reflection mode and measures the wavefront
aberrations caused by the IOL front surface (Figure 1). The
fibre-coupled UV-radiation (365 nm) is directed to the sam-
ple by a beam-splitter. The main part of the incoming beam
is reflected by the first surface, while the rest is absorbed in
the lens because of its high absorption in the near-UV range.
The reflected part passes through the beam splitter and is
imaged by a microlens array to the SHS. The components are
optimized for UV radiation and measure the deviation from a
spherical wavefront. This deviation is labelled “residual” in
this work.

Figure 2 shows a standard measurement procedure: every
sample is measured along the optical axis in two critical
positions: the cat’s eye position (CE) and measurement
position (MP). They are similar to interferometric measure-
ments. In the cat’s eye position, the surface’s apex is imaged;
each ray is reflected in its opposite direction towards the
sensor. The measurement position is distinguished by the
fact that each ray is reflected back to its original position
(see arrows in Figure 2(b)); the entire area is imaged. In
this position, the device measures the residual (Difference of
Figure 1: Scheme of the beam path of the WaveMaster Reflex UV. The light is coupled into the left. It hits the beam splitter and is then imaged to the sample. The reflected part passes back through the beam splitter. It is imaged onto the SHS which detects the deviation from a purely spherical wavefront.

Figure 2: Scheme of the WaveMaster Reflex UV’s measurement positions. (a) Shows the CE position of the sample, (b) sketches the MP. The path difference along the optical axis corresponds to the sample’s best-fit ROC.

Sample topography and its best-fit sphere for the measured area) and displays it in a colour-coded map (Figure 3). The user moves the sensor setup by a motorized stage along the optical axis to find the CE and MP positions. Their axial difference is the sample’s best-fit ROC. This is the common measurement procedure known from interferometric setups.

The device features the fitting of the measured residual to a Zernike composition, displaying the values of the respective Zernike coefficients [9, 10].

The defocus term is used by the device as the criterion for acquiring the CE and MP positions along the optical axis. In those positions, it is required to be below lambda/10, that is, 37 nm.

The coefficients for tilt in the x and y direction are labelled with arrows in Figure 4. They guide the user in the sample centration process. The sample is fixed and aligned to its holder during the production process. The holders themselves are inserted to the mount of the device’s moving table. A tilt of the lens itself is unexpected. Therefore, any measured tilt is associated with a lateral misalignment of the sample with respect to the device’s optical axis. A laterally centered stage results in minimal tilt coefficients.

The measured residual can be compared against a set of surface geometries such as spherical and aspherical, toric and user-defined freeform surfaces. The design topography is limited to the measured part of the surface to ensure comparability. The analysis screen consists of four panels (Figure 5): The first three (upper left, upper right, and lower left, titled “Wavefront,” “Reference,” and “Residual”, resp.) hold colour-coded plots. The “Wavefront” and “Reference” panels show the measured residual and the design residual with a best-fit sphere subtracted from its topography. The corresponding ROC is shown to the right, next to the label “Reference.” The “Residual” panel shows the difference between the measured residual in “Wavefront” and the design residual in “Reference.” The RMS and P2V values are calculated for all three panels and listed to the right of the labels.
In the evaluation process, we record the following parameters: the sample’s best-fit ROC and its residual. The ROC serves as a representation of its lower-order aberrations [11]. It has a major effect on the IOL refractive power and is therefore primarily associated with its basic visual performance. The theoretical value for the ROC is either given by the manufacturer in case of spherical surfaces or derived from the design data by the analysis software of the WaveMaster Reflex UV.

The residual evaluation consists of two parameters: the RMS and P2V values [12–14]:

Let $z_i(x_i, y_i)$ be the height value for the $i$th pixel from the total of $n$ pixels; then

$$\text{RMS} = \frac{\sqrt{\sum_i (z_i(x_i, y_i) - \bar{z})^2}}{n}, \quad \bar{z} = \frac{\sum_i z_i(x_i, y_i)}{n},$$

$$\text{P2V} = \max (z_i(x_i, y_i)) - \min (z_i(x_i, y_i)).$$

The RMS and P2V values of spherical lenses are supposed to be zero. In case of nonspherical lenses, the measurement values have to match the corresponding values of the design data. As the RMS and P2V values represent averaged values of a measured residual, they serve to discern any major deviations between design and actual measurements. They do not reveal any information about the location of defects. This point is addressed by comparing the measured residual map against the design residual (see Figure 5).

3. Results

3.1. ROC Measurements. Table 1 contains the ROC measurements of spherical surfaces. The ROC ranges from 6 mm to 20 mm with a step size of 2 mm. Between 12 mm and 16 mm, a smaller step size of 0.5 mm was chosen. The measured and the design ROCs are listed in the second column. The fourth column holds the difference between measurement and design in $\mu$m. The average value for the ROC differences between design and measurement was calculated to 18 $\mu$m with a standard deviation (SDV) of 12 $\mu$m.
The ROC measurements for the higher-order surface geometries are listed in Table 2. The average ROC difference between measurement and design was calculated to be $36 \mu m$ with a standard deviation of $5 \mu m$.

Table 3 holds ROC measurements for two IOLs with freeform geometries. As only two surfaces are measured here, the data is provided for descriptive purposes only.

The values for the measured residual of the spherical surfaces are listed in Table 4. Their average values are calculated to be $79 \text{nm}/422 \text{nm}$ with a standard deviation of $49 \text{nm}/149 \text{nm}$.

Table 5 shows the results for the residual analysis of the higher-order samples. The last two columns hold the differences between measurement and design for the respective values of RMS and P2V. The average values for the differences are found in the last two lines and are calculated to be $97 \text{nm}/415 \text{nm}$ with corresponding values for their standard deviations of $99 \text{nm}/439 \text{nm}$.

The results for the residual analysis are found in Table 6. The resulting differences between measurement and the design data are in the range previously measured: Several $10 \text{nm}$ for RMS values and several $100 \text{nm}$ for the P2V values. Although the two surface geometries are quite different from each other, the numbers are in the same order of magnitude.

### Table 4: Residual analysis for spherical surfaces.

| Sample | Measured RMS/\(\mu m\) | Measured P2V/\(\mu m\) |
|--------|--------------------------|-------------------------|
| Sph 6  | 0.060                    | 0.319                   |
| Sph 10 | 0.051                    | 0.308                   |
| Sph 12 | 0.066                    | 0.369                   |
| Sph 12.5 | 0.061                | 0.400                   |
| Sph 13 | 0.068                    | 0.435                   |
| Sph 13.5 | 0.044                 | 0.305                   |
| Sph 14.5 | 0.060                 | 0.344                   |
| Sph 15 | 0.233                    | 0.844                   |
| Sph 15.5 | 0.066                 | 0.505                   |
| Sph 16 | 0.046                    | 0.325                   |
| Sph 18 | 0.098                    | 0.564                   |
| Sph 20 | 0.100                    | 0.346                   |
| Average | 0.079                | 0.422                   |
| SDV    | 0.049                    | 0.149                   |

### 3.2. Residual Maps of Patient Data.

The results for freeform surface 1 are shown in Figure 5(a). The surface shows a saddle-shaped pattern, typical for toric surfaces. A direct comparison of "Wavefront" with "Reference" may lead to the conclusion that the measured residual matches the design residual. However, looking at the "Residual" panel reveals the major differences in the peripheral areas to the left and to the bottom of the display.

The graphical residual analysis for the second freeform surface is listed in Figure 5(b). The major differences between measurement and design data are located in the centre and calculated to be about $1 \mu m$. The cross-section panel reveals a slight dip in the centre with a depth of about $0.2 \mu m$.

### 4. Discussion

The measurement of individual IOL surfaces by the wavefront analyser in the near-UV range is straightforward and accurate. Measurements on clinically available topographers revealed that there can be only a limited range of ROCs measureable by the device [15]. In contrast, the device is able to measure all ROCs between $6 \text{mm}$ and $20 \text{mm}$. The average deviations are less than $20 \mu m$ for spherical samples. This might be due to the z-stage's moving precision or manufacturing precision of the sample. The small standard deviation in the ROC acquisition demonstrates the minor amount of statistical errors in the acquisition of the CE and MP positions. The measurements on higher-order samples result in larger ROC differences between measurement and design data. The average value is with $36 \mu m$ higher than in case of spherical surfaces. As individual freeform components of varying magnitudes are introduced, the concept of a definitive ROC is ambiguous. The sample's design ROC is calculated according to the least-mean-squares method while the measured ROC is acquired as the axial difference between CE and MP positions. The standard deviation of $5 \mu m$ indicates that the ROCs of higher-order surface geometries are accurately measured. In case of the freeform IOL surfaces, the deviations are much higher compared to the previous ones. They consist of values around $340 \mu m$. This increase is caused by the increasingly complex surfaces. Calculating a ROC is an approximation to the measured area, which explains the larger deviations.

Measuring the RMS and P2V values of spherical surfaces shows the precision of the device. The values are well below $1 \mu m$, with the RMS values being one order of magnitude less than their corresponding P2V values. Since the design data consist of spherical surface geometries, those numbers directly reflect the manufacturing and measurement precision. The measurements on the higher-order samples match their respective design data. From Ho 1 to Ho 3 there is an increase of values, as is the case with Ho 4 through Ho 6. Ho 3 has the highest amount of values for both RMS and P2V values, which is in accordance with it having the highest amplitudes of Zernike coefficients. Ho 2 and Ho 6 share the same amplitude in their Zernike terms (0.003), with different angle values (0° and 180°). Hence, it was expected that the measurements of those samples should give equal values. This is experimentally confirmed. The surface geometries are more complex; therefore, the standard deviation is higher than in the case of measuring spherical samples. The measurements of the freeform samples lead to similar results.

The measurements of individual freeform surfaces result in smaller values for the RMS and P2V differences than in the case for higher-order sample geometries.

Looking at the graphical analysis of the first freeform surface, the patterns for measurement and its design data closely match. The most critical deviations are located in the lower left part of the measurement area. We conclude that there is a slight decentration of the sample which results in the pattern seen in Figure 5. This issue can be solved by an individual postprocessed centration of the IOL. The patterns of the second freeform surface differ more. Particularly the
Table 5: Residual analysis for higher-order surfaces.

| Sample | Measurement | Design | Difference |
|--------|-------------|--------|------------|
|        | RMS/μm | P2V/μm | RMS/μm | P2V/μm | RMS/nm | P2V/nm |
| Ho 1   | 0.114  | 0.533  | 0.034  | 0.263  | 80     | 270    |
| Ho 2   | 0.251  | 1.353  | 0.143  | 1.125  | 108    | 228    |
| Ho 3   | 0.333  | 2.279  | 0.255  | 1.938  | 78     | 341    |
| Ho 4   | 0.166  | 0.883  | 0.046  | 0.306  | 120    | 577    |
| Ho 5   | 0.151  | 0.943  | 0.096  | 0.641  | 55     | 302    |
| Ho 6   | 0.263  | 1.617  | 0.124  | 0.845  | 139    | 772    |
|        | Average | 0.097  | 0.415  |         |        |        |
|        | SDV    | 0.099  | 0.439  |         |        |        |

Table 6: Residual analysis for freeform surface geometries.

| Sample  | Measurement | Design | Difference |
|---------|-------------|--------|------------|
|         | RMS/μm | P2V/μm | RMS/μm | P2V/μm | RMS/nm | P2V/nm |
| Freeform 1 | 3.002  | 14.582 | 3.023  | 14.805 | 21     | 223    |
| Freeform 2 | 1.750  | 9.880  | 1.681  | 9.603  | 69     | 277    |

blue ridge in the lower left part of the “Reference” panel is not seen in the wavefront graph. We attribute the reason for this disaccordance to a decentration of the sample. The measurements on the residual maps lead to the conclusion that the graphical evaluation is an accurate method to describe differences in topography.

Although convex and concave lens surfaces can be measured by the WaveMaster Reflex UV, we limit this study to the measurement of biconvex IOL designs.

5. Conclusion

The WaveMaster Reflex UV represents a major advancement in the application of measuring individual IOL surfaces, which was impossible if the inspected IOL was required sterile for implantation. The operation in the near-UV range ensures the suppression of reflexes from the IOL back side without desterilizing the IOL. The device operates on a wide range of ROCs with smooth and nonpolished surfaces. The software's capability of measuring and analysing in real time makes it applicable for quality testing in the field of freeform IOL production and manufacturing. Future measurements will show the limits of the device’s range in applicability.

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