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Influence of Instrumental Factors in the Measurement of Power Profiles of Intraocular Lenses with a Commercial Deflectometer

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Abstract: Deflectometry is an optical technique for determining properties such as power distribution, wavefront, etc., and measurement of the optical properties of an intraocular lens can provide relevant information for clinicians. The aim of the current study was to establish a protocol for measuring lens power maps and profiles of various optical designs of intraocular lenses with a deflectometer based on the phase-shifting Schlieren principle (NIMO TR1504, Lambda-X, Nivelles, Belgium). The results are discussed with respect to accuracy and repeatability, the influence of the use of filters, and whether to consider the intraocular lens as a thin or thick lens.

Keywords: intraocular lens; deflectometry; power profile

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1. Introduction

The design of intraocular lenses (IOLs) has undergone significant changes in recent years due to an increased demand for spectacle independence and improved visual quality among patients, particularly those who are younger and cannot undergo corneal refractive surgery [1]. This has led to a surge in the number of lens surgeries, yet clinicians often only have access to limited information about the technical and physical characteristics of the manufactured lenses, owing to patents and copyright protection. To address this, independent research groups are providing additional information about the lenses implanted in patients to help improve prescription and optimize outcomes [2,3]. For instance, spherical aberration (SA) is an aspect for which limited information is currently available; most laboratories provide a value for SA, but without indicating which optical zone it corresponds to, or how SA evolves across different optical zones.

Measurement of the optical properties of an intraocular lens can provide further information to the clinician. Deflectometry is an optical technique for determining properties such as power distribution, wavefront, etc. [4], for the measurement of the deflection of rays after passing through the lens. This technique has been implemented in commercial devices for measuring contact and intraocular lenses. One of these devices is the NIMO TR1504 (Lambda-X, Nivelles, Belgium). This device is a deflectometer based on the phase-shifting Schlieren principle [5], which combines this principle with the phase-shifting method of interferometry [6]. This device is capable of measuring light beam distortions and using this information to calculate the power characteristics of optical lenses, as well as conducting wavefront analysis with up to 105 Zernike coefficients. Additionally, the NIMO TR1504 can be used to obtain power profiles (radial and tangential) and aberrations with varying aperture diameters that simulate different pupil sizes, making it a valuable tool in providing information on some of the characteristics of IOLs.

Although several articles have been published using the NIMO TR1504 to characterize contact lenses (CLs) [7–10], there are very few publications about its use with IOLs [11–13]. This is likely due to the differences in conditions, as intraocular lenses are thicker, and have higher powers compared to CLs, which makes measurements with the NIMO TR1504 more challenging.

One of the controversies surrounding the NIMO TR1504 instrument is that it has been suggested to produce unreliable results for measurements within the central 1 mm diameter of any lens. However, these suggestions were made based on measurements taken with CLs [14], not IOLs.

In deflectometry, noise can significantly impact power measurements, as power is calculated from the derivatives of the deflection maps. Consequently, any noise in the deflection maps is intensified by the derivative operation. To address this concern, some authors recommend utilizing filters when taking measurements, particularly in the central zone, though only CLs were evaluated in those publications [14]. Given the physical differences between CLs and IOLs, these parameters should also be analyzed for IOLs.

Due to the questions surrounding the use of the NIMO TR1504 system to measure IOLs and the correct methods for taking these measurements, the current study aimed to identify which measurements taken with this device can be deemed reliable and under what conditions. To that end, three parameters were analyzed: (1) the accuracy and repeatability of the measurements made by the NIMO; (2) the influence of the use of filters on the measurements; (3) and whether considering the intraocular lens as a thin lens or a thick lens affects the quality of the measurement.

2. Materials and Methods

This study was conducted at the laboratory facilities of the Optics and Optometry Faculty of the Universidad Complutense de Madrid, Spain, under stable conditions of temperature and humidity.

The NIMO TR1504 (Lambda-X, Nivelles, Belgium) is a device based on the 'Phase-Shifting Schlieren' technique, used to produce high-contrast fringe patterns whose image is distorted by the lens. The measurement operation consists of applying the phase-shifting principle to map the light beam deviation on the camera. The instrument's resolution depends on the number of pixels in the camera, leading to higher resolution compared to other methods. The measurement captures both the x and y components of the light beam deviation, providing a comprehensive characterization of the lens power. Customized software Version 2.17.3 is then used to calculate various power-related dimensions of the lens, such as power, sphere, cylinder, and axis. This is achieved by fitting the calculated wavefront to a Zernike polynomial combination. Additionally, high-resolution power maps are calculated for each pixel within the optic zone of the lens. The instrument's software also enables wavefront analysis via Zernike polynomial decomposition at different aperture diameters of the lens [15].

By measuring the fringe pattern distortion using phase-shifting techniques it is possible to compute the light deflection and hence the wavefront and power [16]. The instrument's light source exhibits a radiance peak at 546 nm, which is close to the spectral relative luminance efficacy peak of the human visual system, located at 555 nm under photopic conditions [17].

To prevent surface deformation and dehydration during measurements, IOLs are immersed in a saline solution in a quartz cuvette devoid of aberrations. Without a lens present, the chamber illuminates uniformly. However, when a lens is introduced into the instrument's object plane, light rays from the source are shifted or deflected. The intensity of light reaching the high-resolution CCD (charge-coupled device) camera's pixels is also modulated by the LCD (liquid crystal display) pattern, producing Schlieren fringes. The greater the power of the test lens, the greater the deviation of light rays, resulting in more fringes. Using phase-shifting techniques [18], maps of the horizontal and vertical components of ray deflection are obtained. The corresponding power maps are then derived from the ray deflection map [18].

The reproducibility of the NIMO TR1504 instrument has been reported by Joannes et al. [19] for spherical and toric CLs. They have concluded that single measurements are sufficient to determine the sphere power to current ISO tolerance limits with 95% confidence and with reproducibility standard deviations of 0.05 D.

According to ISO 11979-2:2014 [20], which applies to IOL, the dioptric power of spherical and aspheric lenses specified by the manufacturer on the IOL labeling must meet a tolerance limit of ±1.00 D, depending on the base power. In the case of the intraocular lenses used in this study, up to +15.00 D, the tolerance can be up to ±0.30 D, and for lenses between +15.00 and +25.00 D, the tolerance increases to ±0.40 D.

All measurements reported in this study represent the mean value of 10 measurements, following the usual practice in metrology [21,22]. For each measurement, the lens was removed from the NIMO device, re-centered, and then re-measured. To ensure the accuracy of the measurements, a previous calibration was performed with the NIMO calibration lens (LAMBDA-X CALI S/N: G-312-C-98) for different aperture diameters.

2.1. Calibration Lenses

Since we were unable to find calibration intraocular lenses, we measured the accuracy of the instrument with three precision calibration lenses, with high positive power, to verify that the nominal power matches the labeling and complies with ISO standards. These three calibration lenses were plano-convex lenses fabricated from RoHS-compliant N-BK7 glass (Thorlabs Inc., Germany, (THORLABS)) and they possessed a high positive power comparable to the usual power of an intraocular lens to be implanted in an eye under normal conditions. All lenses had a diameter of 12.7 mm. The LA1207 lens had a focal length of 99.7 mm, center thickness of 2.2 mm, and power in air of +10.00 D; the LA1213 lens had a focal length of 49.8 mm, center thickness of 2.6 mm, and dioptric power in air of +20.00 D; and the LA1289 had a focal length of 29.9 mm, center thickness of 3.2 mm, and power in air of +33.33 D.

The manufacturer of the three high-power calibration lenses provides the necessary data (radius of curvature, thickness, index of refraction, etc.) to compute the power profile using Zemax Optics Studio (Zemax Corporation, Version 22.3 (2022)). These physical characteristics of the calibration lenses were incorporated into the NIMO to perform the measurements. To check the precision of the NIMO TR1504, we computed the power profiles of the calibration lenses and compared them to the ones measured with the NIMO. We also checked the repeatability of the power profiles by measuring the power profile of each calibration lens and several intraocular ones ten times in a row.

To measure the power profile, we followed the same methodology for each calibration lens. We measured the average power profile ten times using the NIMO. To ensure centration, we employed a custom mount designed and manufactured at the Universidad Complutense de Madrid (UCM) workshop. This allowed us to completely remove the lens and place it again on the sample platform for the next measurement without significantly changing the lens centration. As a consequence, all subsequent measurements showed accurate lens centering, eliminating any systematic errors due to centering. Additionally, we computed the theoretical power profile using the “pupil map” tool in the ray tracing software Zemax Optics Studio (Zemax Corporation, Version 22.3 (2022)). Applying a standard set of tolerances, in accordance with the lens manufacturer’s specifications, we also computed the tolerance limits, which indicated the maximum change in the theoretical profile when small random errors were introduced in the constitutive parameters of the lens.

From the theoretical and measured power profiles, we have estimated the systematic and random error of the NIMO for the calibration lenses.

The random error is defined [21,22] as

$$\sigma_P = \left(\frac{1}{N-1} \sum_{i=1}^{N} \frac{1}{2a} \int_{-a}^{a} (P_i(x) - P_m(x))^2 dx \right)^{\frac{1}{2}} \quad (1)$$

where N is the number of measurements, $P_i(x)$ is the i-th profile measured, $P_m(x) = \sum_{i=1}^{N} P_i(x)$ is the average of the measured profiles (represented as a continuous blue line in Figure 1), and a is the aperture radius.

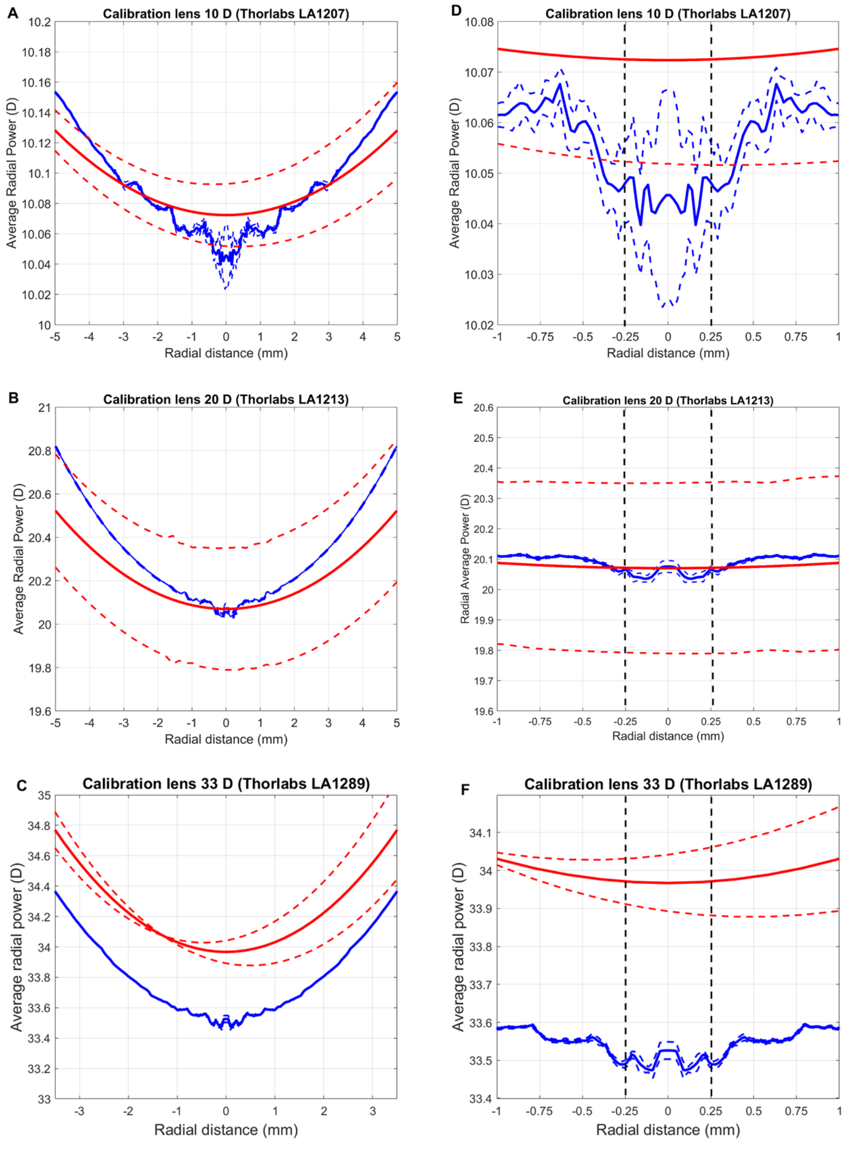

Figure 1. Power profiles for three ophthalmic calibration lenses of +10.00, +20.00, and +33.33 D. (**A**–**C**) show the power profile from the center to the periphery. (**D**–**F**) show the power profiles in the central area amplified for better visualization. Dashed blue lines indicate the confidence interval of the measurement. Dashed red lines represent the tolerance limits. Black dashed lines indicate the extension of the central zone of the lens within a circle of 0.50 mm diameter. Notice that the maximum aperture radius for (**C**) is lower than that of (**A**,**B**) due to the limitations of the NIMO TR1504.

The systematic error is defined as

$$\delta P = \frac{1}{2a} \int_{-a}^{a} (P_m(x) - P_t(x)) dx \quad (2)$$

being $P_m(x)$ the average of the measured profiles defined previously, and $P_t(x)$ the theoretical profile computed by Zemax (continuous red line in Figure 1). Again, a is the radius of the aperture. Note that the systematic error is denoted by the minus sign in Table 1 indicating that the measured power is systematically lower than the calculated one and vice versa for the plus sign.

Table 1. Systematic and random power errors computed from the power profiles.

Lens	Power (D)	Sys. Error (D)	Sys. Error (%)	Rand. Error (D)	Rand. Error (%)
LA1207	10.03	$-4.1{\cdot}10^{-4}$	−0.004	0.002	0.02
LA1207 *	10.03 *	0.03 *	0.3 *	0.013 *	0.13 *
LA1213	20.08	−0.12	−0.6	0.002	0.01
LA1213 *	20.08 *	0.018 *	0.09 *	0.015 *	0.07 *
LA1289	33.44	0.51	1.7	0.003	0.01
LA1289 *	33.44 *	0.47 *	1.4 *	0.016 *	0.05 *

* The asterisk indicates that the corresponding figures have been computed within the central zone of the lens delimited by a circle of 0.5 mm diameter around the optical center of the lens.

In this work, we measured the power of the calibration lenses LA1207 (10 D) and LA1213 (20 D) for an aperture radius $a = 5$ mm. However, due to limitations of the NIMO TR1504 deflectometer (according to the manufacturer's specifications, its effective range is ±30 D for a zone with an 8 mm diameter) we could only measure the power of the calibration lens LA1289 (33 D) for a maximum aperture radius of $a = 3.5$ mm. Note that, for computing the errors at the central zone of the lens, we have taken a = 0.5 mm, as indicated in Table 1.

2.2. Filters

Several publications have highlighted the controversy surrounding the use of filters when performing NIMO measurements [9,10,14]. The NIMO allows for the application of filters in the center of the radial power map. When working with power maps from projection, the center filtering can be adjusted with various parameters, such as transition distance and kernel size. Although filtering produces smooth power profiles and maps, it can also alter the measurement, which may result in power errors due to the smoothing algorithm.

The NIMO TR1504 has several calculus options. When calculating the radial power map there is an option to apply a filter in the center of the map. To do so, the user must supply the values of three parameters that control (1) the size of the kernel (defined as the size of the filter kernel employed in processing within the transition distance region) employed to smooth the power map, (2) the radial distance that limits the zone where the filter is applied (only the central portion of the lens should be filtered as it is the zone where the noise is greater), and (3) the distance that defines the circular area used for computing the average power. With this information, the deflectometer produces the MF Map Transition Distance, MF Map PixelWide, and MF Map Filter Kernel Size. When calculating the radial power map of a multifocal lens, a filter is applied in the center of the map. Basically, when the distance between the calculated point and the lens center is inferior to the MF Map Transition Distance, the value is a linear interpolation between the radial power and the local power projected on the radial axis. Local power at a given point is the power deduced from the deviation difference at a distance of + and − MF Map Pixel Wide from the point. Once the calculation is performed, a median filter is applied, its kernel being indicated by the MF Map Filter Kernel Size parameter. All these parameters are expressed in pixels and the values are of the integer type [15]. As a result, these filters are smoothing methods, often applied to an input vector, time series, or matrix to generate a smoothed version of the input sequence. These filters, transition distance, and kernel size can be changed from their default values of 20 and 20 to improve their ability to resolve sharp transitions within the power profiles. Both filters are applied in the central part of the map, where interpolations are used to smooth the radial power. According to the options available in the NIMO TR1504 and the papers published with filters, the options assessed were no filter, filter 20/20, and filter 5/10 [14].

2.3. Thick Lens or Thin Lens

The NIMO system enables the measurement of IOLs as either thin or thick lenses. For the latter, two parameters must be entered: the central thickness and the curvature of the anterior surface of the lens. However, the vast majority of laboratories do not provide technical details on the physical characteristics of lenses, much less for all the powers used, thus limiting the use of this form of measurement in the NIMO. To check for any differences between the measurements of an IOL as a thin lens or as a thick lens, we used the SN60WF Acrysof® lens (Alcon Laboratories, Fort Worth, TX, USA), power +22.0 D, whose physical characteristics were described by Barbero et al. in one of their publications [23].

2.4. Intraocular Lenses Studied

2.4.1. RayOne

RayOne RAO600C (Rayner Intraocular Lenses, Ltd., Worthing, UK) is a standard aspherical monofocal lens, biconvex when its effective power (also known as the principal plane or equivalent power) is positive, and biconcave when negative. Its anterior surface is aspherical in order to induce neutral spherical aberration. This lens is made of hydrophilic acrylic with a refraction index of 1.46 at 35 °C and an Abbe number of 56. The platform diameter measures 12.50 mm, with an optic zone of 6.00 mm [24]. The base power of this particular lens is +10.00 D.

2.4.2. ReZoom

The ReZoom NXG1 lens (Advanced Medical Optics, Santa Ana, CA, USA) is no longer available on the market, but given its characteristics, the measurements of this lens with the NIMO can help solve some of the questions raised in this study due to its design which features different refractive and transition zones.

The ReZoom IOL is made of soft, foldable hydrophobic acrylic material with an ultraviolet-absorbing filter. The optic size is 6 mm in diameter and the overall length is 13 mm. This lens consists of five concentric refractive areas alternating between distance-dominant and near-dominant vision. The central 4.7 mm zone is divided into five zones: the largest central area (2.1 mm) is a zone for distance vision, the next one (2.1–3.4 mm) is for near vision in comparatively good light conditions, followed by a distance-vision zone (3.4–3.9 mm) and a near-vision zone (3.9–4.6 mm) in low light conditions; the fifth zone (4.6–4.7 mm) is a transient zone with a peripheral spherical lens part that provides 1 diopter of optical power towards distance vision. All spheres for near vision provide a +3.50 D addition of power in the intraocular lens plane, which roughly equates to +2.80 D added power at the corneal plane [25]. The lens under evaluation has a base power of +20.00 D.

2.4.3. SN60WF

The SN60WF AcrySof® IOL (Alcon Laboratories, Fort Worth, TX, USA), is a single-piece, foldable, acrylic IOL with a blue-light filtering chromophore in addition to a standard UV-light filter. This biconvex optic has supporting haptics and is intended for implantation in the capsular bag [26]. The lens has a 13 mm total size with a 6 mm optic. The lens under evaluation has a base power of +22.00 D.

3. Results

3.1. Accuracy and Repeatability

The resulting power profiles for the three precision calibration lenses are shown in Figure 1. Note that the calibration lenses were measured in air as the power of these lenses is specified by the manufacturer. The continuous blue line of the plots in Figure 1 represents the average of the radial power profiles measured by the NIMO. The dashed blue lines are the limits of the confidence intervals and are computed by adding (for the upper limit) or subtracting (for the lower one) the standard deviation of the radial power profiles from the average power profile. Note that these dashed lines are not always distinguishable from the average power, as happens in panels 1B and 1C.

The red continuous line represents the power computed by Zemax Optical Studio from the constitutive data (curvature radius, center and edge thickness, and refractive index of the materials) of the calibration lenses that are supplied by the lens manufacturer. For their part, the dashed red lines represent the limits of the tolerance interval computing using the tolerance tool of Zemax Optics Studio.

The computation of the tolerance intervals is as follows: First, a set of tolerances for the constitutive parameters of the lens is fixed. These tolerances include not only the tolerances of geometrical parameters such as curvature radii or center thickness but also tilt and decentration between the lens surfaces, quality of the lens surface finish, etc. The basic idea is to consider the foreseeable sources of manufacturing errors. Next, Zemax generates a series of lenses presenting random errors in the lens parameters. In this way, we have a set of lenses with different manufacturing errors. Afterward, Zemax computes a parameter related to the image quality (such as the RMS radius of the spot generated by the lens in the focal plane) for each of the lenses of the set. Next, we compute the power profile of the lens of the set that presents the worst quality parameter. Then, we calculate the difference between this profile and the theoretical power profile (computed with no tolerance errors). Finally, we determine the tolerance limits by adding and subtracting the absolute value of this difference and the theoretical power of the lens.

Note that, as computing lens tolerances with Zemax takes into account the tilt and decentering of the lens surfaces, the resulting tolerance intervals can also be decentered with respect to the theoretical profile. Therefore, the tolerance intervals represent the possible manufacturing errors.

From the theoretical and measured power profiles, the systematic and random errors of the NIMO for the calibration lenses were evaluated, as tabulated in Table 1.

For both the +10.00 and +20.00 D lenses, the systematic errors were lower than 1% (in absolute value) of the base lens power. The +33.33 D lens had a higher amount of error (around 1.7%). However, the manufacturer guarantees that the focal length of the three lenses is within 1% error. This translates to $\pm$0.33 D of error in power for the +33.33 D lens, which is close to the 0.50 D measured with the NIMO. Therefore, we can conclude that, for the lenses of +10.00 and +20.00 D power, the systematic error is within the limits given by the lens manufacturer, while the error of the +33.33 D lens is close to this tolerance error ($\pm$0.33 D according to the tolerances specified by the lens manufacturer). Moreover, the shape of the average profile was very similar to the theoretical profile and the errors are below the tolerances set by the relevant ISO standard (ISO 11979-2) [20]. Note that, in Figure 1, although the theoretical profile is symmetrical as corresponds to a lens with well-aligned spherical surfaces, the tolerance limits are not, because these limits are computed introducing small errors in the constitutive parameters of the lens, including tilts and decentrations between the lens surfaces that can occur during the manufacturing process. This lack of symmetry of the tolerance limits is more noticeable for the 33 D lens, as it has greater power.

Regarding random errors, the magnitude was similar for all three lenses. For a 10.00 mm diameter aperture for the +10.00 and +20.00 D lenses, and a 7 mm diameter aperture for the +33.33 D (due to magnification), errors were lower than 0.003 D (0.02% in relative terms), indicating excellent repeatability of the measurements across the whole lens diameter. The central zone had a higher random error. For a 0.50 mm diameter lens, the random errors for all three lenses were lower than 0.02 D, with a maximum relative error of 0.13% for the +10.00 D lens. Again, compare this relative error with the 1% manufacturing error claimed by the manufacturer of the calibration lenses.

To stress this point, a monofocal standard intraocular lens (RayOne) with a power of +10.00 was measured 10 times, as well as a multifocal one (ReZoom) with a base power of +20.00 D. The accuracy of these measurements could not be estimated using the same method as was employed with the calibration lenses because the corresponding theoretical profiles had not been published by the manufacturers. However, we could estimate the repeatability from the random errors. The mean profile and the corresponding confidence interval are presented in Figures 2 and 3.

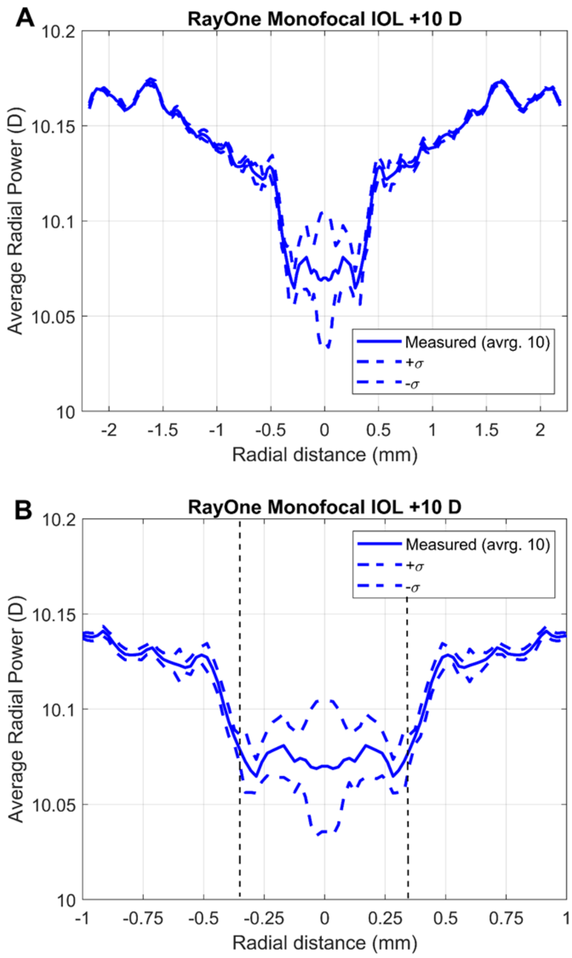

Figure 2. Average power profile of the RayOne RAO600C +10.00 D lens. (**A**) shows the profile along the entire optic size while (**B**) shows the central area. The solid blue line is the average of 10 measurements and the dashed lines are the intervals of confidence computed from the standard deviation. The measurement exhibits good repeatability but for the central zone of the lens marked by the black dashed vertical lines.

The power profile of both intraocular lenses shows good repeatability, particularly at the lens periphery, except for the lens center, where the random error increases. However, it should be noted that the area for which these errors are higher than 0.2% is delimited by a zone with a radius of 0.25 mm. Outside this zone, the confidence intervals closely follow the average power profile for both lenses.

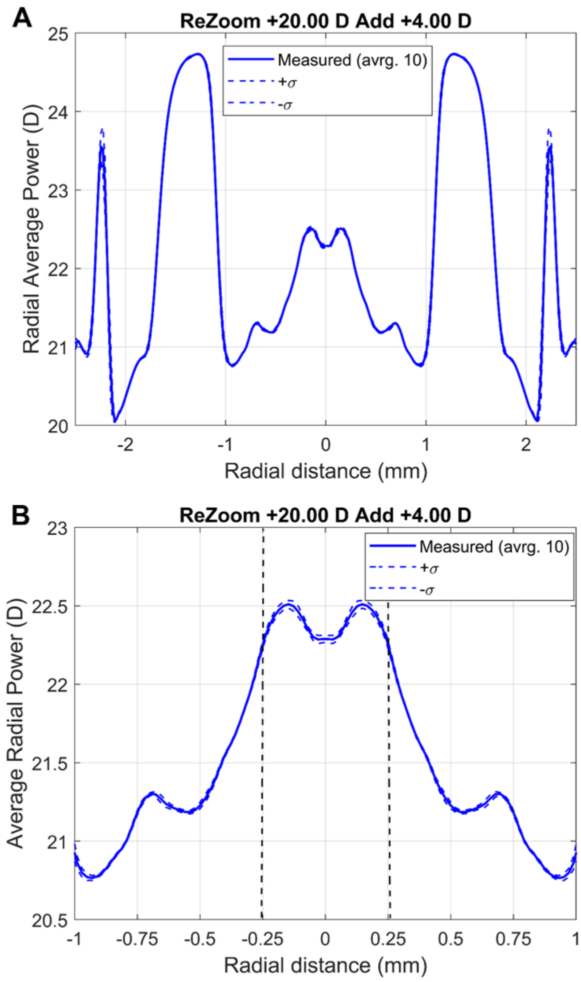

Figure 3. Average power profile of the ReZoom +20.00 D lens. (**A**) shows the profile from the center to the periphery while (**B**) shows the central area. The solid blue line is the average of 10 measurements and the dashed lines are the intervals of confidence computed from the standard deviation. The black dashed vertical lines limit the area with good repeatability.

3.2. Filters

Figure 4 shows the results obtained after applying a pair of filtering options and a measurement without any filter applied in the measurement of the precision calibration lenses. When evaluating the effect of filter application on the calibration lens measurement, it was observed that regardless of the base power of the lens, the filter acted in the area of the central 1 mm approximately (radius 0.50 mm) for the 20/20 filter and 0.50 mm (radius 0.25 mm) for the 5/10 filter. The application of the 20/20 filter yielded much smoother values than the 5/10 filter; however, central irregularities were still observed with both filters, as well as with measurements without a filter.

Figure 5 illustrates the average radial power obtained for the ReZoom lens. The application of filters during the measurements revealed that the 20/20 filter affected a central zone with a diameter of approximately 1.25 mm, while the 5/10 filter had an impact on a central area less than 1 mm in diameter, in comparison to the measurements obtained without any filter.

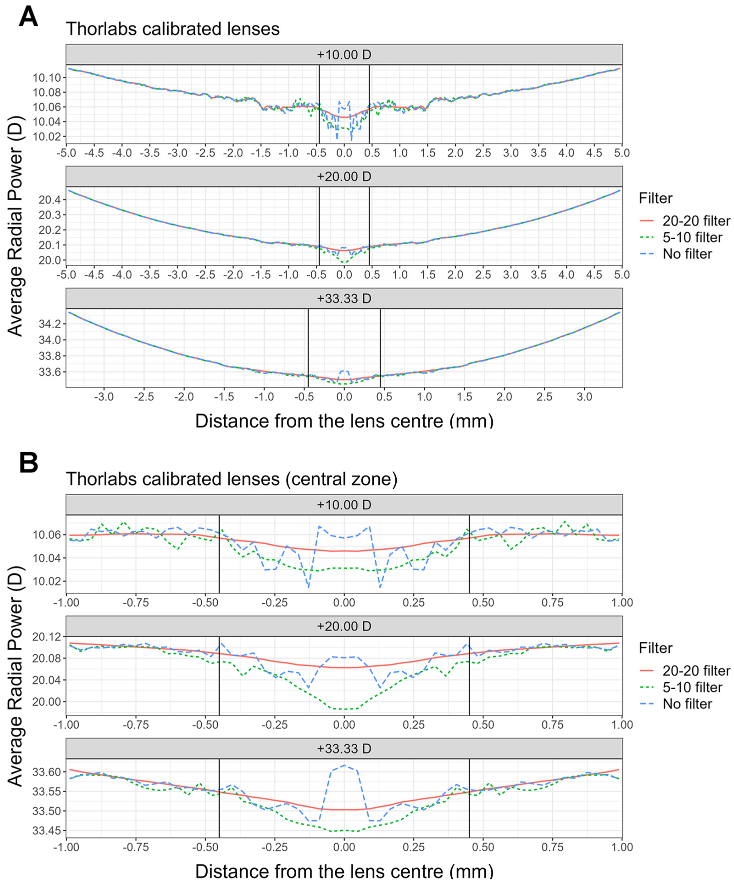

Figure 4. Average radial power vs. lens semi-diameter for the three ophthalmic calibration lenses measured with a 20–20 filter (solid red line), 5–10 filter (dashed green line), and with no filter (dashed blue line) from the center to the periphery in (**A**) and in the central zone in (**B**). The black vertical lines limit the area where the measurements are different depending on the filter used.

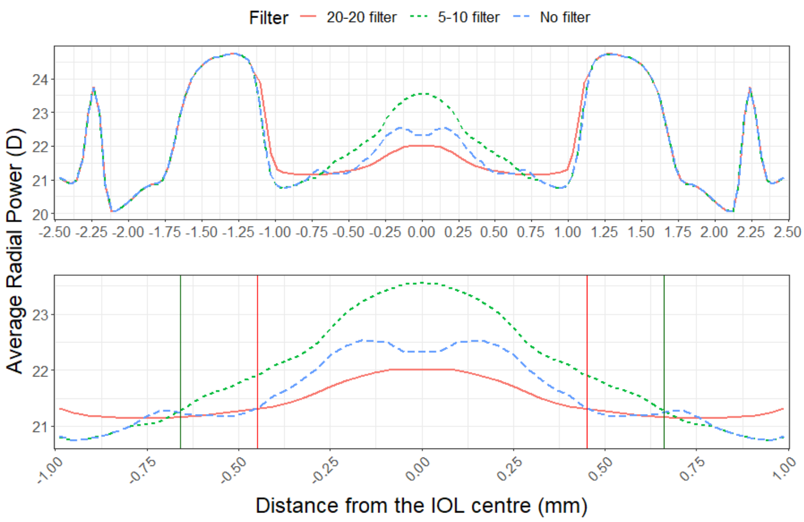

Figure 5. (**Top**) Average radial power vs. IOL semi-diameter for the ReZoom lens measured with a 20–20 filter (solid red line), 5–10 filter (dashed green line), and with no filter (dashed blue line) from the center to the periphery. (**Bottom**) Average radial power vs. IOL semi-diameter in the center zone for the ReZoom lens measured with a 20–20 filter (dashed red line), 5–10 filter (dashed green line), and with no filter (dashed blue line). The vertical lines limit the area where the measurements are different depending on the filter used compared to no filter (red for the 20–20 filter and green for the 5–10 filter).

3.3. Thick and Thin Lens

Usually, the power that a deflectometer measures is the so-called thin lens power [4]. However, if some parameters of the lens such as the center thickness, curvature radius of the first (anterior) surface, and the refractive indexes of the lens and the surrounding medium are known it is possible to compute the thick lens power [4]. The NIMO 1504 has implemented this feature, so we investigated the difference between thin and thick power for an intraocular lens.

To that end, we measured the SN60WF +22.00 D lens in two different ways. The first one considering that it was a thin lens and the other in thick lens mode, using the data previously published in the literature [23], where the central thickness was 0.633 mm and curvature of the first surface of the lens was 19.583 mm. Figure 6 shows the average radial power profiles for the two measurements, while Figure 6 shows the repeatability. No relevant differences were found between the two methods analyzed.

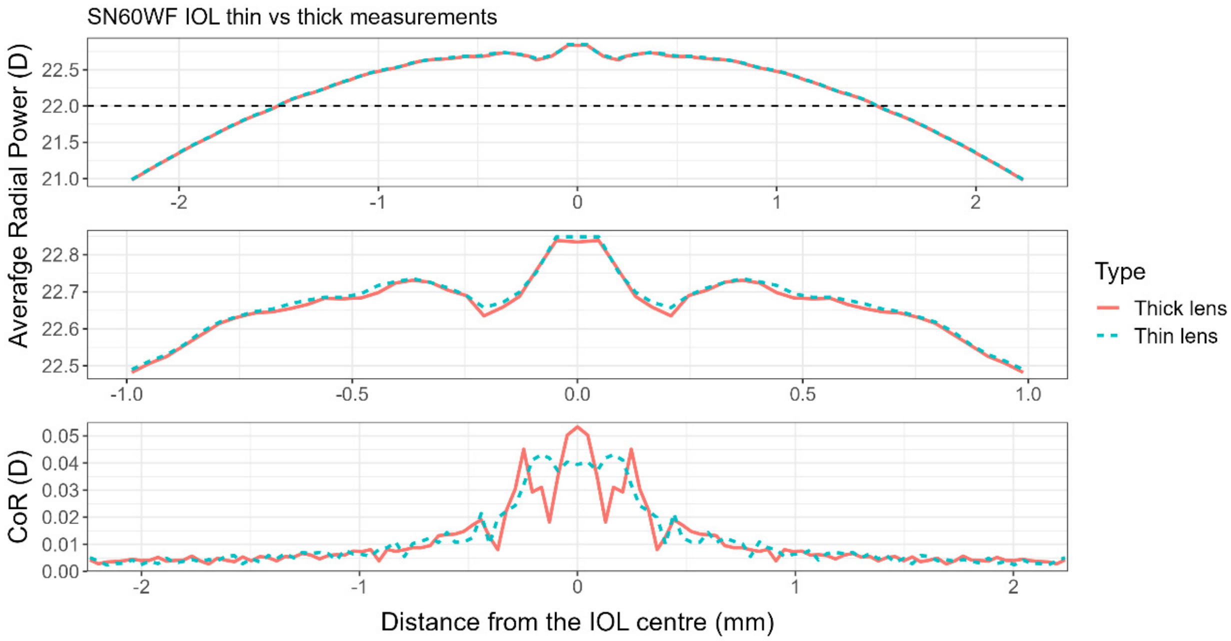

Figure 6. Average radial power vs. IOL semi-diameter for the SN60WF +22.00 measured as a thick lens (continuous red line) and thin lens (dashed green line) from the center to the periphery (**upper** figure) and in the central zone (**central** figure). The lower figure shows the repeatability of ten measurements as a thick and thin lens.

The mean difference between the results obtained from the 'thin lens' and 'thick lens' measurements was 0.006 D, with values ranging from 0.000 D (at a distance of 1.8 mm from the IOL center) to 0.077 D (at a distance of 0.2 mm from the IOL center).

4. Discussion

The current development of complex IOL designs stresses the importance of assessing the accuracy and precision of the devices employed to measure the lens power maps and profiles of these lenses, particularly if the named devices are not specifically designed for this purpose. Due to their small size (usually an optical zone size of 6 mm) and high power (in a normal eye the power of the lens to be implanted would typically range between +20 and +25 D), these lenses are markedly different from other types, such as ophthalmic lenses or contact lenses. Therefore, by knowing the measurement procedure, more accurate results can be achieved and errors that could lead to incorrect results can be avoided.

The NIMO TR1504 deflectometric system has been predominantly used for measuring the power maps of contact lenses, according to the literature [7,27,28]. This device has also been employed to measure IOL power maps; however, none of the publications reporting the measurements obtained with intraocular lenses states clearly the measurement protocol to achieve more accurate and reliable measurements. Additionally, there are also inconsistencies in the information provided, such as whether it is better to use a filter or not. Therefore, the ultimate aim of this work was to develop a protocol for measuring intraocular lenses using the NIMO TR1504 that can be replicated and lead to more reliable results. At present, there is no publication that establishes this protocol, and it cannot even be found in the manufacturer's manuals or other provided information.

4.1. Accuracy and Repeatability

The measurements and calculations of the calibration lenses indicate that (a) the NIMO shows very good accuracy and repeatability, lower at the lens center, but with random errors under 0.02 D (or 0.13% when expressed as a percentage), (b) the systematic errors are also low and, with the exception of the +33.33 D calibration lens, are always lower than the manufacturing error of 1%, and, (c) the shape of the power profiles measured with the NIMO TR1504 is very close to the theoretical shape computed by a ray tracing software, as shown by the values of the systematic errors in Table 1. These errors computed using Equation (2) are lower than the ISO tolerances for both the 10 and 20 D lenses. Although for the 33 D lens the errors are higher, the shapes of the theoretical and measured power profiles shown in Figure 1C are quite similar. Indeed, the systematic error represents, in this case, a piston between the theoretical and the measured power profiles. Moreover, even at the lens center, a zone of 0.25 mm from the center, and for high-power lenses, the device exhibits high repeatability (equal to or less than 0.13%) and good precision (less than 2% if we consider the +33.33 D lens).

In the case of measurements obtained with both models of intraocular lenses, monofocal and multifocal, the results also align in indicating that the lowest precision of the measurements is confined to a central zone with a radius of 0.25 mm.

The results obtained with both calibration and intraocular lenses suggest that central measurements obtained through deflectometry are less repeatable than non-central measurements within a radius of 0.25 mm from the center.

4.2. Filters

In deflectometry, noise is an essential factor to consider when measuring power, as power is calculated from the derivatives of the deflection maps measured by a deflectometer. Thus, any noise present in the deflection maps is amplified in the derivative operation. This is why the instrument software has the option to apply average filtering to reduce noise [29].

Servin et al. studied the noise associated with the combination of mean filtering and phase shifting [29]. They determined that these processes introduce a Gaussian noise in the phase measured (and thus in the lens power). Therefore, the noise in the lens power should also be Gaussian noise and not symmetrical. As already pointed out by other authors, the deflectometry technique has a lower precision for central measurements [19,30].

After comparing the results obtained with the 20–20 filter and the 5–10 filter to the measurements obtained without a filter, it was observed that both filters significantly reduce the information in the central region of the analyzed optic size, with the effect being more pronounced in the case of the 20–20 filter. This smoothing effect is observed in both ophthalmic lenses and intraocular lenses, with the smoothed zone extending to a central area of 1 mm.

This smoothing or mitigation of information in the central area, combined with the previously observed lower precision of the device in this region, can lead to the loss of valuable information, particularly when measuring lenses that have distinct characteristics in its central area. Therefore, we believe that to avoid any smoothing effect that may result in measurements deviating further from the actual values, filters should not be used during the process of measuring intraocular lenses with the NIMO TR1504 system. Instead, a better procedure to reduce noise is to take several measurements (ensuring that the lens is properly centered) and compute the average of these measurements. This is equivalent to the temporal averaging procedure widely employed in image processing.

4.3. Thick and Thin Lens

Some of the articles published using the NIMO system with contact lenses include information about their physical characteristics, such as thickness and curvature, to enable them to be measured [9,27,28]. However, in published works with intraocular lenses [12,13] this information does not appear, and it is not indicated whether the procedure was performed with the lens being treated as a thin or a thick lens. Our experience has demonstrated that it is highly challenging, if not impossible, to obtain these data from laboratories due to patents and the protection of related information. Consequently, we investigated whether the outcomes from the NIMO, when measuring an intraocular lens as a thin lens or a thick lens, would differ and thus necessitate certain conditions for measurement.

The measurements conducted using both procedures, repeated ten times each, showed similar results throughout the entire optical size except for the central zone. The observed differences in the central zone are in line with the previously evaluated points in this study and can be attributed to the loss of precision exhibited by the NIMO TR1504 system within the central 0.5 mm (radius 0.25 mm). This makes sense as the central thickness of an IOL is lower than that of the natural eye lens while the refracting power of the IOL surface is roughly the same as that of the natural eye lens. In a standard eye model (Arizona Eye Model, for example [31]) the difference between the back vertex power and the principal plane's power is already small (around 0.42 D), so for a thinner lens with roughly the same curvature radius, this difference would be even smaller.

5. Conclusions

According to the results obtained in this study and based on the stated objectives, we can draw the following conclusions regarding the intraocular lens measurement protocol with the NIMO TR1504 system: (1) it is necessary to take ten measurements of each area to be evaluated in order to obtain average values; (2) the measurements should be conducted without any filter; (3) the measurement can be performed with a thin lens, eliminating the need to know the central thickness and curvature of the lens.

Additionally, we can conclude that the NIMO device is a reliable system for characterizing intraocular lenses, particularly in terms of parameters such as radial power. However, it is important to note that, like other deflectometers, its precision is reduced within the central 0.5 mm (radius of 0.25 mm).

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