A Reconstruction Technique to Estimate the Gradient-Index Distribution of the Crystalline Lens Using Ray Aberration Data

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❶ Motivation

Gradient index distribution (GRIN) provides the crystalline lens of the eye with unique optical properties. While it is expected to play a major role in the change of refraction with age and accommodation, and in the spherical aberration of the eye (and its change with age) most knowledge of the crystalline lens GRIN structure relies on in vitro measurements.

Also, in general, techniques that reconstruct GRIN profiles of the lens have never been validated against 'gold standard'.

In this study:

1) We developed reconstruction techniques to estimate lens GRIN distribution and tested them on lenses with known GRIN profiles.

2) We explored the possibility of GRIN measurements in vivo from retinal spot diagrams.

❷ Background

Several approaches have been used to estimate GRIN distribution of crystalline lenses:

1) Destructive techniques (in vitro) (Palmer 1981, Nakao 1968, Fagerholm 1981)
2) Magnetic Resonance Imaging (in vitro) (Moffat 2002)
3) Tomographic reconstructions from laser beam deflections after the lens (in vitro). (Campbell 1984, Chan 1988, Garner 2001, Barbero 2004, Acosta 2005)
4) Regression techniques, with ocular spherical aberration and power as input, GRIN and biometric data as fitting parameters (Pomerantzeff 1984, Al-Ahdali 1995)

❸ Methods

RECONSTRUCTION ALGORITHM

We used a commercial optical design program (ZEMAX) to implement an algorithm of optimization and search for the best gradient index that fits our experimental data

Merit Function to be minimized

$$MF^2 = \frac{\sum W_i (V_i - T_i)^2}{\sum W_i}$$

V_i are the experimental data
T_i are the computer simulated data
W_i are the weight of each data

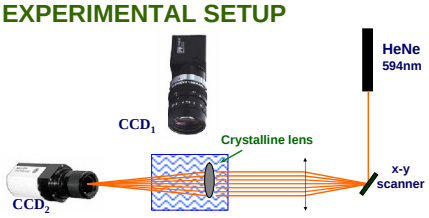
· The search of the minimum of the merit function was performed with genetic algorithms to avoid local solutions

· We constrained the space of solutions setting the surface index to ±0.002 the original and the GRIN function to be continuous and monotonic.

Parameters supposed to be known

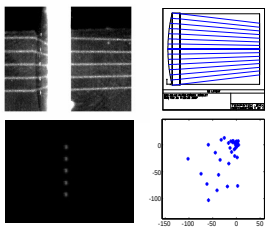
· anterior and posterior lens surface
· polynomial shape of the GRIN function

EXPERIMENTAL SETUP



CCD 1 lateral ray deflection

CCD 2 ray impact



The x-y scanner combined with 150mm focal lenght lens delivers 200 rays to the lens with an estimated precision of 11.5±0.8µm.

Lateral viewing of raytrace (setup with water) is imaged with a TELI CS8550DiF camera (CCD1) and a objective focusing plane of rays.

Retinal spot (setup without water) is imaged with a RETIGA 2000-R (CCD2) with the bare CCD.

CALIBRATION

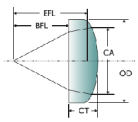
Validation of the techniques was performed with artificial lenses of known index (homogeneous and GRIN)

· Homogeneus index lens.

Newport optical glass BK7. KPX-088
Focal length: 71 mm in air, 270mm in water

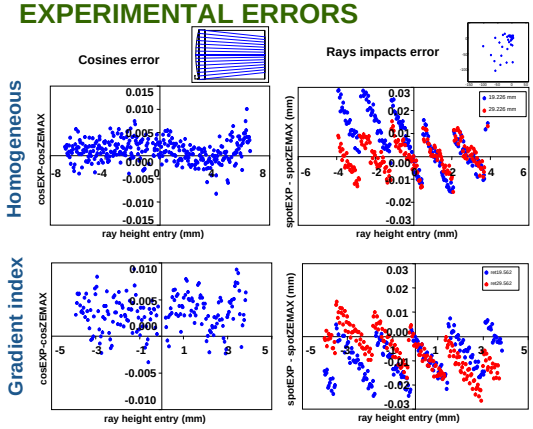
· Gradient index lens.

LightPath Tecnologies,Inc. GRADIUM GPX 30-60
Focal length: 75 mm in air, 145mm in water
Profile: Axial. 11th polynomial degree



❹ Results

EXPERIMENTAL ERRORS



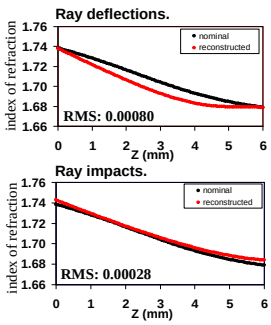
Average differences between the experimental and theoretical data are 0.005 in cosines (0.6 degrees) for lateral ray deflaction and 20 µm for ray aberration

RECONSTRUCTED INDEX

▪ homogeneous

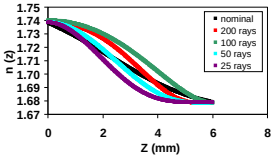
Ray deflections
· Nominal value 1.51653±0.00001
· Recovered value 1.519429
Ray impacts.
· Nominal value 1.51653±0.00001
· Recovered value 1.516535

▪ gradient index lens

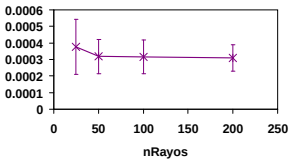


In vivo measurements are limited by measuring time (proportional to the number of delivered rays). Previous estimates were based on 200 rays. We studied to which extent the number of rays could be decreased without compromising the outcome. We performed reconstructions using 100, 50 and 25 rays.

Reconstructed index with different number of rays with retinal spot



Error in reconstructions with different number of rays



We found that, on average, GRIN is quite accurately reconstructed using less number of rays. Increasing the number of rays above 25 rays reduces variability.

❺ Conclusions

1. We have presented a reconstruction technique to estimate the gradient-index distribution of the crystalline lens with data from lateral ray deflection and ray impact.
2. We have performed experiments with a homogeneous lens and a gradient index lens. In both of them the estimated index distribution is within the error of manfacturer.
3. With information of the anterior and posterior corneal and lens surfaces and intraocular distances our results show that it could be possible to measure the gradient-index of the crystalline lens *in-vivo* from retinal spot data.

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