Theoretical and experimental investigation, and numerical modeling of human visual acuity

PhD thesis booklet

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Background of the research

I carried out my doctoral research at the Department of Atomic Physics, in collaboration with ophthalmologists from the Department of Ophthalmology, Semmelweis University related to the project "Medical technological research and development on the efficient cure of cataract", led by Medicontur Medical Engineering Ltd.

Nowadays, cataract surgery is one of the most common surgical procedures, during which the patient's crystalline lens, which has become opaque due to increased light scattering, is replaced with an IntraOcular Lens (IOL). However, clinically applied IOLs cannot restore all features of the subject's own crystalline lens. Their main deficiency is that they cannot accommodate or correct for chromatic aberrations. When first IOLs were introduced, cataract was typically an elderly disease, so patients were absolutely satisfied with the image quality achieved by simple lenses involving only spherical surfaces and having fix focal length. In contrast, recently cataract develops even in case of subjects in their active age bracket, therefore, it has become necessary to provide better correction for visual defects, and to resolve focusing without additional eyeglasses [Jinabhai et al., 2013]. According to the increasing demand, manufacturers are steadily improving their products and investing more resources in the precise design and optimization of premium type (e.g. aspherical, toric shape, diffractive) and customized lenses. However, beyond individual factors, successful treatment of a particular patient depends on the diagnosis, pre-operative biometry, surgical procedure, recovery cure, and of course, IOL design and quality. The quantity that ophthalmologists use to describe subjective vision quality is the visual acuity value, the precise, repeatable measurement of which is essential to evaluate treatment efficacy.

Objectives

The primary aim of my research was to support the evaluation and design of intraocular lenses to improve the achievable visual quality. Thus, in order to provide a reliable model, the whole visual train has to be taken into consideration, which involves retinal sampling, neural transfer and additive noise, as well as cortical character recognition, beyond the optical imaging properties of the human eye [Nestares et al., 2003; Watson et al., 2008; Watson et al., 2015]. Therefore, my goal was to develop a new neuro-physiological vision model that accurately characterizes optical imaging by a realistic schematic eye, and it supplemented with a simple numerical neural model to determine human monocular foveal visual acuity. By simulations,

I intended to answer the following question: if the objective physical parameters of an eye are known, then what would its visual acuity be as observed by a human subject? I aimed to build my vision model on the wavefront aberration of the given eye as an objective physical measure, which can be derived from precise simulations implemented in optical design software, or from direct in vivo measurements as well. As such a model enables the user to modify the opto-mechanical structure, and to analyze the resulting effects on vision quality, it opens up the possibility to optimize individual visual optical devices (e.g. IOLs) directly for improved visual acuity instead of technical quantities describing image quality (point spread function, optical transfer function, modulation transfer function, contrast sensitivity function, etc.) [Barten, 1999; Watson et al., 2008].

Furthermore, if wavefront aberration is derived from real measurements, the model can simulate the visual acuity of the tested subject. This method provides a new, objective alternative to subjective vision tests based on letter identification, even in cases when these are infeasible. This possibility points to the other research area of my PhD: reducing the statistical error of visual acuity tests. The demand for measurement development arose in two ways. First, adequate data were needed to calibrate my vision model, and on the other hand, since treatment efficacy is determined based on the measured progression of the visual acuity value, in certain clinical cases more accurate procedures are required than standard vision tests (e.g. examining subjects with cataract or retinal disease) [Rabbetts, 2007; Vanden Bosch et al., 1997]. In order to accomplish both aims together, my goal was to develop a new, precise and accurate, measurement/evaluation procedure that decreases the statistical error of the measurements without causing systematic offset relative to standard acuity tests.

New scientific results

T1 I developed and calibrated a novel, correlation-based scoring method for visual acuity tests that takes into account the physical similarities of letters by cross-correlation and showed that it reduces the statistical error of the most accurate clinical visual acuity measurements by 20...30% depending on the number of tested letters and the environmental conditions of the test. I demonstrated that the systematic offset between the visual acuity values determined by traditional true/false scoring with 50% probability threshold, and by correlation-based scoring with calibrated 68% correlation threshold is negligible. I suggested the application of correlation-based scoring as a more precise alternative to monitor disease progression, or evaluate surgical results in ophthalmic research. [P1], [P2]

T2 I proved by ophthalmologic trials that my new, correlation-based scoring method decreases the statistical error of clinical vision tests by 20%, so that measurement time is increased by only 10%. This corresponds to the same amount of error reduction as if the number of letters was doubled, which would double the measurement time as well. I verified that the systematic offset of visual acuity determined by the new method with the corresponding 68% correlation threshold is negligible compared to the acuity value measured by the standard Early Treatment Diabetic Retinopathy Study trial. [P5], [P7]

T3 I designed and implemented a new far-field, infrared pupil measuring system that enables the continuous monitoring of the subject's eye and allows for real-time, synchronized pupil diameter measurement during visual acuity tests. I showed that my evaluation algorithm applying automatic magnification correction and adaptive circular Hough transform determines the pupil diameter with 0.2 mm spatial accuracy, exceeding that of similar commercially available devices (i.e. 0.5 mm). [P3]

T4 I developed a new, complex neuro-physiological vision model to simulate the monocular foveal visual acuity of emmetropic subjects (whose vision quality is in the normal range without prescription eyeglasses). I showed that the model precisely characterizes the properties of optical imaging by a physiologically accurate personalizable schematic eye implemented in optical design software, overcomes existing limitations, and provides opportunity to analyze custom setups and the effects of modifying opto-mechanical parameters in the eye. I demonstrated that the vision model can describe retinal sampling by an ideal hexagonal receptor structure and can take into account neural processes, including effects of neural transmission, neural noise and character recognition, by a simplified neural model having only the additive Gaussian white noise (σ) and discrimination range ($\delta\rho$) as two free parameters. [P4]

T5 I showed through calibration measurements that using wavefront aberration and pupil diameter data together with the calibrated average values of the neural parameters ($\sigma = 0.1$; $\delta\rho = 0.0025$) as input, the new vision simulation can determine the monocular visual acuity of near-emmetropic subjects (−0.5…+0.5 diopters) with normal vision (0…−0.3 logMAR, Minimum Angle of Resolution). I demonstrated that, based on the residual of the calibration group, the accuracy of the simulations is approximately 0.045 logMAR, which exceeds the accuracy of general clinical visual acuity measurements. [P4]

T6 I determined the direct relationship between the d pupil diameter and the V_{ave} average visual acuity value of healthy subjects with normal vision in the common 2…6 mm diameter range by analyzing the results of visual acuity simulations performed using my new vision

model. The obtained 0.04 logMAR/mm slope of $V_{ave}(d)$ is in good agreement with observations presented in the literature. Based on the results, I concluded that for the sake of comparability of acuity values, the pupil diameter has to be measured too with at least 0.5 mm spatial accuracy during visual acuity tests. [P4], [P6], [P7]

References

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Further results

In order to demonstrate the widespread applicability of my vision model, I simulated the achievable through-focus visual acuity of pseudophakic subjects with diffractive multifocal intraocular lens implanted, based on their biometric and kertometric data. In order to properly model vision quality in case of large aberrations (in this case large defocus), I implemented a new more realistic retinal cone mosaic, in which receptor cells broaden with eccentricity, and the corresponding noise increases with cell size towards the periphery. My results showed that the applied retina model (quasi-regular hexagonal structure, or realistic cone mosaic) does not

effect the outcome of the simulation significantly in case of small defocus; however, for larger defocus the realistic retina model remarkably increases the accuracy of the simulations, up to ~20% reached over +3 diopters. My model can determine the visual acuity value achievable with implanted intraocular lens in the −2.5…+1.5 diopter range with 0.15 logMAR accuracy on average, which approximately equals the accuracy of standard line-assignment-based visual acuity tests, and thus confirms the reliability of the method. As the relation between the simulated and measured visual acuity values is always monotonic, besides predicting (even post-operative) visual acuity based on objective measurements, my algorithm may also be suitable for comparison and optimization of visual devices (e.g. customized IOLs) directly for perceived vision quality. [to be published]

Utilization of the results

My correlation-based scoring method makes it possible to take high-precision visual acuity measurements aligned with the ophthalmological standard both in case of scientific research and in clinical practice. By simulations using my new neuro-physiological vision model, the subjects' visual acuity can be determined based on the objective opto-mechanical parameters of their eyes, which provides an alternative approach in cases where conventional means are not feasible, e.g. testing illiterate adults or pre-school children. Furthermore, my method can be applied to predict the achievable visual acuity with visual optical devices, which greatly contributes to surgical forecast and their custom design (e.g. implanted IOLs during cataract surgery).

Publications

[P1] Erdei, G., Fülep, Cs. *Measuring visual acuity of a client*. World Intellectual Property Organization, WO/2018/020281 A1, PCT/HU2016/000050, patent pending (2016).

[P2] Fülep, Cs., Kovács, I., Kránitz, K., Erdei, G. *Correlation-based evaluation of visual performance to reduce the statistical error of visual acuity*. Journal of the Optical Society of America A, 34(7), 1255-1264 (2017).

[P3] Fülep, Cs., Erdei, G. *Far-field infrared system for the high-accuracy in-situ measurement of ocular pupil diameter*. IEEE Proceedings of the 10th International Symposium on Image and Signal Processing and Analysis, 31-36 (2017).

[P4] Fülep, Cs., Kovács, I., Kránitz, K., Erdei, G. *Simulation of visual acuity by personalizable neuro-physiological model of the human eye*. Scientific Reports, 9:7805, 1-15 (2019).

[P5] Fülep, Cs., Kovács, I., Kránitz, K., Nagy, Z. Zs., Erdei, G. *Application of correlation-based scoring scheme for visual acuity measurements in the clinical practice*. Translational Vision Science and Technology, 8(2):19, 1-13 (2019).

[P6] Timár-Fülep, Cs., Erdei, G. *Investigation of the effect of pupil diameter on visual acuity using a neuro-physiological model of the human eye*. IS&T International Symposium on Electronic Imaging 2019: Human Vision and Electronic Imaging 2019 proceedings, HVEI-207 (2019).

[P7] Timár-Fülep, Cs., Kovács, I., Kránitz, K., Erdei, G. *Új lehetőségek a látóélesség-vizsgálati tesztek pontosságának növelésére*. Fizikai Szemle, 69(6/774), 195-200 (2019).