Analysis of age-dependence of the anterior and posterior cornea with Scheimpflug imaging

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Abstract

Purpose: The assessment of keratometric and higher order aberrations (HOA) of the anterior and posterior cornea and their age-related changes.

Patient and methods: Our study investigated one healthy eye of 227 subjects (age: 55.15±21.2 years, range: 16-90 years, right eye 135, left eye 92). Images were captured from each eye with Pentacam HR using automatic mode. Keratometric, astigmatism data and corneal HOA were analyzed.

Results: With respect to laterality, no deviance was found in any of the parameters ($p>0.05$). Mean refractive error was 0.52±0.23 D. Regarding both the anterior and posterior corneal surfaces, the level of astigmatism decreased significantly with advancing age ($p<0.05$). The overall root mean square (RMS) of the HOA is continuously increasing with age ($r=0.517$; $p<0.01$), which can be explained by the combined effect of the increase in both the anterior and posterior corneal RMS HOA. Of the HOAs, the constant increase of the primary and the secondary spherical aberration (SA) with aging ($p<0.01$) is caused by the SA growth of the anterior surface. Apart from these, only the vertical coma aberration of the posterior surface and the vertical trefoil aberrations of both anterior and posterior surfaces showed a significantly positive correlation with aging ($p<0.05$). Horizontal components of coma and trefoil aberrations showed no deviation with advancing age.

Conclusions: Corneal astigmatism shows a significant decrease with aging. Of the higher order aberrations, primary and secondary spherical aberrations, vertical coma and vertical trefoil significantly increase with age, while other HOAs show no correlation with aging.

Keywords: higher order aberration, corneal spherical aberration, coma aberration, Pentacam HR

Introduction

The cornea represents about 80% of the refraction of the eye. In addition to lower order aberrations (prism, defocus), higher order aberrations (HOA) of the eye and the cornea are also known. Significant deviations in HOA can affect visual quality and contrast sensitivity negatively. Subsequent to ophthalmic surgeries, subjects often complain about dysphotopsia and low contrast sensitivity, especially under low-light conditions. Higher order aberrations of the eye can account for some of such symptoms.[1] One of the HOAs being most particularly investigated is spherical aberration (SA). Modern, aspheric intraocular lenses are designed for its correction in different ways.

In order to develop appropriate aspheric intraocular lenses it is highly important to investigate corneal SA measurements and to understand what changes they may undergo with aging. Intraocular lenses are to compensate such HOAs of the eye as strongly as possible bringing it close to the optimal state free of aberrations.

Both the anterior and the posterior surfaces contribute to the lower and higher order aberrations of the cornea, however earlier, posterior surface examinations could be carried out only with Orbscan. At present, posterior corneal analysis based on Scheimpflug imaging has become well known with its good repeatability.[2]

A human eye changes with advancing age: in addition to several anatomic parameters, higher-order aberration of the cornea will also undergo alterations.[3] Our goal was to analyze corneal aberrations of both the anterior and posterior surfaces changing with age using the high resolution version of Pentacam (Pentacam HR) based on Scheimpflug imaging, the already widely used device for the assessment of the anterior segment. According to our knowledge this is the first study, involving a larger population, to assess anterior and posterior corneal aberrations and to investigate their correlations with aging using Pentacam HR device.

Patients and methods

Our study comprised healthy volunteers with good distance vision (minimum of 20/25 Snellen equivalent) who had no clinically documented ocular deviation other than low refraction error (lower than 0.75 D) and cataract. None of them was contact lens wearer.

Subsequent to the visual acuity test and prior to any other measurements and slit-lamp examination 3 images were captured of each eye with the high resolution version of Pentacam (Pentacam HR, software version 1.17r139) using Scheimpflug imaging. The device was set to a 25 images/second mode and images were taken in auto mode at perfect eye-set. In case of image distortion (e.g. blinking) or lack of data, the snapshot was repeated. Images were captured of only one randomly choosen eye of each patient, which underwent further evaluation.

The anterior segment rotating Scheimpflug camera rotates along the optical axis of the eye. This device uses 475 nm monochromatic blue light for imaging, the camera captures 25, 50 or 100 scans in two seconds with 2760 measuring points. The software allows for automatic analysis of the anterior segment, anterior and posterior topography of the cornea, pachymetry, calculation of the chamber angle, volume, chamber height (anterior chamber depth) and analysis of the lens. Finally, the instrument creates a 3D model of the anterior segment. The software of the device corrects distortions in the Scheimpflug images based on the geometry of the Scheimpflug principle.

Pentacam also allows us to assess and analyze the lower and higher order aberrations of the eye. It calculates Zernike coefficients and also the values of the root mean square (RMS) of the coma (square root of the sum of the squared coefficients of Z(3,-1), Z(3,1), Z(5,-1), and Z(5,1)) and the RMS of the spherical aberration (square root of the sum of the squared coefficients of Z(4,0) and Z(6,0)). Aberrations were evaluated at 8.0 mm pupil setting. The research protocol adhered to the tenets of the Declaration of Helsinki.

Statistical analysis was performed with MedCalc 10.0. Descriptive statistical results were described as mean, standard deviation (SD) and 95% confidence interval (95% CI) for the mean. Normality of data was tested by Kolmogorov-Smirnov test. If the normality was rejected ($p<0.05$), nonparametric test was used. Mann-Whitney U test was carried out for comparison between groups or variables, and Spearman rank test for correlation. Besides, we performed linear regression analysis adjusting aberrometric data for age. A P value below 0.05 was considered statistically significant, and Bonferroni correction was applied for multiple tests.

Results

Our study examined one eye of each of the 227 subjects (age: 55.15±21.2 years, range: 16-90 years, 95% CI: 52.37-57.9 years). In 135 cases the right eyes, in 92 cases the left eyes were investigated. With respect to laterality, no deviance was found in any of the parameters ($p>0.05$). Mean refractive error was 0.52±0.23 D (range: -0.75- +0.75 D). Normality was rejected for all parameters examined ($p<0.001$). Detailed keratometric results of the anterior and posterior corneal surfaces are displayed in Table 1. No significant correlations were found between keratometric data and age ($p>0.05$), however the level of keratometric astigmatism in both the anterior and posterior surfaces decreased weakly, but significantly with advancing age ($p<0.05$) (Table 1). During the assessment of lower order aberrations of the eye, at Z2 level, the anterior and posterior corneal surface measurements demonstrated that the level of aberrations increase significantly with aging ($p<0.01$) (Table 2). Intraclass correlation was good for all HOA data (ICC=0.86-0.91). The examination of corneal aberration RMS shows that the overall RMS and the total RMS HOA are continuously increasing with age ($p<0.01$). This process is due to the increase of the RMS and RMS HOA of the anterior surface ($p<0.01$); while the values of RMS and RMS HOA of the posterior surface do not show any deviations with increasing age ($p>0.05$) (Table 3). Of the HOAs, the constant increase of the primary and secondary spherical aberration with age is striking ($p<0.01$), which is due to the increase of the SA of the anterior surface (Figure 1). The investigation of coma aberration showed a significant and positive correlation between vertical coma aberration of the posterior surface and age ($r=0.273$; $p<0.05$). (Figure 2.) However, vertical coma values of the anterior and the entire corneal surface did not change significantly with advancing age. Regarding trefoil aberration the vertical trefoil values of the posterior corneal surface increased with age ($r=0.154$; $p=0.02$), while vertical trefoil values of the anterior and the entire corneal surface slightly decreased with age ($r=-0.134$; $p=0.04$ and $r=-0.15$; $p=0.02$) (Figure 3.). The horizontal components of coma- and trefoil aberrations showed no deviation with aging ($p>0.05$). The correlation between tetrafoil aberration and age was not significant ($p>0.05$). Detailed HOA data presented in Table 4.

Discussion

The investigations of the higher order aberration of the cornea and its correlation with age have had controversial results so far, highly due to the differences in the investigation methods. Present study, the first in literature, aimed to investigate the keratometric, lower and higher order aberration of the anterior and posterior surfaces and their changes with age using the high resolution version of Pentacam based on Scheimpflug imaging.

The keratometric parameters and the assessment of the anterior corneal surface have already been well defined; however the level of the astigmatism of the posterior cornea was investigated by only few studies.[4,5] The mean posterior power in healthy eyes was -6.2 D,[6] corneal curvature ranged between 5.8-6.78 mm.[5,7] Dunne found that the spherical component was -6.25--6.45 D and the cylindrical component was 0.34-0.38 D in the posterior corneal surface.[4] Our results, verifying a -6.15 D/-6.48 D mean keratometry in the posterior surface comparable well with Dunne's findings.

The correlation between biometric data and age has already been observed and published in cross-sectional examinations,[8-12] and was partly explained with the reduction in the length of the constituent collagen fibers in tissues.[8] According to the findings of Ho and his coworkers using Pentacam,[13] there were age-related shifts toward against-the-rule and with-the-rule astigmatisms for the anterior and posterior corneal surfaces, respectively. Our data demonstrate that keratometric astigmatism decreases slightly, however significantly in both the anterior and posterior surfaces of the cornea with age. Contradictory, at Z2 level, aberration data increase significantly with aging. Keratometric and Zernike astigmatism are not calculated in the same way, and we think that the reason for this apparent contradiction is that the latter one was calculated at large pupil diameter.

Certain higher order aberrations of the entire eye have already been investigated for at least 50 years ago[14-16] The reducing effect of HOA on image quality are also widely known.[17] The posterior surface of the cornea has a role in these errors, but has been by far the least investigated up till now. OrbScan[18] and later Pentacam provided the opportunity for assessment of the posterior surface, however, the limitations of Orbscan are well known.[19]

HOA measurements can be obtained with several devices.[16,19,20-22] The dissimilarity of the methods may give explanation for the differences in the results in the studies observing the changes of total and corneal HOA with aging.

Eye aberrations belonging to various groups of refraction errors can be of different levels;[23,24] however, corneal topography[10] and the total eye aberrometry[25] did not verify this difference. In present study, eyes with high refractive errors were excluded, so the possible correlation between the refractive state and the total corneal aberration was not analyzed.

The total corneal HOA, SA and coma are higher than the total ocular aberrations,[26] although Artal's study suggests that this applies only for a young age, at an older age it is just the opposite.[27] Some of the total ocular aberrometric deviations change with advancing age.[27,28] Previous publications supported the increase of the corneal[9,26,29] and the total ocular[16,27,28] coma aberration with aging. Other researches involving smaller population and using spatially resolved refractometer observed that total corneal SA increases with aging, but coma aberration shows no deviation.[16] Our results are similar to the these findings, although it obtained only the change of the vertical component of the coma aberration on the posterior corneal surface. McLellan et al.[16] described that the overall RMS wavefront error (excluding tilt, astigmatism and defocus) significantly increases with advancing age especially with respect to the fifth and seventh order. However, our data prove that the sixth order secondary spherical aberration shows a significant change with age, while such deviation was not detected in the fifth and seventh order.

The change of corneal SA with age is also controversial: according to several researchers, corneal SA shows no change with aging,[26,29] although topographic and videokeratographic investigations[9] reported changes and increase with aging. Using Scheimpflug photography, they observed an increase with advancing age[30] because the spherical aberration of the posterior corneal surface is negative at a young age and becomes positive at an older age.[30] Another study using Pentacam suggests, that the anterior corneal surface accounts for most of the corneal HOAs, and coma and spherical aberration also increase with age.[31] Our investigations based on Scheimpflug analysis demonstrated that the total HOA of the cornea significantly increases with advancing age due to the increase of the SA, though the coma and the vertical components of the trefoil aberration also play a role in the increase of total HOA. Glasser et al. found that the overall SA of the examined eyes was 0.25 μm.[32] According to our measurements the corneal SA is much higher this value.

The videokeratographic and wavefront aberration results of Amano[3] suggest that the increase of the coma aberration of the total eye is mainly due to corneal changes. The age-related increase of the ocular spherical aberration is not to be attributed to corneal changes, but to the increase of the spherical aberration of the internal optics and the deviations in the compensating effects of the crystalline lens radius[33,34] and the refractive index[35] may also contribute to its development. Systems compensating for refraction errors are known both in young[27,36] and in older eyes.[37] On one hand, the astigmatism of the posterior corneal surface partially compensates for the astigmatism of the anterior corneal surface.[5] The age-related increase of SA can be of a lens origin,[27,28] moreover, with the development of cataract the total HOA also changes.[38] In a young eye the negative SA of the lens compensates for the positive SA of the cornea,[35] however, at an older age, the SA of the lens increases, thus the total ocular SA also increases.[27,35] This can be the root cause of the development of a decreasing image quality with an advancing age.[9] It is known, that it is mainly the vertical coma that can help the reading ability of a presbyopic eye because of its increasing effect on the depth of focus, although we could only verify the increase of the vertical component of the trefoil aberration with similar effect. Eventually, the degradation of the optics of an older eye is due to the overbalance between the corneal and other surfaces of the eye.[27] Besides, it is known that the HOA is pupil dependent,[29] and the pupil is becoming more miotic with age,[11,39] so the decreasing effect of corneal aberrations on vision quality impair decrease, moreover, the Stiles-Crawford effect[40] decreases the effect of aberrations on visual acuity.

In conclusion, our data prove that the assessment of the anterior and posterior corneal surfaces shows that the level of astigmatism continuously, weakly decreases. We proved that primary and secondary spherical aberration and vertical trefoil aberration change significantly with age. Along with other changes of the eye, these changes are probably part of a complex system compensating for presbyopia, which may serve as a base for further studies.

References

1. Fan-Paul NI, Li J, Miller JS, Florakis GJ. Night vision disturbances after corneal refractive surgery. *Surv Ophthalmol.* 2002;47:533-546.

2. Chen D, Lam AKC. Intrasession and intersession repeatability of the Pentacam system on posterior corneal assessment in the normal human eye. *J Cataract Refract Surg.* 2007;33:448-454.

3. Amano S, Amano Y, Yamagami S, Miyai T, Miyata K, Samejima T, Oshika T. Age-related changes in corneal and ocular higher-order wavefront aberrations. *Am J Ophthalmol.* 2004;137:988-992.

4. Dunne MC, Royston JM, Barnes DA. Normal variations of the posterior corneal surface. *Acta Ophthalmol (Copenh).* 1992;70:255-261.

5. Dubbelman M, Sicam VA, Van der Heijde GL. The shape of the anterior and posterior surface of the aging human cornea. *Vision Res.* 2006;46:993-1001.

6. Seitz B, Langenbucher A, Hofmann B, Behrens A, Kus MM. Refractive power of the human posterior corneal surface in vivo in relation to gender and age. *Ophthalmologe.* 1998;95:S50.

7. Seitz B, Torres F, Langenbucher A, Behrens A, Suárez E. Posterior corneal curvature changes after myopic laser in situ keratomileusis. *Ophthalmology.* 2001;108:666-672.

8. Leighton DA, Tomlinson A. Changes in axial length and other dimensions of the eyeball with increasing age. *Acta Ophthalmol.* 1972;50:815-826.

9. Guirao A, Redondo M, Artal P. Optical aberrations of the human cornea as a function of age. *J Opt Soc Am A Opt Image Sci Vis.* 2000;17:1697-1702.

10. Philip K, Martinez A, Ho A, Conrad F, Ale J, Mitchell P, Sankaridurg P. Total ocular, anterior corneal and lenticular higher order aberrations in hyperopic, myopic and emmetropic eyes. *Vision Res.* 2012;52:31-37.

11. O'Donnell C, Hartwig A, Radhakrishnan H. Correlations between refractive error and biometric parameters in human eyes using the LenStar 900. *Cont Lens Anterior Eye.* 2011;34:26-31.

12. Xu L, Cao WF, Wang YX, Chen CX, Jonas JB. Anterior chamber depth and chamber angle and their associations with ocular and general parameters: the Beijing Eye Study. *Am J Ophthalmol.* 2008;145:929-936.

13. Ho JD, Liou SW, Tsai RJ, Tsai CY. Effects of aging on anterior and posterior corneal astigmatism. *Cornea.* 2010;29:632-637.

14. Ivanof A. About the spherical aberration of the eye. *J Opt Soc Am.* 1953;46:901-903.

15. Castejón-Mochón JF, López-Gil N, Benito A, Artal P. Ocular wave-front aberration statistics in a normal young population. *Vision Res.* 2002;42:1611-1617.

16. McLellan JS, Marcos S, Burns SA. Age-related changes in monochromatic wave aberrations of the human eye. *Invest Ophthalmol Vis Sci.* 2001;42:1390-1395.

17. Chalita MR, Krueger RR. Correlation of aberrations with visual acuity and symptoms. *Ophthalmol Clin North Am.* 2004;17:135-142.

18. Wang Z, Chen J, Yang B. Posterior corneal surface topographic changes after laser in situ keratomileusis are related to residual corneal bed thickness. *Ophthalmology.* 1999;106:406-409.

19. Cairns G, McGhee CNJ. Orbscan computerized topography: attributes, applications, and limitations. *J Cataract Refract Surg.* 2005;31:205-220.

20. Webb RH, Penney CM, Thompson KP. Measurement of ocular wavefront distortion with a spatially resolved refractometer. *Appl Optics.* 1992;31:3678-3686.

21. Liang J, Grimm B, Goelz S, Bille JF. Objective measurement of wave aberrations of the human eye with the use of a Hartmann-Shack wave-front sensor. *J Opt Soc Am A.* 1994;11:1949-1957.

22. Guirao A, Artal P. Corneal wave aberration from videokeratography: accuracy and limitations of the procedure. *J Opt Soc Am A Opt Image Sci Vis.* 2000;17:955-965.

23. Paquin MP, Hamam H, Simonet P. Objective measurements of optical aberrations in myopic eyes. *Optom Vis Sci.* 2002;79:285-291.

24. He JC, Sun P, Held R, Thorn F, Sun X, Gwiazda JE. Wavefront aberrations in eyes of emmetropic and moderately myopic school children and young adults. *Vis Res.* 2002;42:1063-1070.

25. Cheng X, Bradley A, Hong X, Thibos LN. Relationship between refractive error and monochromatic aberrations of the eye. *Optom Vis Sci.* 2003;80:43-49.

26. Wang L, Dai E, Koch DD. Optical aberrations of the human anterior cornea. *J Cataract Refract Surg.* 2003;29:1514-1521.

27. Artal P, Berrio E, Guirao A, Piers P. Contribution of the cornea and internal surfaces to the change of ocular aberrations with age. *J Opt Soc Am A Opt Image Sci Vis.* 2002;19:137-143.

28. Wang L, Koch DD. Ocular higher-order aberrations in individuals screened for refractive surgery. *J Cataract Refract Surg.* 2003;29:1896-1903.

29. Oshika T, Klyce SD, Applegate RA, Howland HC. Changes in corneal wavefront aberrations with aging. *Invest Ophthalmol Vis Sci.* 1999;40:1351-1355.

30. Sicam VA, Dubbelman M, van der Heijde RG. Spherical aberration of the anterior and posterior surfaces of the human cornea. *J Opt Soc Am A Opt Image Sci Vis.* 2006;23:544-549.

31. Cermáková S, Skorkovská S. Corneal higher order aberrations and their changes with aging. *Cesk Slov Oftalmol.* 2010;66:254-257.

32. Glasser A, Campbell MCW. Presbyopia and the optical changes in the human crystalline lens with age. *Vision Res.* 1998;38:209-229.

33. Brown N. The changes in lens curvature with age. *Exp Eye Res.* 1974;19:175-183.

34. Dubbelman M, Van der Heijde GL. The shape of the aging human lens: curvature, equivalent refractive index and the lens paradox. *Vis Res.* 2001;41:1867-1877.

35. Smith G, Atchison DA, Pierscionek BK. Modeling the power of the aging human eye. *J Opt Soc Am A.* 1992;9:2111-2117.

36. Artal P, Guirao A, Berrio E, Williams DR. Compensation of corneal aberration by the internal optics in the human eye. *J Vis.* 2001;1:1-8.

37. He JC, Gwiazda J, Thorn F, Held R. Wave-front aberrations in the anterior corneal surface and the whole eye. *J Opt Soc Am A Opt Image Sci Vis.* 2003;20:1155-1163.

38. Kuroda T, Fujikado T, Maeda N, Oshika T, Hirohara Y, Mihashi T. Wavefront analysis of higher-order aberrations in patients with cataract. *J Cataract Refract Surg.* 2002;28:438-444.

39. Buckley C, Curtin DM, Docherty J, Eustace P. Ageing and alpha adrenoreceptors in the iris. *Eye.* 1987;1:211-216.

40. Stiles WS, Crawford BH. The luminous efficiency of rays entering the eye pupil at different points. *Proc R Soc Lond B.* 1933;112:428-450.

Legends of figures

Figure 1.

Corneal primary spherical aberration (SA) as a function of age. It can be seen, that the total SA increase of the cornea ($r=0.273$; $p<0.001$) is due to the SA increase of the anterior corneal surface ($r=0.255$; $p=0.001$).

Figure 2.

Graph showing the correlation between vertical coma aberration and age. The vertical coma aberration of the posterior surface showed a slight regression line with age ($r=0.291$; $p<0.01$). Values of total corneal vertical coma and that of the anterior surface showed no significant change with advancing age.

Figure 3.

Vertical trefoil aberration changes of the total cornea, the anterior corneal surface and the posterior corneal surface with age. The vertical trefoil value of the posterior corneal surface increases moderately with age ($r=0.162$; $p=0.018$), while the vertical trefoil values of the anterior surface and the entire cornea moderately decrease ($r=-0.146$; $p=0.048$ and $r=-0.151$; $p=0.031$.

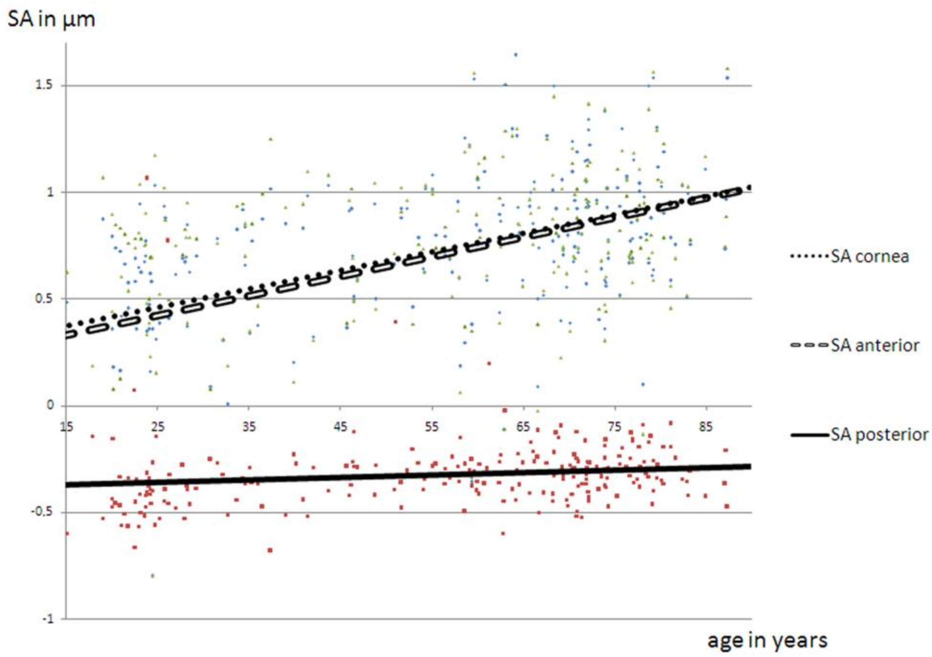

Figure 1

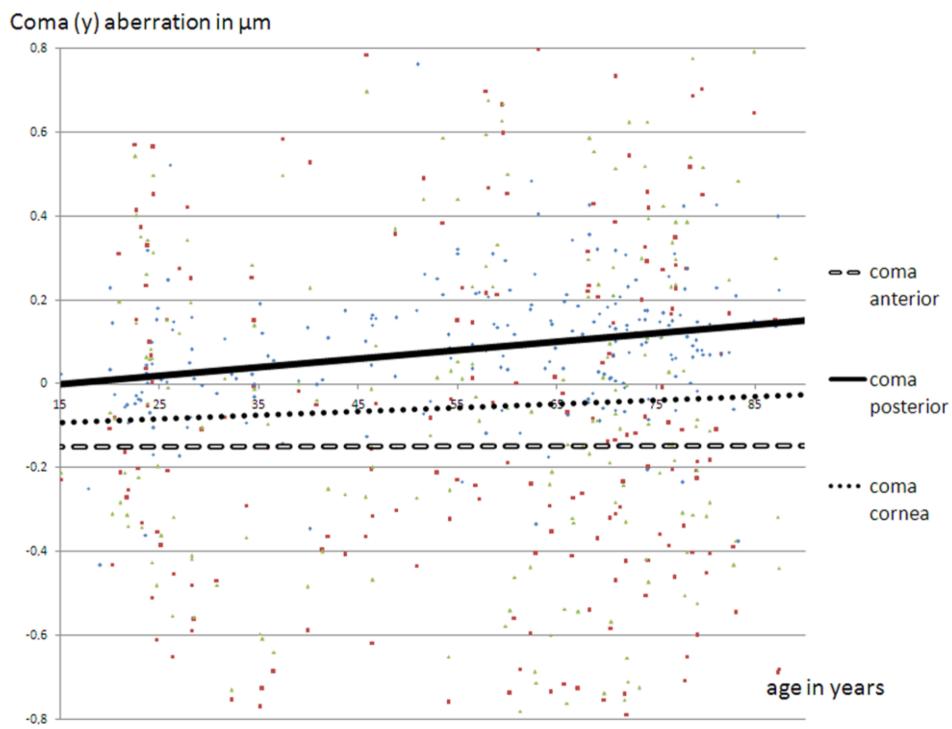

Figure 2

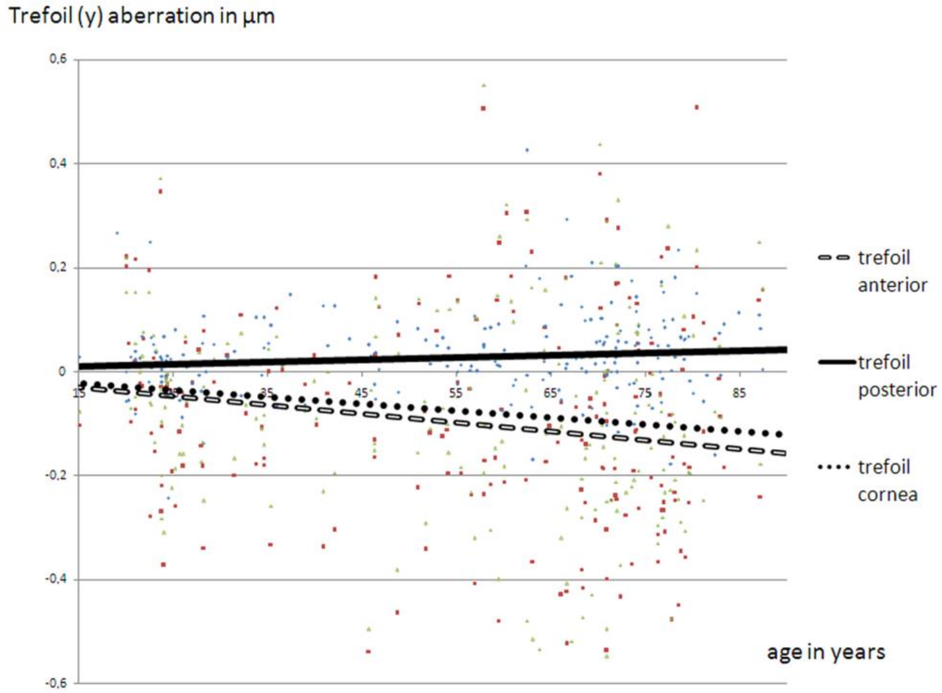
Trefoil (y) aberration in µm
0,6
0,4
0,2
0
-0,2
-0,4
-0,6
45
55
65
75
85
age in years
trefoil anterior
trefoil posterior
trefoil cornea

Figure 3

	Mean	SD	95% CI	Minimum	Maximum	b	p
K1 B (D):	-6.15	0.28	-6.19 - -6.11	-7.73	-4.93	0.008	0.508
K1 F (D):	43.24	1.95	42.98 - 43.45	38.66	48.76	0.031	0.381
K2 B (D):	-6.47	0.32	-6.52 - -6.43	-9.23	-5.70	0.134	0.114
K2 F (D):	44.21	1.88	43.96 - 44.46	40.03	57.36	0.091	0.147
Astigmatism B (D):	0.32	0.19	0.29 - 0.35	0.03	1.56	-0.170	0.010
Astigmatism F (D):	0.96	1.14	0.81 - 1.11	0.03	9.33	-0.259	<0.001

Table 1.: Statistical data of keratometric values in a healthy population measured with Pentacam HR (N=227). K1: keratometric value in diopter (D) on anterior corneal surface (F) and posterior corneal surface (B), in flat axis, K2: keratometric value in diopter (D) in the steep axis on anterior corneal surface (F) and posterior corneal surface (B). SD: standard error of mean, 95% CI: 95% confidence interval for mean, b: regression coefficients between age and the dependents, p: significance level of regression

	name of Zernike order	Mean	SD	95% CI	Minimum	Maximum	b	p
Z 2 -2 in µm (CB):	astigmatism (y)	0.0443	0.231	0.014 - 0.075	-0.604	0.772	-0.072	0.265
Z 2 -2 in µm (CF):	astigmatism (y)	-0.037	1.088	-0.182 - 0.106	-4.900	4.527	0.243	<0.001
Z 2 -2 in µm (Cornea):	astigmatism (y)	-0.033	1.235	-0.197 - 0.130	-6.281	3.932	0.215	<0.001
Z 2 0 in µm (CB):	defocus	-1.443	0.974	-1.572 - -1.314	-4.426	6.020	0.493	<0.001
Z 2 0 in µm (CF):	defocus	3.167	1.721	2.625 - 3.711	-4.062	8.132	0.312	<0.001
Z 2 0 in µm (Cornea):	defocus	3.397	1.690	2.947 - 3.391	-8.280	7.512	0.478	<0.001
Z 2 2 in µm (CB):	astigmatism (x)	0.371	0.319	0.328 - 0.413	-1.305	1.555	-0.365	<0.001
Z 2 2 in µm (CF):	astigmatism (x)	-0.905	1.807	-1.144 - -0.666	-7.641	11.713	0.436	<0.001
Z 2 2 in µm (Cornea):	astigmatism (x)	-0.640	1.276	-0.893 - -0.386	-13.12	10.503	0.497	<0.001

Table 2.: Astigmatism as a lower order aberration of the entire cornea and the anterior corneal surface (CF) and posterior corneal surface (CB) respectively, measured with Pentacam HR. SD: standard error of mean, 95% CI: 95% confidence interval for mean, b: regression coefficients between age and the dependents, p: significance level of regression

	Mean	SD	95% CI	Minimum	Maximum	b	p
RMS in µm (CB):	1.175	0.541	1.108 - 1.252	0.393	3.905	0.042	0.531
RMS in µm (CF):	3.119	1.631	2.954 - 3.446	0.589	10.929	0.383	<0.001
RMS in µm (Cornea):	2.905	1.661	2.683 - 3.127	0.603	9.895	0.512	<0.001
RMS HOA in µm (CB):	0.274	0.165	0.252 - 0.291	0.085	0.945	0.304	<0.001
RMS HOA in µm (CF):	0.858	0.698	0.766 - 0.950	0.206	3.882	0.496	<0.001
RMS HOA in µm (Cornea):	0.834	0.731	0.737 - 0.931	0.170	5.695	0.517	<0.001
RMS LOA in µm (CB):	1.138	0.524	1.069 - 1.207	0.380	3.882	0.027	0.681
RMS LOA in µm (CF):	2.973	1.445	2.779 - 3.167	0.524	7.121	0.476	<0.001
RMS LOA in µm (Cornea):	2.783	1.565	2.573 - 2.992	0.531	9.710	0.532	<0.001

Table 3.: Root mean square (RMS) values with respect to lower and higher order aberration (LOA and HOA), regarding the entire cornea and the anterior corneal surface (CF) and posterior corneal surface (CB) with Pentacam HR, in a healthy population (N=227). SD: standard error of mean, 95% CI: 95% confidence interval for mean, b: regression coefficients between age and the dependents, p: significance level of regression

	name of Zernike order	Mean	SD	95% CI	Minimum	Maximum	b	p
Z 3 -3 in µm (CB):	trefoil (y)	0.028	0.109	0.013 - 0.042	-0.637	0.630	0.162	0.018
Z 3 -3 in µm (CF):	trefoil (y)	-0.123	0.577	-0.198 - -0.046	-4.34	4.585	-0.146	0.048
Z 3 -3 in µm (Cornea):	trefoil (y)	-0.049	0.521	-0.157 - 0.058	-3.795	4.035	-0.151	0.031
Z 3 -1 in µm (CB):	coma (y)	0.078	0.164	0.056 - 0.099	-0.45	0.762	0.291	<0.001
Z 3 -1 in µm (CF):	coma (y)	-0.136	0.703	-0.229 - -0.042	-3.652	2.134	-0.027	0.678
Z 3 -1 in µm (Cornea):	coma (y)	-0.045	0.683	-0.136 - 0.045	-3.378	3.757	0.039	0.535
Z 3 1 in µm (CB):	coma (x)	0.017	0.162	-0.004 - 0.038	-0.665	0.806	0.047	0.395
Z 3 1 in µm (CF):	coma (x)	-0.118	0.677	-0.203 - -0.028	-4.785	2.638	0.055	0.354
Z 3 1 in µm (Cornea):	coma (x)	-0.114	0.604	-0.194 - -0.034	-4.387	2.076	0.145	0.092
Z 3 3 in µm (CB):	trefoil (x)	0.011	0.098	-0.002 - 0.024	-0.343	0.978	-0.118	0.124
Z 3 3 in µm (CF):	trefoil (x)	-0.011	0.325	-0.055 - 0.031	-1.922	2.052	0.041	0.522
Z 3 3 in µm (Cornea):	trefoil (x)	-0.015	0.384	-0.065 - 0.036	-3.349	1.759	0.037	0.651
Z 4 -4 in µm (CB):	tetrafoil (y)	0.008	0.085	-0.002 - 0.020	-0.252	0.884	0.031	0.665
Z 4 -4 in µm (CF):	tetrafoil (y)	-0.082	0.479	-0.141 - -0.018	-4.311	0.458	-0.07	0.256
Z 4 -4 in µm (Cornea):	tetrafoil (y)	-0.062	0.478	-0.123 - 0.002	-3.803	2.527	-0.076	0.224
Z 4 -2 in µm (CB):	secondary astigmatism (y)	0.002	0.056	-0.004 - 0.010	-0.268	0.404	-0.122	0.092
Z 4 -2 in µm (CF):	secondary astigmatism (y)	0.025	0.289	-0.012 - 0.063	-1.243	2.009	0.041	0.522
Z 4 -2 in µm (Cornea):	secondary astigmatism (y)	0.021	0.279	-0.015 - 0.058	-1.131	1.941	0.039	0.488
Z 4 0 in µm (CB):	primary spherical	-0.323	0.175	-0.346 - -0.300	-0.682	1.063	0.139	0.014
Z 4 0 in µm (CF):	primary spherical	0.711	0.753	0.612 - 0.811	-5.291	2.877	0.255	0.001
Z 4 0 in µm (Cornea):	primary spherical	0.729	0.667	0.641 - 0.817	-3.992	3.682	0.273	<0.001
Z 4 2 in µm (CB):	secondary astigmatism (x)	-0.035	0.076	-0.045 - -0.025	-0.589	0.359	-0.345	<0.001
Z 4 2 in µm (CF):	secondary astigmatism (x)	-0.042	0.373	-0.091 - 0.006	-1.415	3.115	0.123	0.084
Z 4 2 in µm (Cornea):	secondary astigmatism (x)	-0.061	0.413	-0.115 - -0.005	-1.342	3.266	0.034	0.654
Z 4 4 in µm (CB):	tetrafoil (x)	-0.032	0.087	-0.043 - -0.020	-0.891	0.213	-0.032	0.567
Z 4 4 in µm (CF):	tetrafoil (x)	-0.058	0.422	-0.115 - -0.002	-2.933	4.094	0.041	0.462
Z 4 4 in µm (Cornea):	tetrafoil (x)	-0.114	0.533	-0.184 - -0.043	-5.337	3.303	0.065	0.342
Z 6 0 in µm (CB):	secondary spherical	0.011	0.043	0.005 - 0.016	-0.322	0.158	-0.377	<0.001
Z 6 0 in µm (CF):	secondary spherical	-0.075	0.184	-0.099 - -0.050	-0.608	1.509	-0.286	<0.001
Z 6 0 in µm (Cornea):	secondary spherical	-0.067	0.234	-0.098 - -0.036	-2.648	1.286	-0.378	<0.001

Table 4.: Higher order aberrations labeled on the basis of Zernike pyramid for the entire cornea, and the anterior corneal surface (CF) and posterior corneal surface (CB). SD: standard error of mean, 95% CI: 95% confidence interval for mean, b: regression coefficients between age and the dependents, p: significance level of regression