The Relationship Between Preoperative Anterior Corneal Higher Order Aberrations and Topography-Guided Excimer Ablation Depth

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ABSTRACT

PURPOSE: To determine the correlation and relative contribution of preoperative anterior corneal Zernike coefficients to higher order aberration ablation depth (HOA-AD) with topography-guided excimer laser correction.

METHODS: Retrospective study of 46,271 consecutive preoperative virgin eyes. Anterior corneal Zernike coefficients (C6 to C27) and HOA-AD data on a 6.5-mm optical zone were analyzed from the Contoura (Alcon Laboratories, Inc) treatment software. Pearson correlations were performed to assess the relationship between Zernike coefficients and HOA-AD.

RESULTS: A strong direct relationship was found between the total root mean square (RMS) anterior corneal HOA and HOA-AD (R = 0.84; P < .001). The 3rd order HOAs (C6 to C9) accounted for most of the HOA-AD (R = 0.83; P < .001). Zernike orders 4, 5, and 6 had significantly weaker correlations (4th order: R = 0.30; 5th order: R = 0.38; 6th order: R = 0.29). Vertical coma was the individual HOA with the highest correlation (R = 0.59; P < .001). Combining vertical and horizontal coma as total RMS coma increased the correlation significantly (R = 0.76; P < .001). The average HOA-AD increased by 1.5 µm for each additional 0.1-µm increment of total RMS coma.

CONCLUSIONS: Anterior corneal Zernike coefficients directly and strongly correlate to the HOA-AD, with anterior corneal coma having the greatest contribution to HOA-AD.

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The ablation profiles of current excimer lasers are proprietary and may differ slightly from one laser to another.[1] The relationship between the depth of ablation in microns and the diopters of treated sphere and cylinder at a given optical zone has been known for more than three decades, and was first described by Munnerlyn et al.[2] However, the complex relationship between the higher order aberration ablation depth (HOA-AD) and the treated Zernike coefficients with topography-guided correction remains to be investigated.

The WaveLight Topolyzer VARIO topographer (Alcon Laboratories, Inc) images the cornea, and the Contoura planning software (Alcon Laboratories, Inc) generates an HOA ablation profile derived using a proprietary Alcon algorithm showing the ablation depth data.[3] The Contoura surgical workflow involves verifying the HOA ablation map to determine if the deeper areas of HOA ablation correspond to the topography anterior elevation map.[3] The HOA-AD is also an important parameter that Contoura surgeons rely on to rapidly and globally gauge the amount of corneal irregularity as part of their Contoura candidacy criteria and preoperative planning. The individual HOAs, which also convey such information, are not readily available to assess on the Contoura software at the laser and require viewing a second screen with

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complex interpretation of individual Zernike coefficients (C6 to C27 values) or going back to reference the VARIO topographer, which is not available in the operating room. As such, the corneal HOAs are not commonly looked at. Because the HOA-AD is readily available in the treatment planning software and is easily visualized, it is used by experienced Contoura surgeons routinely. Surgeons have their own varying criteria as to how much HOA-AD treatment they will accept to proceed with Contoura treatment or rather revert to wavefront-optimized or Custom-Q software,[4,5] whereas others use higher HOA-AD values as an indication to use Contoura treatment.[3] However, with no publications to date, surgeons can only assume that the deeper the HOA-AD, the greater the anterior corneal HOAs, which is the premise of the technology. The exact relationship between these variables remains to be elucidated. This study set out to investigate, for the first time, the correlations between anterior corneal HOAs and HOA-AD, and the relative contribution of individual anterior corneal Zernike coefficients to HOA-AD.

PATIENTS AND METHODS

Selection of Patients

A retrospective electronic medical record database review of consecutive preoperative virgin eyes that underwent Contoura topography-guided planning using the WaveLight EX500 excimer laser (Alcon Laboratories, Inc) between June 2017 and June 2019 was conducted. Eyes with naturally occurring irregular astigmatism and/or asymmetrical topographies on keratometric maps were not excluded from Contoura planning, as was done in the U.S. Food and Drug Administration Contoura approval study.[6] Examples of asymmetrical keratometric maps are reported elsewhere.[7] Standard exclusion criteria for laser in situ keratomileusis (LASIK) with exclusions for forme fruste or frank keratoconus were used, as described previously.[3,7-9] In addition, eyes with deep HOA-AD greater than 10 µm were not excluded from surgical planning, as some surgeons advocate. Examples of such deep HOA-AD ablation profiles were recently published.[3] The current authors also have extensive experience and have published on eyes with deep HOA-AD, with good outcomes.[3] Inclusion of eyes with deep HOA-AD enabled this study to investigate the relationship between HOA-AD and Zernike coefficients over a large range of HOA ablation depths. This retrospective study was approved by the Ethics Review Board of the Canadian Ophthalmic Research Centre. All patients provided a written consent for use of anonymized data for research. All experiments conformed to the principles of the Declaration of Helsinki.

Topography Acquisition

As previously described elsewhere,[3,7-9] 4 to 8 corneal topographies were acquired on undilated eyes with the WaveLight Topolyzer VARIO. The Topolyzer VARIO was calibrated as per manufacturer guidelines before all surgical planning days. The criteria for image acceptance included appropriate recognition of the pupil and the mire edge by the software, mires with minimal breaks, the absence of significant missing data (shadow from the eyelids, eyelashes, nose, or dry tear film), and a percentage of data obtained (analyzed area) greater than 90% in the 6.5-mm zone. Maps were compared to assess the reproducibility of the scans, including keratometry, Q value, and axis of astigmatism. The median absolute deviation is a measure of how spread out the set of Topolyzer scans is. A median absolute deviation variability score below 0.10 was necessary for inclusion. Sets of images that did not meet the above criteria were excluded. The remaining cases were exported to the Contoura software to generate the HOA ablation profiles.

HOA Ablation Map Image Production

The treatment ablation map generated by the Contoura software includes both lower order aberrations and HOAs. By manually inputting the sphere and cylinder treatment to zero in the Contoura treatment planning software prior to surgery, only the HOA ablation map was isolated and generated.[3] The maximum ablation depth of the HOA map was recorded and termed HOA-AD. The HOA-AD value is only available on the treatment planning screen and not on the Topolyzer when images are acquired. All treatments were planned using a 6.5-mm optical zone.

Zernike Coefficients of the Planned Treatments

The anterior corneal Zernike coefficients of the planned Contoura treatments from the WaveLight EX-500 laser software were analyzed. These planned treatment Zernike coefficients are generated by the software based on the VARIO scan data and are used by the laser for Contoura ablation. The Contoura planning software does not allow selective treatment of individual higher order Zernike terms, nor does it enable partial correction of selected HOAs. Therefore, all higher order Zernike coefficients are incorporated into Contoura treatments.

The higher order Zernike coefficients examined were C6 to C27 and the lower order coefficients C0 to C5 were excluded. The total RMS corneal and total RMS 3rd, 4th, 5th, and 6th order aberrations were also analyzed. The total RMS coma was obtained by calculating the squared root of the sum

TABLE 1
Average and Range of the HOA-AD and Zernike Coeeficients

Parameter	Mean ± SD	Range
HOA-AD	8.23 ± 2.79	1.99 to 26.8
Total RMS anterior corneal aberrations		
3rd order (C6 to C9)	0.29 ± 1.12	0.03 to 1.02
4th order (C10 to C14)	0.15 ± 0.06	0.02 to 0.71
5th order (C15 to C20)	0.05 ± 0.03	0.01 to 0.39
6th order (C21 to C27)	0.03 ± 0.02	0.00 to 0.16
3rd to 6th order (C6 to C27)	0.34 ± 0.11	0.10 to 1.08
3rd order anterior corneal aberrations[a]		
Vertical trefoil (C6)	0.13 ± 0.09	-0.64 to 0.36
Oblique trefoil (C9)	0.10 ± 0.07	-0.52 to 0.49
Vertical coma (C7)	0.18 ± 0.14	-0.94 to 0.97
Horizontal coma (C8)	0.15 ± 0.11	-0.98 to 0.78
Total coma (C7 and C8)	0.26 ± 0.14	0.01 to 1.00

HOA-AD = higher order aberration depth; SD = standard deviation; RMS = root mean square
[a]Average of the absolute values.

TABLE 2
Correlations Between Zernike Coefficients and HOA-AD Depth

HOAs	*R*	*P*
Total RMS anterior corneal aberrations		
3rd order (C6 to C9)	0.8256	< .0001
4th order (C10 to C14)	0.2965	< .0001
5th order (C15 to C20)	0.3764	< .0001
6th order (C21 to C27)	0.2853	< .0001
3rd to 6th order (C6 to C27)	0.8408	< .0001
3rd order anterior corneal aberrations		
Vertical trefoil (C6)	0.3986	< .0001
Oblique trefoil (C9)	0.3080	< .0001
Vertical coma (C7)	0.5901	< .0001
Horizontal coma (C8)	0.4480	< .0001
Total coma (C7 and C8)	0.7634	< .0001

HOA-AD = higher order aberration ablation depth; RMS = root mean square

of C7 squared and C8 squared. Eyes with total RMS corneal coma above 1.00 were excluded due to inadequate sample size above this value (less than 0.25% of the population).

Statistical Analysis

Statistical analyses were conducted in MATLAB R2019a software (MathWorks, Inc). The Pearson correlation coefficient was used to assess the relationship between selected Zernike coefficients and the HOA-AD. Statistical significance was set at a P value of less than .05.

RESULTS

A total of 46,271 eyes with planned Contoura treatment were included in this study. The range of HOA-AD was 1.99 to 26.8 µm with a median and mean of 8.00 and 8.23 ± 2.79, respectively. The range and mean values of corneal HOAs are reported in **Table 1**.

There was a strong direct relationship between the total RMS anterior corneal HOA (C6 to C27) and the HOA-AD (R = 0.84; P < .001; **Table 2**). The total RMS 3rd order anterior corneal HOA (C6 to C9) accounted for most of the correlation to HOA-AD (R = 0.83; P < .001, **Table 2**). Higher orders above 3rd (4th to 6th) had significantly weaker correlations (4th order: R = 0.30; 5th order: R = 0.38; 6th order: R = 0.29; P < .001, **Table 2**).

Further breakdown of the 3rd order anterior corneal aberrations revealed that anterior corneal vertical and oblique trefoil contributed to a small extent to HOA-AD (R = 0.40; P < .001; **Table 2**). In contrast, anterior corneal vertical and horizontal coma were the individual HOA with the highest correlation with HOA-AD (R = 0.59; P < .001; **Table 2**, **Figures 1A-1B**). Combining vertical and horizontal coma as total RMS anterior corneal coma significantly increased the strength of the correlation (R = 0.76; **Table 2**, **Figure 1C**). From 0 to 1 µm of total RMS preoperative anterior corneal coma, the average HOA-AD increased from 5 to 20 µm, with a 1.5-µm increase of HOA-AD for each additional 0.1-µm increment of total RMS coma (**Figure 1C**).

DISCUSSION

Contoura technology is based on topographical measurements of anterior corneal HOAs, expressed as Zernike coefficients, that are then used to create a custom HOA ablation map to perform a topography-guided treatment. No information is supplied by the manufacturer as to the algorithm that produces the HOA ablation map, or the derivation of the HOA-AD. The current study is the first to investigate relationships between anterior corneal HOAs and HOA-AD, and to examine the contribution and clinical relevance of individual anterior corneal Zernike coefficients to HOA-AD.

Only one other published study described HOA-AD values in LASIK patients.[3] The range and mean of HOA-AD in the current study is comparable to that reported previously. The current study confirms that anterior corneal HOAs are directly and highly correlated to HOA-AD. The RMS 3rd order anterior corneal HOAs accounted for most of the HOA-AD and were found to have the same correlation strength as all anterior corneal HOAs combined. This finding indicates how significant the 3rd order HOA is, comprising mainly coma. In fact, total RMS anterior corneal coma was the most important individual HOA contributing to HOA-AD, explaining 76% of the variance. Despite the strong correlations (highest $R = 0.84$) found in the current study, the predictability of the HOA-AD based solely on individual Zernike coefficients or total RMS values remains limited, with a maximum coefficient of determination (R^2) of 0.71. Future studies characterizing the HOA-AD as a function of both Zernike coefficients and optical zone size could determine whether the prediction is better with smaller optical zone size.

The novel information presented here is clinically relevant to the practicing surgeon, who can now use the HOA-AD with confidence as a useful metric, to not only generally assess how aberrated and irregular a cornea is, but more specifically to gauge the approximate amount of anterior corneal coma a patient has preoperatively. Deeper HOA-AD values translate into larger amounts of preoperative anterior corneal coma. A useful clinical estimate that can be used during treatment planning is that, on average, every 1.5-µm increment of HOA-AD translates into 0.1 µm of additional coma. These findings may prove useful to refine excimer nomogram accuracy.

The HOA-AD value gives surgeons the ability to easily detect eyes with high HOA preoperatively. Eyes with naturally occurring significant preoperative coma with deep HOA-AD can preferentially benefit from a topography-guided ablation to avoid iatrogenically inducing quality of vision symptoms.[3] The HOA-AD value therefore provides surgeons with an additional indication of the importance of using topography-guided software versus a symmetrical treatment with wavefront-optimized or Custom-Q ablation on any given patient. In addition, this preoperative metric improves the consent

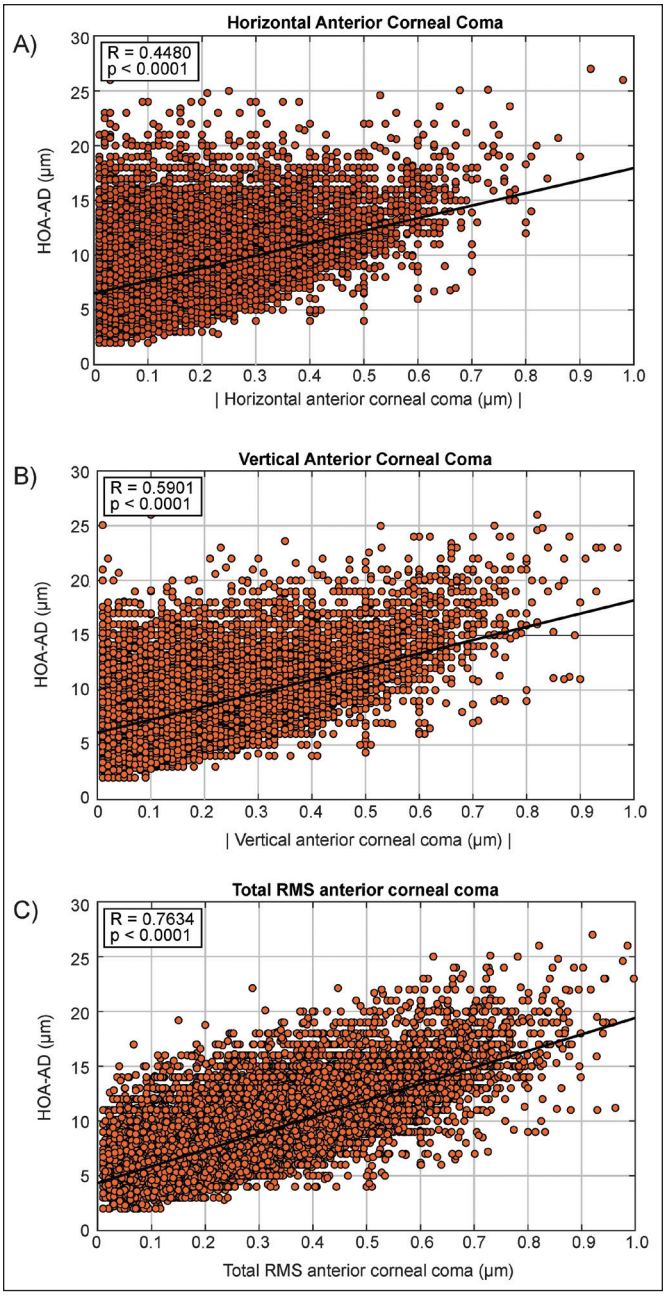

Figure 1. (A) Higher order aberration ablation depth (HOA-AD) in relation to the absolute value of the anterior corneal horizontal coma in 46,271 eyes, and linear fitting of this relationship (black line). The Pearson correlation coefficient *R* and associated *P* value are given in the text box. (B) HOA-AD in relation to the absolute value of the anterior corneal vertical coma in 46,271 eyes and linear fitting of this relationship. (C) HOA-AD in relation to total root mean square (RMS) anterior corneal coma in 46,271 eyes and linear fitting of this relationship.

process by adding information regarding the patient's specific outcomes, because published data show visual and refractive results for high HOA-AD to be comparable to eyes with high cylinder.[3]

The current study confirms that the amount of anterior corneal HOAs directly correlates to HOA-AD, where the higher the anterior corneal HOAs, the deeper the HOA-AD. Total RMS coma contributes the most to HOA-AD. This information adds clinical utility to the practicing surgeon.

AUTHOR CONTRIBUTIONS

Study concept and design (AW, MG); data collection (MG); analysis and interpretation of data (AW, MG, MC); writing the manuscript (AW, MG); critical revision of the manuscript (AW, MG, MC); statistical expertise (MG); supervision (AW, MC)

REFERENCES

1. Gatinel D, Hoang-Xuan T, Azar DT. Volume estimation of excimer laser tissue ablation for correction of spherical myopia and hyperopia. *Invest Ophthalmol Vis Sci*. 2002;43(5):1445-1449.
2. Munnerlyn CR, Koons SJ, Marshall J. Photorefractive keratectomy: a technique for laser refractive surgery. *J Cataract Refract Surg*. 1988;14(1):46-52. doi:10.1016/S0886-3350(88)80063-4
3. Wallerstein A, Gauvin M, Cohen M. Effect of anterior corneal higher-order aberration ablation depth on primary topography-guided LASIK outcomes. *J Refract Surg*. 2019;35(12):754-762. doi:10.3928/1081597X-20191021-02
4. Faria-Correia F, Ribeiro S, Monteiro T, Lopes BT, Salomão MQ, Ambrósio R Jr. Topography-guided custom photorefractive keratectomy for myopia in primary eyes with the WaveLight EX500 platform. *J Refract Surg*. 2018;34(8):541-546. doi:10.3928/1081597X-20180705-03
5. Cummings AB. Topography-guided and Contoura™ laser vision correction. In: Sinjab MM, Cummings AB, eds. *Customized Laser Vision Correction*. Springer International Publishing; 2018:115-165. doi:10.1007/978-3-319-72263-4_4
6. Stulting RD, Fant BS, Bond W, et al; T-CAT Study Group. Results of topography-guided laser in situ keratomileusis custom ablation treatment with a refractive excimer laser. *J Cataract Refract Surg*. 2016;42(1):11-18. doi:10.1016/j.jcrs.2015.08.016
7. Wallerstein A, Caron-Cantin M, Gauvin M, Adiguzel E, Cohen M. Primary topography-guided LASIK: refractive, visual, and subjective quality of vision outcomes for astigmatism ≥2.00 diopters. *J Refract Surg*. 2019;35(2):78-86. doi:10.3928/1081597X-20181210-01
8. Wallerstein A, Gauvin M, Adiguzel E, et al. Clinically significant laser in situ keratomileusis flap striae. *J Cataract Refract Surg*. 2017;43(12):1523-1533. doi:10.1016/j.jcrs.2017.09.023
9. Wallerstein A, Gauvin M, Qi SR, Bashour M, Cohen M. Primary topography-guided LASIK: treating manifest refractive astigmatism versus topography-measured anterior corneal astigmatism. *J Refract Surg*. 2019;35(1):15-23. doi:10.3928/1081597X-20181113-01