Problems with wavefront aberrations applied to refractive surgery: Developing standards

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ABSTRACT

Refractive surgery is evolving rapidly. A recent development uses wavefront aberration information to improve the surgical outcome. Before the wavefront information can be used effectively a number of problems must first be resolved. One of the main concerns is the presence of halos during night driving conditions. It seems clear that this problem occurs when the pupil is large enough to overlap the ablation transition zone. Several questions associated with the transition zone are examined. Shape descriptors to characterize the transition zone are discussed. Better ways of quantitatively characterizing the transition zone and predicting its properties are needed to help specify the ablation. Many of the issues associated with improving refractive surgery can be addressed by establishing a standards committee that includes basic researchers and clinicians. This committee can become a forum for developing techniques to assess visual outcomes, it can make recommendations for developing a database that would allow researchers to compare the intended outcome of ablation with the actual outcome. In order for this enterprise to be successful increased openness about surgery parameters and surgery outcome would be helpful.

1. INTRODUCTION

New ideas for refractive surgery have been developing extremely rapidly in the past two years. Most of the laser companies are exploring customized ablation based on the individual eye's wavefront aberrations. Although it looks like progress is rapid, the recent history of refractive surgery is troubling. One example is the failure of the refractive surgery community to adequately deal with the problems of night vision. A large percentage of post refractive surgery eyes have large pupils at night that result in disturbing visual halos. This paper is largely inspired by the desire to minimize future problems by developing standards for how and when to do refractive surgery. The four sections of the paper are as follows:

Section 2 discusses an earlier effort to develop standards under the auspices of an Optical Society of America taskforce. It may well be that this taskforce will evolve into the standard setting body that I am hoping for. Section 2 discusses what the committee has accomplished so far and offers suggestions for improvements on their efforts. Section 3 brings up the topic of the disturbing halos seen at night and examines methods for minimizing them. Section 4 considers new methods for displaying and quantifying aspects of the wavefront that are relevant for visual function. Finally, Section 5 discusses future research that is needed in this area, and also discusses the need for honesty and openness to optimize future developments.

2. COMMENTS ON THE REPORT OF THE OSA WAVEFRONT STANDARDS TASK FORCE

Two years ago at the Optical Society's Vision Science and Its Applications (VSIA) meeting in Santa Fe a group of researchers decided to form a taskforce to develop standards for specifying wavefront aberrations. At the following year's VSIA meeting (2000) this taskforce gave their report[112]. An overview is available on the web at:

http://www.opt.indiana.edu/people/faculty/thibos/VSIA/VSIA-2000 taskforce/

A downloadable very detailed pdf file can be found at:

http://www.osa.org/Homes/vision/resources/intro.htm

The taskforce had three subgroups: 1) Standardize the reference origin and axis direction, 2) Standardize the Zernike notation, 3) Develop a test shape for calibrating wavefront devices. I strongly support the activity of this taskforce and the following comments on the taskforce report are meant to encourage the taskforce to continue with its good work. The present article is my attempt to further the development of standards for wavefront analysis as applied to refractive surgery. As will be discussed in Section 5, the fact that millions of people will be affected by the quality of refractive surgery makes the development of standards essential.

Ophthalmic Technologies XI, Fabrice Manns, Per G. Söderberg, Arthur Ho, Editors,
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2.1 Reference axis subgroup.
The reference axis subgroup recommended that the line of sight (LOS) be used as the reference axis. The LOS is the chief ray from the fixation point to the center of the entrance pupil and ends at the fovea. That the ray ends up on the fovea is expected since the observer moves his/her eye until the fixation point is foveated. The committee recommended an objective method and a subjective method for determining the LOS. Klein and Garcia[3] raised several questions regarding the subgroup's suggestion.
1) The proposed objective and subjective methods are probably not as accurate as determining the LOS directly from the measured wavefront. Most methods that measure wavefronts directly generate an image of the pupil. From that image one can determine the pupil center. In addition, most methods that measure wavefronts actually measure the wavefront slope. Knowledge of the wavefront slope at the pupil center determines the LOS. There is an ambiguity in locating the pupil center since its location depends on the pupil diameter. That topic will be considered in Section 3.1 where it is argued that the center for large pupils should be used. This section considers the LOS direction.
2) Klein and Garcia[3] also point out that the direction of the LOS is ambiguous. The official textbook definition of LOS is that it follows the one ray going through the pupil center. However, the objective and subjective methods suggested by the taskforce actually base the LOS on the average slope of a bundle of rays. That makes sense. It is often assumed that the chief ray is at the centroid of the blur function, but when coma is present (as is often the case) the chief ray is displaced from the centroid. The centroid is typically what the observer places at the center of the fovea when fixating the target. The slope centroid is well specified by the Zernike prism term. Klein and Garcia[3] provide a quantitative example showing how the two definitions of LOS can lead to very different looking wavefront height displays,

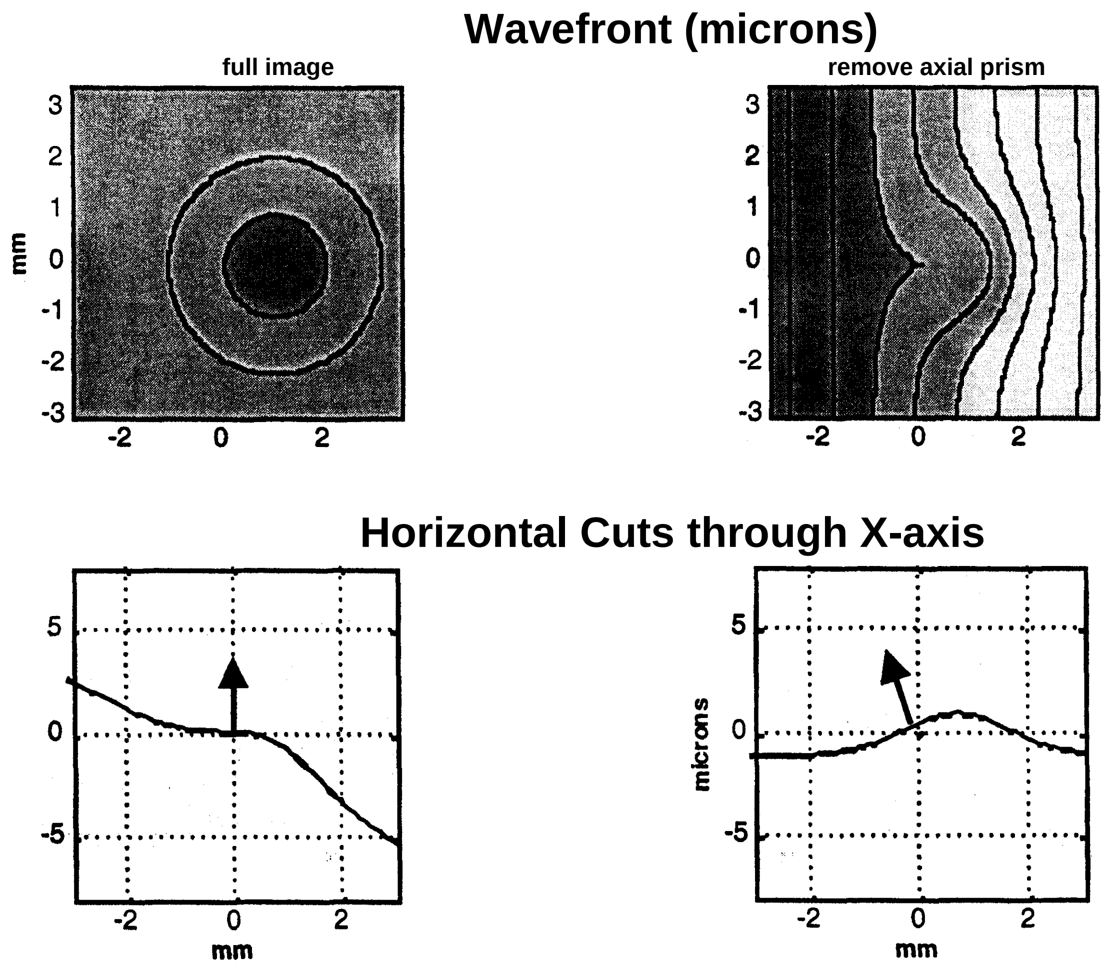


Figure 1

The wavefront considered by Klein and Garcia[3] and shown in Fig. 1, is given by:

$W(x, y) = 2 \exp(-((x -1)^2 + y^2)\hat{}\,) - 2 \exp(-l/2)$ microns (1)

Distances (x, y) are measured in mm and the wavefront, W, is measured in microns. This wavefront is a symmetric Gaussian with a 1 mm standard deviation and shifted by 1 mm to the right. The term 2 exp(-l/2) is subtracted off since we desire the wavefront height to be zero at the origin (x=y=0). This wavefront was chosen to simulate a very mild keratoconic distortion with peak curvature of 2 diopters (500 mm radius of curvature of the wavefront). A more typical keratoconic distortion would have a peak power of 20 D rather than 2 D. By choosing a small aberration of 2 D we are in the range of aberrations of normal corneas. The upper left panel of Figure 1 is a contour plot of Eq. l. The lower left panel gives the profile of the wavefront along the x axis (y=0). The slope of the wavefront at the origin (shown by the arrow that is normal to the wavefront) is 2 exp(-l/2) = 1.2131 milliradians corresponding to 0.12131 prism diopters or 4.17 minutes of arc. The direction of the arrow is the direction of the textbook definition of LOS (the direction of the wavefront normal at the pupil center). If we were to use the textbook definition of LOS the wavefront would need to be rotated so that the wavefront slope at the origin vanishes. This is accomplished by subtracting a prism term of 0.12131 prism diopters giving the results shown in the right panels. Note that in the lower right panel the wavefront normal is now vertical, indicating the textbook definition of LOS is being used as the reference direction for the z axis. Inspection of the upper right panel seems to indicate, incorrectly, a poor quality wavefront. The left panels provide a more useful representation of the wavefront than the right panels since the Gaussian bump is localized and the flat region around the bump will produce a sharp point spread function. The image quality produced by that wavefront is thus better seen in the left panels than the right panels. The example shown in Fig. 1 was chosen to show that a rotation of the LOS as small as 4 minutes can have a substantial effect on the appearance of the wavefront.

It is sometimes said that the precise choice of the LOS direction isn't important since it just corresponds to the choice of the how much prism to add to the wavefront. It is commonly believed that the amount of prism is irrelevant since the shape of the point spread function (PSF), and thus the aberrations, is independent of the amount of prism. Although prism does not affect the shape of the PSF (ignoring issues of chromatic aberration), to conclude that the amount of prism is irrelevant is not correct when considered in terms of refractive surgery. In refractive surgery prism cannot be ignored. Consider the following three cases:

1) Suppose the initial wavefront aberration has a lot of coma. This coma is typically present because the cornea has a displaced apex.

2) Suppose the biomechanics and initial shape of the cornea are such that the predicted transition zone is asymmetric.

3) Suppose the patient's eyes are slightly misaligned and he/she is normally given spectacles with some prism to compensate for the misalignment.

In each of these cases ablating an amount of prism might improve the visual outcome. In the first two cases it is possible that this improvement could be achieved while ablating less of the cornea.

A quantitative calculation might help. Suppose that based on one or more of the three criteria listed above one would like to tilt the wavefront by 0.1213 prism diopters (pd) as in the above example. The connection between wavefront tilt and comeal tilt is:

$$\text{tilt}=(n-1)A100$$

where tilt is the wavefront tilt in prism diopters, n=1.376 is the comeal index of refraction and A is the ablation angle in radians. For tilt=0.1213 prism diopters the ablation angle is;

$$A == 0.1213/(1.376-1)/100 = 3.2 \text{ milliradians}$$

For a 6 mm ablation zone this amount of prism would have a base depth of 19 microns, a substantial amount given the quite small distortion of Eq. 1.

In the case when prism is added to correct an eye turn the amount of prism is much larger and the effect on lateral chromatic aberration can become large. The amount of chromatic aberration can be calculated since the chromatic aberration is about 2% of the dioptric power. Thus if the yellow rays are bent by 1.0 pd, the difference in bending between the red and blue rays would be 0.02 pd. Across a 3 mm diameter pupil this differential tilt would amount to 0.02*.01*3 mm = 0.6 micron which is about one wavelength of light. Thus the addition of one prism diopter of prism to the ablation introduces a substantial amount of lateral chromatic aberration. The addition of prism could thus be used to eliminate some of the lateral chromatic aberration from the eye.

Summary; Prism (overall tilt) should not be dismissed when displaying the wavefront aberrations and when calculating the optimal ablation. Fig. 1 showed that tilts as small as 3 arc min can dramatically change the appearance of the wavefront height. We also argued that fairly large amounts of prism may be desired in the ablation in cases where the wavefront or the cornea was asymmetric or in cases of eye misalignment. Prism is rarely considered in designing the ablation profile. I hope the standards committee will not ignore issues associated with prism since the choice of the prism term can have a profound effect on the amount of tissue ablated and on the healing process.

The following question is often asked: "How many Zernike terms should be included when planning the ablation?" I believe that this is a bad question. The optimal ablation should be planned in terms of the full wavefront and comeal shape rather than the Zernike breakdown. Normal cornea has a fairly sharp onset of flattening that at around 5 mm diameter that is not well represented in the Zernike expansion. The standards taskforce could help by clarifying this issue.

2.2 Zernike notation subgroup.

A second subgroup of the OSA Standards Taskforce had the job of standardizing the notations for Zernike polynomials. Zernike polynomials are commonly used for specifying the wavefront aberrations. There are several reasons for the popularity of these polynomials.

1. They are familiar to the optics community
2. Their orthonormality makes it easy to calculate wavefront variance.
3. Their smoothness is useful for ablating smooth patterns.

The purpose of this section is to examine whether the Zernike expansion might be too smooth for the case of refractive surgery. The transition zone following refractive surgery may not be well fit by the Zernike expansion. In order to develop a feeling for the problem it is useful to look at the raw data generated by Shack-Hartmann (SH) lenslet arrays. Habib Hamam[4] has several shots of the raw data that show the bunching up of the lenslet images beyond the transition zone.

In order to calculate the error associated with fitting the SH slope data using Zernike polynomials we will consider a simple wavefront whose slope is;

$$\text{slope} = \begin{cases} 0 & r<ra \quad \text{(optic zone)} \\ D*rb(r-ra)/(rb-ra) & ra<r<rb \quad \text{(transition zone)} \\ D*T & r>rb \quad \text{(original cornea)} \end{cases} \qquad (2)$$

where r is the distance from the corneal point to the center of ablation and D is the amount of ablation specified as a curvature in diopters. If D is in diopters and r in mm, the slope is in milliradians. The transition zone goes from ra to rb. Outside the transition zone the slope is given by Prentice's rule as expected for a spherical surface. The transition zone makes a smooth connection in slope from inside to outside the transition zone. For a transition zone that goes from ra=2.5 to rb=3.5 mm, the curvatures are 0, 3.5D, D diopters inside, within and outside the transition respectively. We then fit the slope to a Zernike expansion for slope and obtain a set of coefficients for the Zernike expansion. Slope rather than height is fit, similar to the SH procedure. With these coefficients we can get the Zernike fit for the height, slope and curvature. Curvature is given by Curvature = $h''/(1+h'^2)^{3/2}$, where h' and h'' are the first and second derivatives of the wavefront height with respect to r. To an excellent approximation the curvature is given by the second derivative of height since the slope is very small for the wavefront aberration (contrary to the situation for comeal curvature). In the following table we present the error in height, slope and curvature for the wavefront whose slope is specified by Eq. 2. Zernike orders of n = 2, 4, 6, 8 and 10 are examined, corresponding to 5, 14, 27, 44 and 65 terms. The zeroth order term, not specified by the slope, is chosen so that the mean difference of the true and fit wavefront is zero. The values in the five columns on the left side of the table are the maximum of the absolute value of the difference between the true values and the Zernike fit. The values on the right side are the root mean square (rms) values of the difference.

	maximum difference					rms difference				
Zernike order	2	4	6	8	10	2	4	6	8	10
number of terms	5	14	27	44	65	5	14	27	44	65
height (microns)	5.7	1.9	0.32	0.47	0.12	2.6	0.58	0.19	0.13	0.06
slope (minutes)	31.7	10.3	9.9	5.5	4.3	15.5	4.7	2.8	1.9	1.3
curvature(diopters)	15.1	8.7	14.9	9.7	16.9	10.7	4.5	5.6	3.4	4.3

The height, slope and curvature are reported in microns, minutes and diopters respectively.

The values in the table are for a myopic refractive correction of 5.0 diopters. Thus the curvatures are 0, 17.5 and 5 diopters in the central, transition and outer zones. The Zernike fit is taken over a 7.0 mm diameter, just to the outer edge of the transition zone (3.5 mm radius). The maximum slope is given by Eq. 2 to be D*3.5 = 17.5 mrad or 60.2 min. The maximum wavefront height is 0.5*3.5*D = 8.75 microns, since we only need to consider the transition zone.

The table shows that the curvature is poorly fit by the Zernike expansion. For 27 Zernike terms (through sixth order) the rms curvature error is 5.6 diopters, quite a huge error. However, wavefront curvature is not a good indicator of visual quality. When aberrations are large, wavefront slope in min (geometric optics) gives a good estimate of visual quality. When aberrations are small, wavefront height (physical optics) is the appropriate measure of visual quality. For 27 Zernike terms the maximum and rms slope errors are 9.9 min and 2.8 min and the height errors are 0.32 and 0.19 microns. The slope errors are substantial. The height errors of about a half wavelength of light seem less of a problem. If we go to less than 27 terms the maximum and rms height errors of 1.9 and 0.58 microns are more troublesome (1.9 microns is more than three waves). Thus a minimum of 27 Zernike terms are needed to adequately handle post-refractive surgery corneas.

2.3 A test shape for calibrating wavefront measuring instruments.

As part of the OSA task force Rob Webb has developed a test lens with known aberrations for testing the accuracy **of** wavefront measuring instruments. The wavefront produced by this test lens is fairly smooth. That is an excellent beginning. I would like to suggest that it would be nice to also develop a shape that is similar to what one finds with refractive surgery.

The reason for this suggestion is that a refractive surgery wavefront can be challenging to measure. Near the transition zone some of the SH devices with large focal lengths will have problems with overlapping lenslet images at the transition zone. In order to clarify the problem of measuring the transitions zone wavefront, consider the wavefront specified by Eq. 2. Suppose the lenslets have a focal length of f meters and are spaced by d millimeters. The separation between lenslet images is d(l-fD') where D' is the curvature of the wavefront in diopters (D'= D rb/(rb-ra) = 5*3.5 = 17.5 diopters for the transition zone considered earlier. For a focal length of f = 0.04 m the lenslet image spacing is 1-17.5*.04 = 0.3 times the lenslet spacing. This is sufficiently crowded that some wavefront analyzers would have trouble getting accurate centroids of the images. The development of a test shape that produces crowded images would provide an excellent test of wavefront measuring instruments.

If the intended ablation had been 7 rather than 5 diopters, then the transition zone would be 24.5 diopters and the image spacing would be only 0.02 times the lenslet spacing. Some of the images of post-refractive surgery eyes have this extremely crowded bunching of images.

One of the benefits of implementing standards for wavefront measuring instruments is the development of methods for assessing the quality of different instruments. One must independently assess accuracy (how close is the measured wavefront to the actual wavefront) and precision (what is the test-retest reliability). To measure accuracy, several test 'lenses' need to be developed that produce a variety of wavefronts to test the capability of wavefront instruments along several independent dimensions. To measure precision, one needs to do multiple tests on each of several human eyes including post-refractive surgery eyes. The statistical methodology for calculating accuracy and precision needs to be set by the standards committee as is discussed next.

2.4 Relevance of the ANSI standards for corneal topography

On October 18, 1999, the American National Standards Institute (ANSI) approved a standard for corneal topography instruments. I wrote up a summary of that topography standards document together with a commentary on it in the OSA TOPS volume[5] that was connected with the VSIA 2000 meeting. Although the standards are voluntary, they do encourage common usage of terminology as well as a common method for testing the accuracy and precision of the instruments. The ANSI corneal topography standards devoted substantial effort to the details of how to measure accuracy and precision. As I pointed out in my review[5] improvements can be made in how accuracy and precision are assessed. The important point however, is that it is through these discussions that improvements are possible. The types of discussions that occurred for corneal topography should also be occurring for wavefront analysis.

The OSA wavefront standards taskforce made a good beginning for what could become an ANSI standards committee. However the scope can be widened beyond the areas discussed in above three sub-sections. Standards can be developed for the problem areas of refractive surgery such as the degraded visual performance at night, the topic of the next section. We need to standardize how night vision is tested. We need to set standards on how to measure and assess the transition zone that produces the night vision halo. Another area where standards are needed is the issue of how to go beyond the Zernike expansion in order to get an improved representation of wavefront shape, the topic of Section 4. The ANSI corneal topography efforts are directly relevant to the present discussion of wavefront aberrations and are well worth examining.

3. NIGHT VISION PROBLEMS AND THE TRANSITION ZONE

Night vision is an embarrassing topic for refractive surgery. It has been known for some time that the main complaint is related to night driving. This is not surprising given the rapidly changing comeal curvature at the transition zone. We have previously presented evidence based on 58 PRK eyes that due to the healing process, the transition zone migrates inward towards the pupil center[6]. What is embarrassing is that there is a very simple improvement that could have been made once the problem was recognized several years ago. Instead of giving everyone a 6 mm diameter ablation, it would have been possible to ablate a larger diameter for the lower myopes. A 10 D myope requires a deep ablation, which limits the diameter of the ablation zone to 6 mm. However a 5 D myope has substantially less tissue removed if the same 6 mm ablation diameter is used. It makes very little sense to have the same diameters for the 5 and the LQ D patients. If, for the lower myopes a larger ablation zone had been used, many of the night vision problems could have been avoided. The standards committee might be able to make recommendations on various aspects of this night vision issue. It could become a pressure group for improved refractive surgery care.

3.1 Calculating the extent of the blur halo.

When the pupil is large enough to cover the full transition zone, the wavefront slope at the end of the transition zone can be calculated by Prentice's rule:

$$\Theta = r*D \qquad (3)$$

where r is the radius of the pupil in mm (for pupils larger than the transition zone), D is the magnitude of the ablation in diopters and Θ is the wavefront slope in milliradians. If we take r=3.5 mm and D=5 diopters, as in the example of Eq. 1, then Θ= r*D =17.5 mrad = 60.2 min. This slope is the radius of the blur halo. The diameter of the halo would be twice this value, or about 2 deg. This is quite a large sized blur circle, so it is not surprising that there are night vision complaints if the pupil diameter is large enough to cover the transition zone. If it covered a smaller portion of the transition zone, the blur diameter would be reduced. The point of this calculation is that the type of halo produced by refractive surgery is quite different from the glare associated with cataract or the blur associated with spherical aberration. The halo produced by myopic refractive surgery has a fixed outer diameter specified by the Prentice rule limit given in Eq. 3.

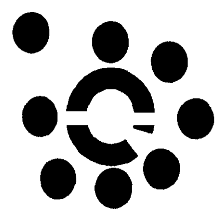
A question that is often asked is how should one choose the center of the pupil since the center shifts position as the pupil dilates. The considerations of the present section give an answer to this question. One should center the ablation zone at the pupil center for night driving conditions when the pupil is large. For daytime conditions when the pupil is small the pupil will be within the region of a flat wavefront, presuming the ablation shape has been perfected to give a reasonably flat central wavefront. For nighttime conditions when the pupil is large and overlaps the transition zone it makes sense to have the ablation well centered so that the maximum extent of the halo is minimized. Further psychophysical research in this area would be good. At this point it isn't definite that a decentered halo is more bothersome than a centered halo. It is a working hypothesis.

3.2 The need for a new night vision test.

Given the night vision complaints it is surprising that a good night vision test isn't commonly used for assessing vision after refractive surgery. A good excuse for not testing night vision is that there isn't a good test available. The ingredients for such a test are simple enough:

1) The most important condition is that the testing room should be dark so that the pupils are large to simulate night driving conditions on a dark night. The pupil diameter could be measured with an infra-red camera as part of the exam.

2) The test letter should be surrounded by a small bright annulus. The inner radius of the annulus might be 8 min with the central letter being an 8 position Landoldt C whose diameter is around 5 min. The purpose of this annular surround is to mask the test letter. It might be good for the surround to be non-uniform noise so that the masking is strong. An example of a possible masking surround is shown in the adjacent figure. The surrounding circles are positioned irregularly to provide extra masking. For normal eyes that have a small diameter point spread function the annulus wouldn't interfere much with the Landoldt C task. This arrangement is similar to what would be used for a glare test. The main difference is that for the glare test the mask would be extended to cover as large an area as possible to maximize the masking. For the refractive surgery test, on the other hand, we would like to keep the interfering pattern small (<1-2 deg diameter) so that the bright mask doesn't constrict the pupil.



3) The test letter should have fairly low contrast so that the test cue is easily masked by the tails of the light from the surround.

4) Other conditions such as the stimulus duration, and the size of the test pattern would be chosen to ensure that very high levels of acuity (low thresholds) are obtainable. This would also be relevant to measuring spherical aberration and coma that would have a smaller diameter PSF than that produced by the refractive surgery transition zone.

5) It would be nice to have this test be done on a computer screen to facilitate the gathering of many trials near threshold in order to establish tight error bars on the threshold estimate.

3.3 Night vision simulation

One of the troubling aspects associated with the night vision problem is that one suspects that patients weren't adequately prepared for possible night vision losses. Improved methods are needed to prepare patients for what their night vision might look like. The first step would be to use an infra-red camera to measure pupil size in the dark. A second step would be to develop a realistic display showing typical scenes associated with night driving for persons that would like to drive at night. A scene of stars would be used for people who enjoy star gazing (I'd like to think that includes everyone).

3.4 Transition zone research

There are at present many unknowns regarding the transition zone.

a) What is the shape of the transition zone for a given individual? What is its curvature profile? What is its uniformity across different meridia?

b) What determines the shape of the transition zone? Several possible factors are:

• Comeal thickness: The biomechanics of the stromal response to intraocular pressure will depend on corneal thickness as emphasized by Cynthia Roberts[7]. Her modeling of the biomechanical effects are quite important.

• Preoperative comeal topography. It is quite possible that the topography of peripheral cornea plays an especially important role in the shape of the transition zone. This is because there is a very large variability in the shape of peripheral cornea across individuals. Another important factor is the location of the comeal apex. The corneal apex is the point of the cornea that has greatest curvature. Mandell, Chiang and Klein[8] showed that the location of the comeal apex relative to the pupil center varies across individuals. It is possible that meridional anisotropies of the transition zone are related to the location of the comeal apex.

• Epithelial regrowth was an important factor for PRK ablation where the epithelium was ablated away. It might also play a role in the transition zone of LASIK ablation.

Given that the transition zone plays an important part in the night vision problems associated with refractive surgery, one might wonder why more is not known about the transition zone. My guess is that an adequate technology isn't commonly available for measuring the transition zone. Recently, a great emphasis has been put on wavefront analysis. However, the wavefront has limited use both because the 6-7 mm pupil size is too small to cover the full transition zone, and also because the increased curvature of the transition zone forces the lenslet images to get all bunched up, as discussed in Section 2.3. One would think that the solution is to use comeal topography to measure the transition zone. However, the commonly used Placido image based comeal topography instruments tends to be limited to the central 8 mm of the cornea. There do exist topographers that are not based on the Placido image and these topographers are able in principle to measure the full corneal shape and some topographers measure scleral shape as well. Full coverage is needed not only to get the full transition zone, but also to measure the full shape of the eye since that might well affect the biomechanics of how the transition zone develops following refractive surgery. By fusing the comeal topography and wavefront information, improved knowledge of the transition zone will become available.

4. NEED FOR NEW SHAPE DESCRIPTORS, NEW MAPS AND STANDARDS 4.1

Shape descriptors for post-refractive surgery wavefronts and corneal topography

Section 2.2 discussed the problems of using a Zernike expansion for characterizing the transition zone. The curvature of the transition zone changes too rapidly to be able to be followed by the smooth Zernike polynomials even with 65 terms (see Table 1 above). The previous discussion was in the context of correcting myopia. The dramatic change of curvature in the transition zone is much more extreme for correcting hyperopia where the curvature can go from 45 D to zero (or negative) curvature at the beginning of the transition zone to 70 D at the end of the transition zone, all within 2 mm. Simulations of the raw Placido images for hyperopia were shown in Fig. 1 of Klein[5]. The zig-zag shape of the Placido image is such that no present Placido based instrument would be able to analyze the hyperopic image shown[5]. Non-Placido instruments would be needed for the task. The point here is that the curvature changes so rapidly that Zernike expansions are not able to adequately characterize the post-refractive surgery shape.

In order to properly display the wavefront curvature the Zernike expansion would need to be supplemented by a set of shape descriptors specific to the particular type of transition zone. The shape descriptors have advantages that go beyond their need for displaying curvature:

• Knowing the precise shape of the transition zone is critical for improving the ablation profile.

• Once the transition zone information is reduced to a small number of meaningful parameters (size, maximum curvature, decentration, meridional isotropy) it can be included in the patient's record. That would facilitate following up changes.

• As was discussed in Section 2.2 and Table 1, the improved fit also improves the accuracy of the calculated PSF.

• Conclusions drawn from a purely Zernike fit can be misleading. For example, the Zernike fit to the refractive surgery wavefront of Eq. 2 would indicate that spherical aberration was present. However, there is actually no spherical aberration until one reaches the transition zone. The properties of the Eq. 2 wavefront are quite different from the standard spherical aberration implied by a low order Zernike fit.

We will be presenting further details on our transition zone shape descriptors at ARVO-2001 and in future publications.

4.2 New maps for displaying wavefront aberrations.

The standard way to display the wavefront is to present a contour plot of wavefront height. Klein and Garcia[3] described a number of other displays that can provide different insights regarding the aberrations associated with the wavefront. The alternative displays are based on wavefront slope and wavefront curvature.

Wavefront curvature gives the dioptric power of the wavefront. Meridional power, given by the second derivative of the wavefront height in the radial direction is especially useful for displaying residual spherical and cylindrical power in the wavefront. The ANSII corneal topography standards has chosen the name meridional curvature rather than instantaneous curvature for this quantity[5]. Meridional curvature is also probably the clearest way to represent the transition zone shape following refractive surgery. Representations of the transition zone in terms of height or slope are more difficult to interpret. One useful property of meridional curvature is that it is integrable and provides a full specification of the wavefront shape. Plots of maximum and minimum curvature also useful. They are obtained by calculating the principal curvatures at each comeal point. For complex wavefronts such as found in keratoconus a plot of maximum curvature is appropriate. For normal preoperative wavefronts that are associated with prolate corneas a plot of minimum curvature is useful. This is because of the sharp corneal flattening that occurs at radii of around 2.5 mm. Although wavefront curvature is useful for visualizing properties of the wavefront, we will argue next that wavefront slope is the most useful tool for assessing visual performance in the presence of strong aberrations.

Wavefront slope is an especially interesting representation of the wavefront because of its direct connection to the geometric optics PSF. The normal to the wavefront (specified by wavefront slope) is the direction of the geometric optics ray corresponding to that point on the wavefront. Suppose the wavefront slope is specified in minutes of arc (see Figs. 2 and 3 of Klein and Garcia[3]). A slope of 0 min means that ray would fall on the axis; a slope of 2 min means that ray would fall 2 min from the axis. There are several ways to display slope.

• quiver plot of raw Shack-Hartmann image. The centroid of each lenslet image could be represented by an arrow from the 'perfect' image point to the measured point. This plot would have as many arrows as there are lenslets that had images. This type of plot, using little arrows to show a gradient field is often called a 'quiver' plot.

• cylindrical lenslet images. An alternative to the quiver plot is to connect the Shack-Hartmann centroids by lines. The image centroids of the vertically aligned lenslets would be connected and similarly for the horizontally aligned centroids. This display would be similar to the image obtained by replacing the spherical Shack-Hartmann lenslets by a set of vertical cylindrical lenslet superimposed on an image from horizontal cylindrical lenslets. This produces a pretty plot that Klein and Garcia[3] called a 'spider web' plot. The plots look quite similar to the Tcheming-Howland[9] aberrometer plots.

• contour plot of the magnitude of the slope. This is my favorite plot because of its simplicity and direct connection to the PSF. It has the drawback that information about the azimuthal direction of wavefront slope is lost (similar to the PSF itself). This drawback is of minor importance since it is meant to supplement rather than replace the wavefront height map. The contour plot shows very clearly which parts of the cornea contribute to the tails of the PSF.

An important reason for introducing new methods for displaying aberrations is that new insights are needed to improve predictions of visual performance from the wavefront. Previous prediction attempts have had mixed success. It is clear that wavefronts with lots of aberrations tend to predict degraded performance. The problem is that there is still a disturbingly large variance in the prediction. I believe that a multiplicity of methods are needed to account for visual performance because performance is multidimensional. Visual acuity may be best predicted by the sharpness of the PSF or the CSF around 20 c/deg. However, night vision problems might depend on the tails of the PSF. These tails would be difficult to measure in the PSF or CSF. Night vision halos may be best assessed by examining the wavefront slope at the peripheral cornea (the ablation transition zone) as discussed in this section. This method has the added advantage that it would specify how the glare depends on pupil size.

5.1 Honesty. A spectacle minification example

It is natural for companies to present their product in the best light even if that involves some exaggeration or partial reporting. There is no problem with that natural tendency when the product is a bar of soap. However, when the product is a type of surgery much higher standards of honest reporting are needed. This section discusses one small aspect of whether post- surgical acuity is reported honestly. When reporting the results of myopic refractive surgery it is common to see acuity reported as measured using a phoropter or while wearing spectacles. This is advantageous to the advocates of refractive surgery since preoperatively the spectacle minifies the image thereby reducing acuity. Refractive surgery improves acuity by this trivial mechanism that has nothing to do with the accuracy of the ablation. The improved acuity is similar to what is found by comparing spectacle correction to contact lens correction. The following calculation shows how one calculates this effect. The percent magnification is given by:

$$\%mag = P\, z$$

P is the power of the correction (in diopters) and z is the distance from contact lens to spectacle (in cm). By specifying the distance in cm rather than meters one gets the factor of 100 that gives the results as a percent.

Example: P = -8 diopters, z = 1.5 cm

so %mag=-8*1.5=-12%

This 12% decrease in the size of objects corresponds to a preoperative reduction of acuity from 20/20 to 20/22. This gives the refractive surgery a 12% advantage.

Let's get back to the original question of honesty. How should the refractive surgeon compare post-operative acuity to pre-op acuity? Should one compare best corrected visual acuity while wearing spectacles or while wearing contact lenses? It seems to me the answer is obvious: Be conservative! For a myope it would be conservative to report the change in acuity as if the patient were wearing contact lenses. For a hyperope it would be conservative to report the change as if spectacles were worn. It is unlikely the refractive surgery industry would agree with this recommendation, so the next best strategy would be to do the reporting both ways.

It would be helpful for the refractive surgery standard setting taskforce discussed in this paper to include the topic of conservative reporting standards. By what other mechanism can the refractive surgeons and laser companies be encouraged to report outcomes in an unbiased manner?

The final topic to be discussed is the need for openness and the development of public databases. Millions of people are getting refractive surgery so there is a great incentive to make improvements to the ablation profile as soon as possible. There are many researchers (including my group) who would like to take part in doing the research needed for these improvements but crucial public data is lacking. There are two areas where public data is needed: 1) The connection between the ablation profile and the change in corneal shape. 2) The connection between the aberration wavefront and visual performance.

5.2.1 Ablation profile and resultant comeal shape. Progress in researching the connection between the ablation profile and the change in corneal shape would be enhanced if a database of refractive surgery outcomes were freely available. As a minimum, this database would include pre-op and post-op comeal topography and also the precise ablation profile. If the laser companies would like to keep some secrets they could keep secret the intended refractive correction since that isn't directly relevant to the healing process. The goal of this data would be to give researchers sufficient information about the connection between the ablation profile and the resultant change in comeal shape[7]. It would be critically important to this research effort if this database also included the following items;

• Shape of the full cornea, out to the limbus. Although Placido based topographers are unable to provide this full coverage, some topographers (Orbscan, Euclid) are able to provide the needed information. The need for coverage to the limbus and possibly onto the sclera was discussed earlier. There is a large difference between individuals on the shape of peripheral cornea.

• Thickness of comeal. The Orbscan is able to provide this information. Comeal thickness surely has an impact

• Epithelial growth factors. Were any topical treatments used that would affect epithelial growth?

5.2.2 Wavefront and visual performance. Progress in research regarding the connection between the wavefront shape and visual performance also would benefit from a database of information being freely available. The question here is what is the optimal residual wavefront for a given individual. It might be thought that the optimal ablation is to produce a perfectly flat wavefront. Although that could be an ideal final outcome in some cases, it would not optimal in many others. For example, a myope or hyperope who needs a strong correction might not have a thick enough cornea to support the needed ablation depth. The goal for such an individual would be to come up with an ablation profile that removed less tissue, so that the wavefront wasn't perfectly flat. As another example, a wavefront with some spherical aberration might be desirable to increase the depth of focus.

What sort of database that would be needed to facilitate progress in connecting wavefront shape to visual performance? The database would obviously need to include information about the wavefront shape and information about visual performance. The first item is relatively easy to achieve. The wavefront could be represented as a Zernike expansion if the wavefront were relatively smooth. For wavefronts with rapid changes in curvature such as could be present in the refractive surgery transition zone, then as discussed above it might be necessary to supplement the Zernike expansion with some extra shape descriptors to capture the rapidly changing aspect. The second item (information about visual performance) is difficult to achieve because we don't yet know how to summarize visual performance with a small set of numbers. Furthermore, as discussed in Section 3.2, an adequate test of night vision performance does not presently exist. These would be good topics for the standards taskforce to consider to help develop guidelines.

5.2.3 Why is a public database needed? I am advocating the establishment of two public databases to facilitate progress in the refractive surgery area. This is an unusual suggestion since it differs from the way vision research is normally done. There are at least three reasons this situation differs from standard vision research. First, as mentioned earlier, the vision of millions of people who will be undergoing refractive surgery can be affected by this research. This practical need places a time pressure on getting results fast. Normal vision research doesn't have this time pressure. A large database of available information would allow more investigators to get involved in this research thereby speeding it up. Second, a pooled database would increase the quality of the data and therefore of the conclusions. Third, the data being discussed are not easily acquired. The first database requires information about the actual ablation profile. This information has typically been secret, not available to anyone outside the companies manufacturing the lasers. This database would also benefit from corneal topography information extending over the full cornea. Most comeal topographers have a limited coverage, partly because of the limitations of Placido instruments. It is possible to get full coverage, and that should be done. The second database seeks to connect aberrations to visual performance. Here the problem is to encourage more research on night vision losses and the development of new tests whose output would be a small number of indices for independent aspects of human visual performance.

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