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## **FUNCTIONAL VISION**

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### **Course description:**

New technology in cataract and refractive surgery has engendered a new emphasis on the quality of vision beyond simple visual acuity. Contrast sensitivity testing is gaining increased recognition as a valuable tool for measuring functional vision. It can successfully detect functional vision loss, often caused by early eye disease, and has been proven to provide a more sensitive and comprehensive measurement of visual capability and performance than is provided by Snellen acuity. This course will define functional vision and demonstrate the difference in postoperative functional vision between an IOL designed by wavefront analysis to compensate for corneal spherical aberration and a standard IOL currently in use.

### **Objectives:**

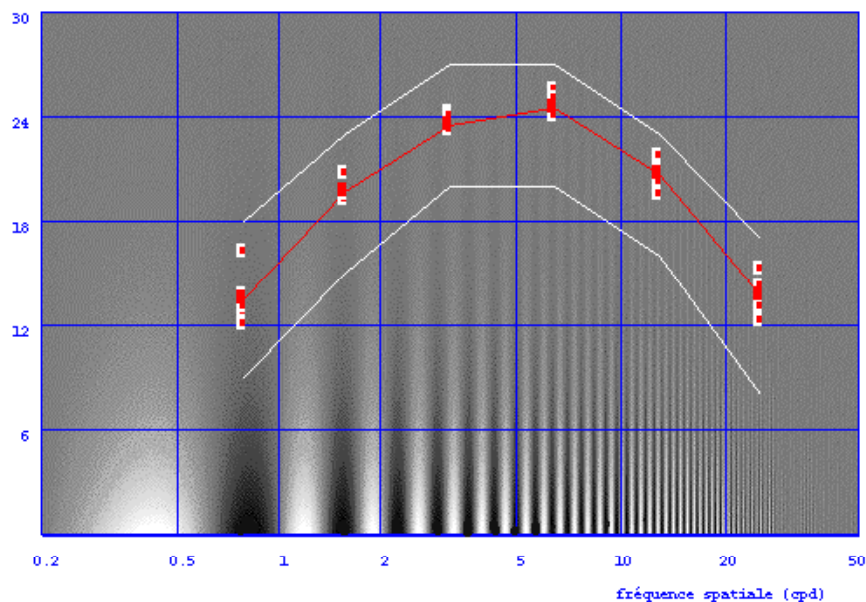
Upon completion of this course, the student should be able to:

1. Describe functional vision related terminology, such as contrast sensitivity, sine wave grating, wavefront analysis, and spherical aberration.
2. Explain optical differences between standard and new wavefront technology IOLs.
3. Describe the difference between the human eye's spherical aberration at age 20 and age 70.
4. List three lifestyle activities for which performance is enhanced by an improvement in contrast sensitivity.

The term functional vision describes the impact of sight on quality of life. Recognizing faces and facial expressions, reading the newspaper, driving at night, performing vocational tasks and participating in recreational pursuits all bear a relation to functional vision for ophthalmic patients. Functional vision not only implies the role of sight in safety and accident prevention, but also suggests the importance of high quality vision in vocations such as astronomy, aeronautics and visual arts.

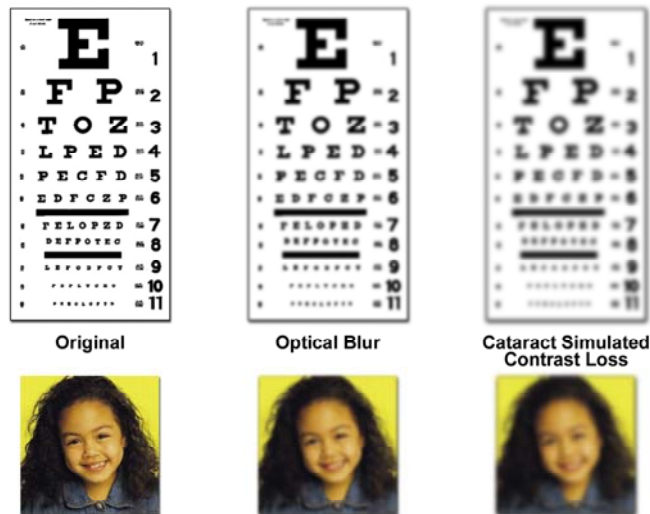
While the achievement of uncorrected 20/20 visual acuity remains the target for any cataract and refractive surgeon, the goal of high quality vision increasingly reflects our understanding of the visual system as a whole. In fact, Snellen acuity (developed in 1862) represents only a small portion of functional vision. A comparison of vision and hearing highlights the limitations of standard visual acuity tests: the auditory equivalent of a standard high-contrast Snellen eye chart would be a hearing test with only one high level of loudness for all sound frequencies. Today, contrast sensitivity testing is emerging as a more comprehensive measure of vision that will probably replace Snellen letter acuity testing, just as audiometric testing replaced the “click” and spoken-word tests used prior to the 1940s<sup>1</sup>.

Engineers understand that Fourier analysis allows the representation of any visual object as a composite of sine waves of various frequencies, amplitudes and orientations. In fact, visual processing in the human nervous system works like Fourier analysis in reverse, with functionally independent neural channels filtering images to create what we see.<sup>2</sup> Thus, sine wave gratings are the building blocks of vision, just as pure tones are the building blocks of audition. (Fig. 1)



Ophthalmologists realize that patients may complain about haziness, glare and poor night vision despite 20/20 Snellen acuity. This anomaly can be understood when one realizes that the Snellen acuity letter recognition test utilizes very high contrast. The jet black letters on the bright white background have a great deal of reserve contrast, so that even a patient with severely reduced contrast sensitivity can still read the chart. That patient perceives the letters as gray on white rather than black on white, but is still able to recognize them. The examiner has no way of knowing just how gray the letters look to any particular patient. Thus Snellen acuity is a relatively insensitive test of visual function. As stated in the American Academy of Ophthalmology Basic and Clinical Science Course, “We know intuitively that given the appropriate set of circumstances each of us with 20/20 vision will function as a visually handicapped individual. Thus, when a person is driving into the sun at dusk, or dawn, changes in contrast sensitivity and the effect of glare alter detail discrimination.”<sup>3</sup>

Multiple scientific studies have demonstrated that contrast sensitivity represents a robust indicator of functional vision.<sup>4, 5, 6, 7, 8, 9, 10, 11, 12</sup> The contrast sensitivity function, measured under varying conditions of luminance and glare, establishes the limits of visual perception across the spectrum of spatial frequencies. Contrast sensitivity testing has the ability to detect differences in functional vision when Snellen visual acuity measurements cannot.<sup>13</sup> For example, a patient with loss of low frequency contrast sensitivity may be able to read 20/20 but be unable to see a truck in the fog. While blur due to refractive error alone affects only the higher spatial frequencies, scatter of light due to corneal or lenticular opacities causes loss at all frequencies. (Fig. 2)

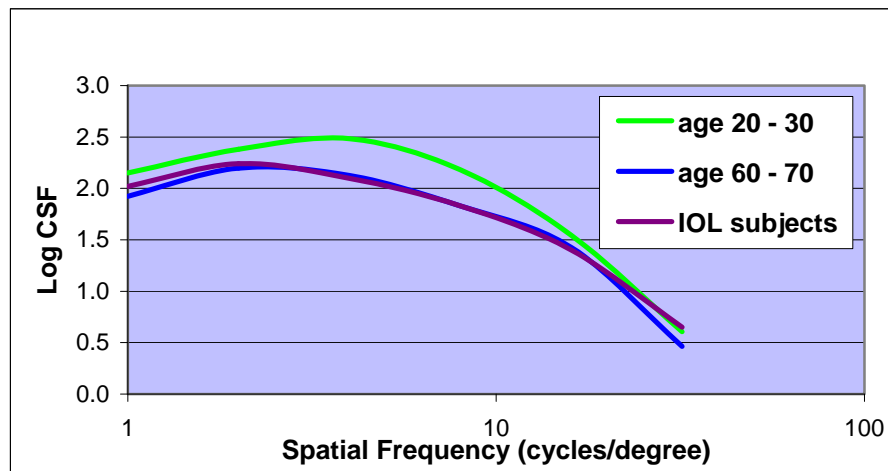


**Fig. 2**

Glaucoma and other optic neuropathies generally produce loss in the middle and low frequencies. Contrast sensitivity testing thus offers critical information to help explain patients' complaints. Numerous studies have demonstrated the relationship of contrast sensitivity and visual performance. From driving difficulty<sup>14</sup> and crash involvement<sup>15</sup>, to falls<sup>16</sup> and postural stability in the elderly<sup>17</sup>, to activities of daily living and visual impairment<sup>18</sup>, to the performance of pilots in aircraft simulators<sup>19</sup>, contrast sensitivity has consistently been found to provide a high degree of correlation with visual performance. Therefore, contrast sensitivity testing effectively describes the function of the physiologic visual system as a whole.

The correction of spherical and cylindrical refractive errors, whether by spectacles, contact lenses or surgery, represents an integral part of the determination of the intrinsic contrast sensitivity of the visual system. Ametropias produce blur and hinder recognition of objects<sup>20</sup>. Higher order optical aberrations such as spherical aberration also have an impact on contrast sensitivity and functional vision.<sup>21, 22, 23, 24, 25, 26, 27, 28</sup> High optical quality is necessary for high contrast sensitivity.

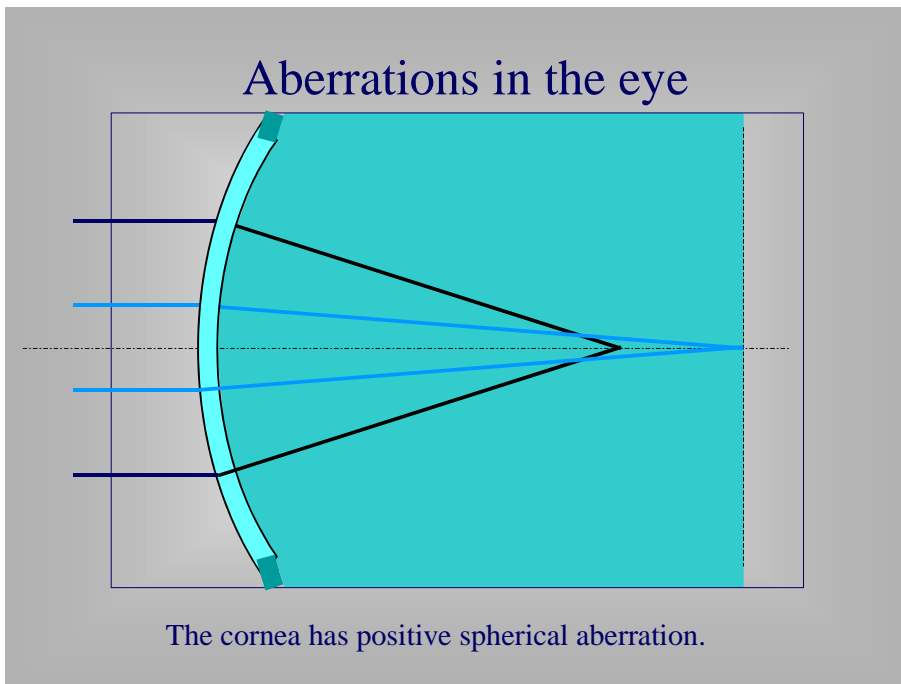
Unfortunately, contrast sensitivity declines with age even in the absence of ocular pathology such as cataract, glaucoma or macular degeneration (Fig. 3). This age-related decline in vision involves changes in the spherical aberration of the crystalline lens.



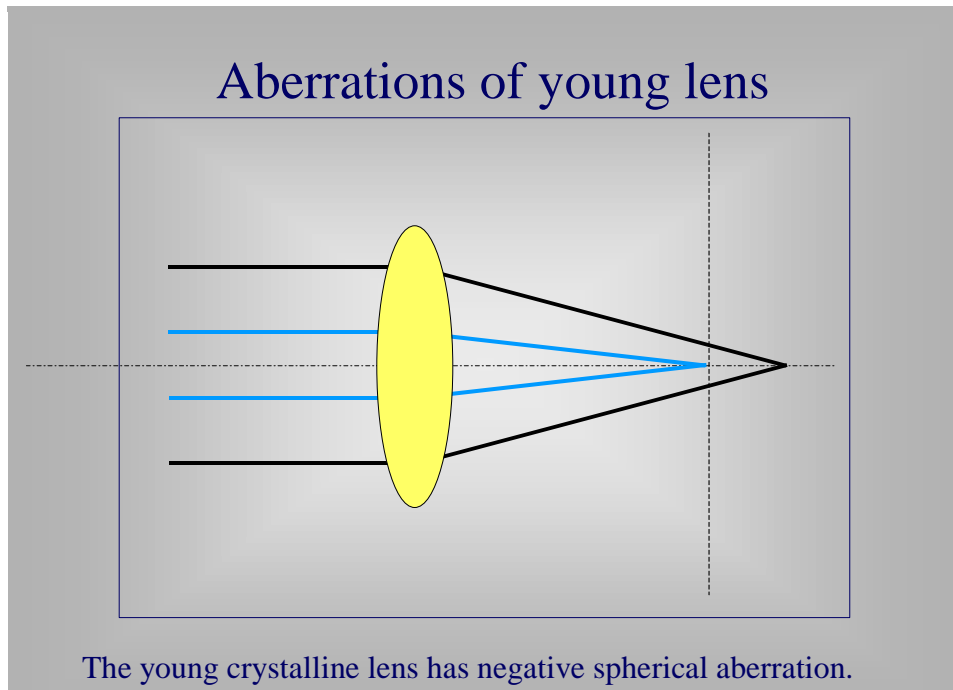
**Fig. 3**

Spherical aberration is a property of spherical lenses. A spherical lens does not refract all parallel rays of incoming light to a single focal point. The lens bends peripheral rays more strongly so that these rays cross the optical axis in front of the paraxial rays. As the aperture of the lens increases the average focal point moves towards the lens, so that a larger pupil produces greater spherical aberration.

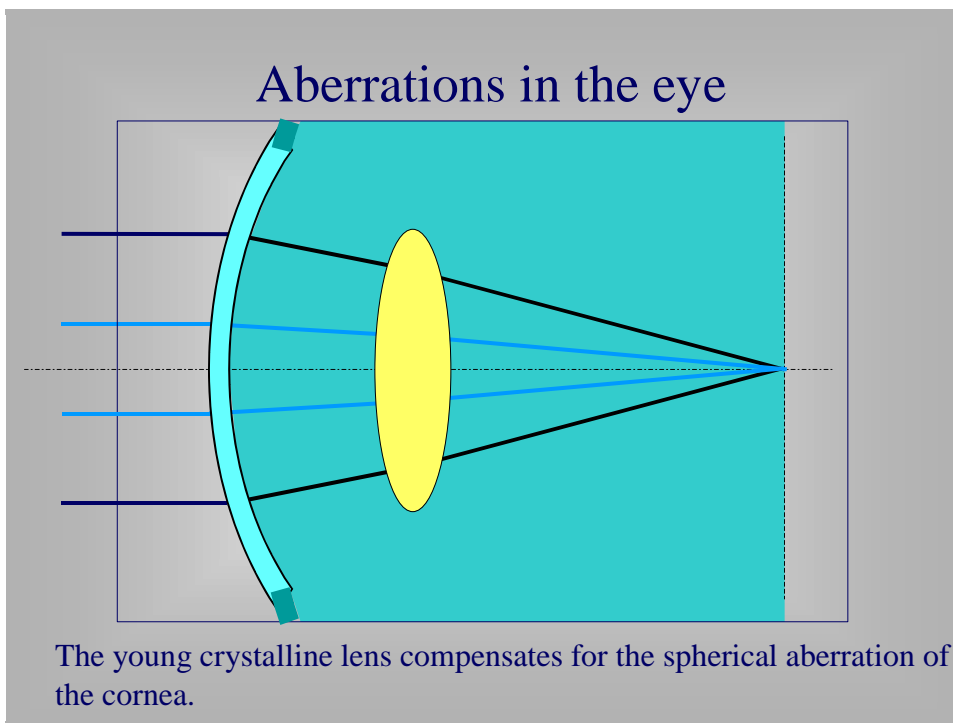
Spherical aberration of the cornea changes little with age. However, total wavefront aberration of the eye increases more than threefold between 20 and 70 years of age<sup>29</sup>. Wavefront aberration measurements combined with data from corneal topography demonstrate that the optical characteristics of the youthful crystalline lens compensate for aberrations in the cornea, reducing total aberration in younger people (Figs. 4-6).



**Fig. 4**

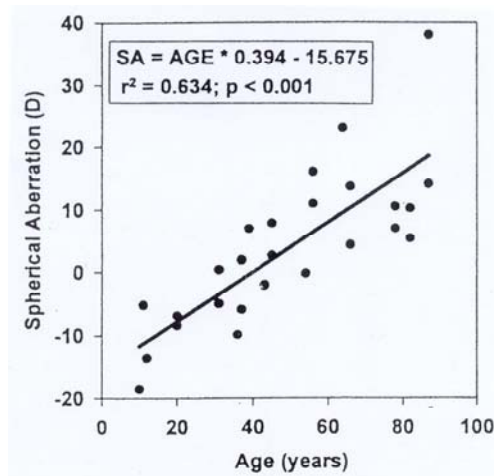


**Fig.5**



**Fig. 6**

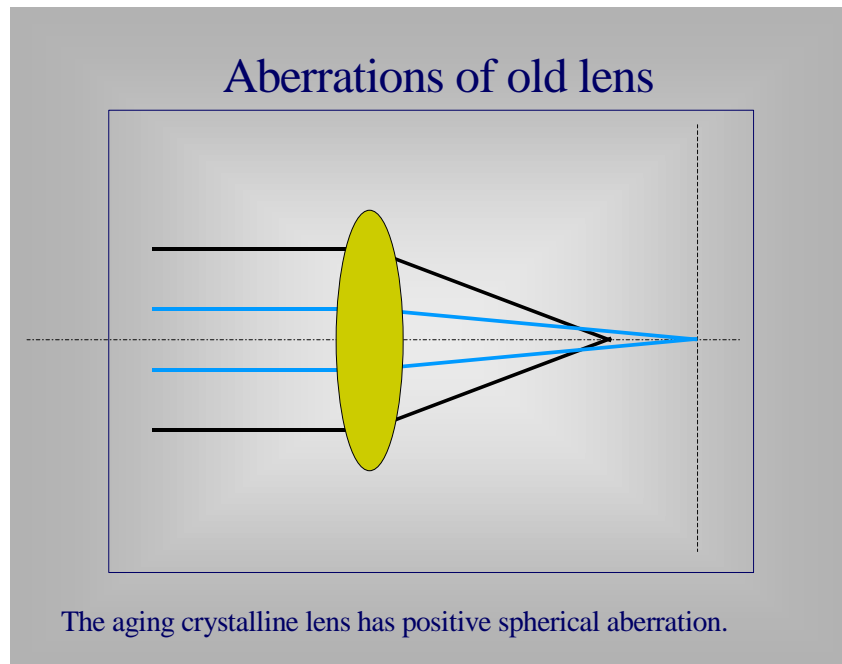
Unfortunately, the aging lens loses its balance with the cornea, as both the magnitude and the sign of its spherical aberration change significantly (Fig. 7).<sup>30</sup>



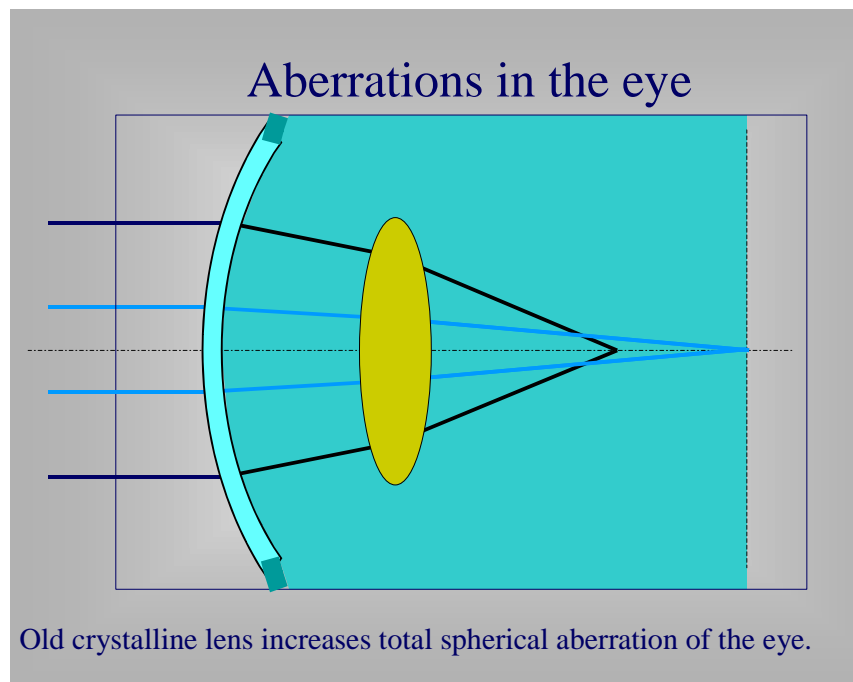
The spherical aberration of the human crystalline lens increases with age (Glasser).

**Fig. 7**

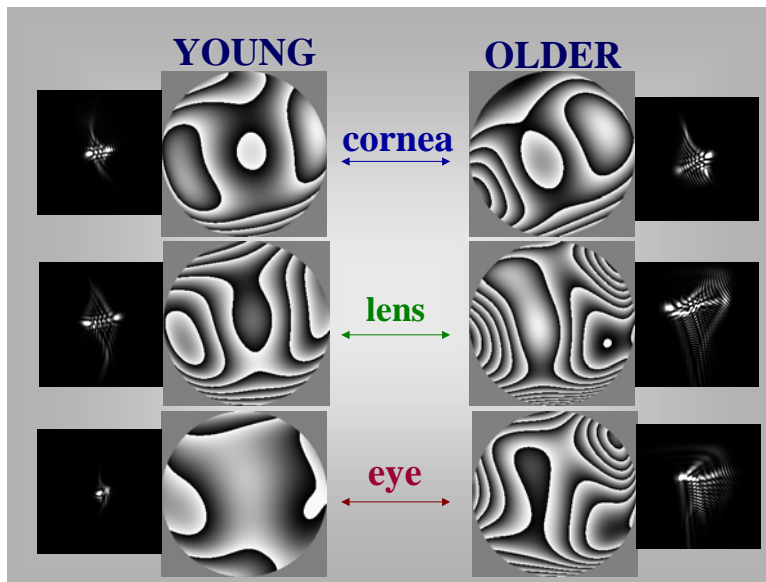
Thus a loss of balance between corneal and lenticular spherical aberration causes the degradation of optical quality in the aging eye (Fig. 8-10 [figure 10 courtesy of Antonio Guirao in Pablo Artal's group, University of Murcia, Spain]).



**Fig. 8**

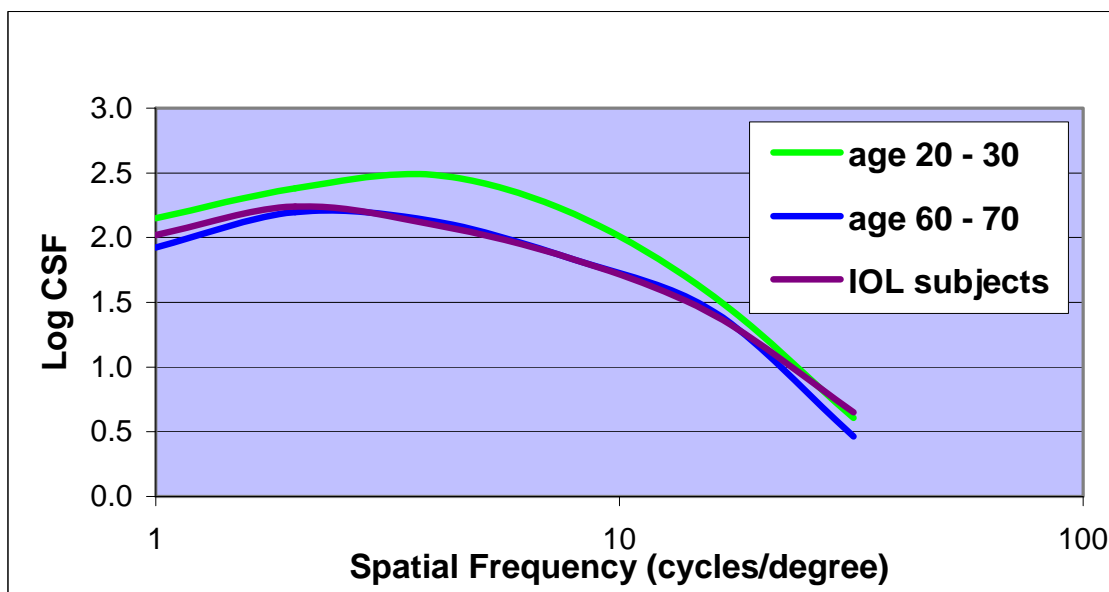


**Fig. 9**



**Fig. 10**

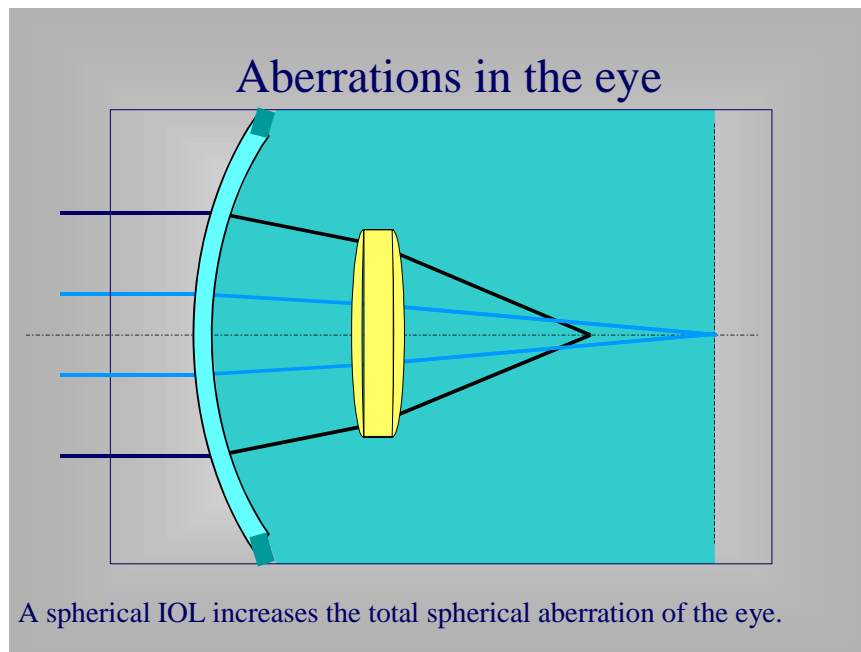
The sine wave grating contrast sensitivity of a pseudophakic patient is no better than that of a phakic patient of a similar age who has no cataract. When a 65 year-old patient with cataracts has the cataracts removed and is implanted with spherical IOLs the resulting visual outcome is no better than the visual quality of a 65-year-old without cataracts (Fig. 3). The fact that the visual quality of the IOL patients is no better than that of their same-age counterparts may seem surprising because an IOL is optically superior to the natural crystalline lens. However, this paradox is explained when one realizes that the intraocular implant has positive spherical aberration like the aging lens. It is not the optical quality of the intraocular lens in isolation that creates the image, but the optical quality of the intraocular lens in conjunction with the optical quality of the cornea.



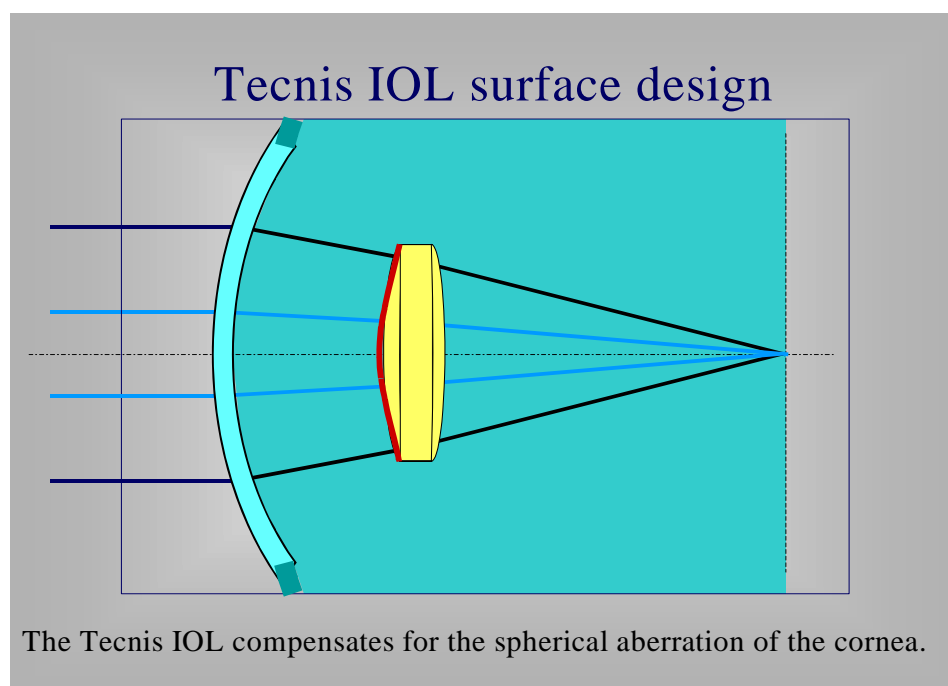
**Fig. 3**

The spherical aberration of a manufactured spherical intraocular lens is in no better balance with the cornea than the spherical aberration of the aging crystalline lens (Fig. 11). Aberrations cause incoming light that would otherwise be focused to a point to be blurred, which in turn causes a reduction in visual quality. This reduction in quality is more severe under low luminance conditions because ocular aberrations increase when the pupil size gets larger.

**Fig. 11**



A new wavefront designed IOL compensates for the spherical aberration of the cornea (Fig. 12)<sup>30</sup>. This lens acts like the youthful crystalline lens and compensates for corneal spherical aberration. The new concept of the wavefront designed IOL is the potential for restoration of youthful optical quality and improvement of functional vision.



**Fig. 12**

Sine wave contrast sensitivity is the principal outcome measurement for the clinical investigations of this new lens. A comparison of corneal and total ocular aberrations demonstrates the improved wavefront of the eye with the wavefront designed IOL. The improvement in total aberrations demonstrates the critical compensatory relationship of cornea and lens in reducing spherical aberration. Peak contrast sensitivity has been compared in healthy, normal eyes, stratified by age of patient, and eyes implanted with the wavefront-designed (Tecnis) IOL, an acrylic spherical IOL, or a silicone IOL.<sup>33</sup> Special emphasis was given to the peak contrast sensitivity values because they have, in general, the highest degree of correlation with functional vision. For example, as mentioned above, peak contrast sensitivity correlates well with pilots' detection and identification distances.

As expected based on previous results, mesopic contrast sensitivity declined with age. Among 69 eyes of 36 patients, ranging in age from 21 to 61, mean peak mesopic contrast sensitivity at 3 cycles per degree of 72.4 for the 20 to 30 year olds was found. Patients aged 30 to 50 years demonstrated mean peak mesopic contrast sensitivity of 51.9. Ten eyes implanted with the wavefront-designed IOL in patients of average age 69.5 years achieved a mean peak mesopic contrast sensitivity at 3 cycles per degree of 83.8, better than the 20 to 30 year old group. Meanwhile, eleven eyes implanted with the control IOL in patients of average age 69.4 years demonstrated a mean peak mesopic contrast sensitivity at 3 cycles per degree of 47.1, worse than the 30 to 50 year old age group (Fig. 13). The wavefront-designed IOL reduced total optical aberrations improving contrast sensitivity in the aging eye.

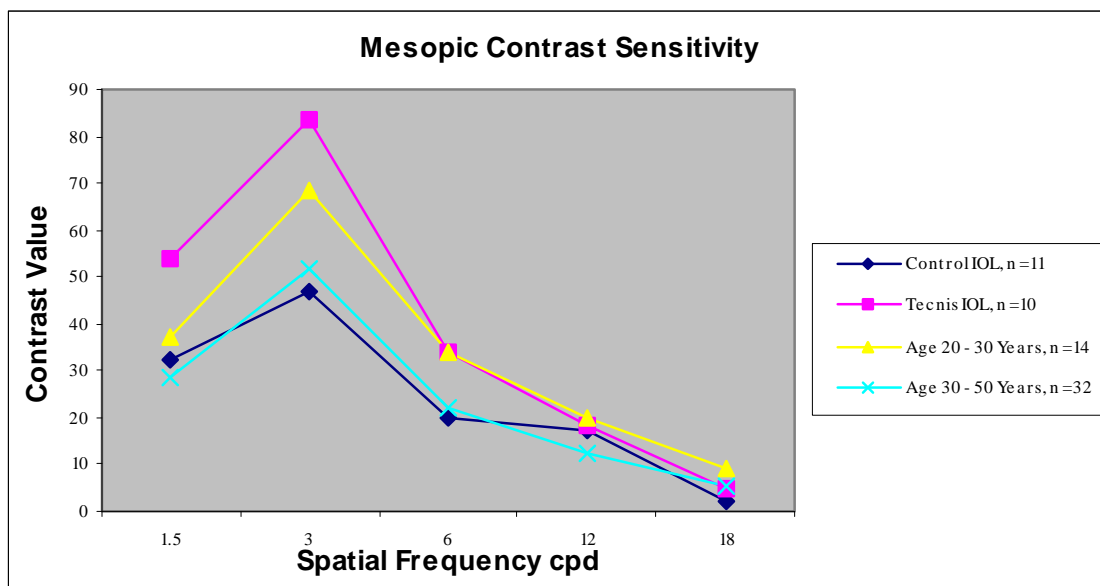
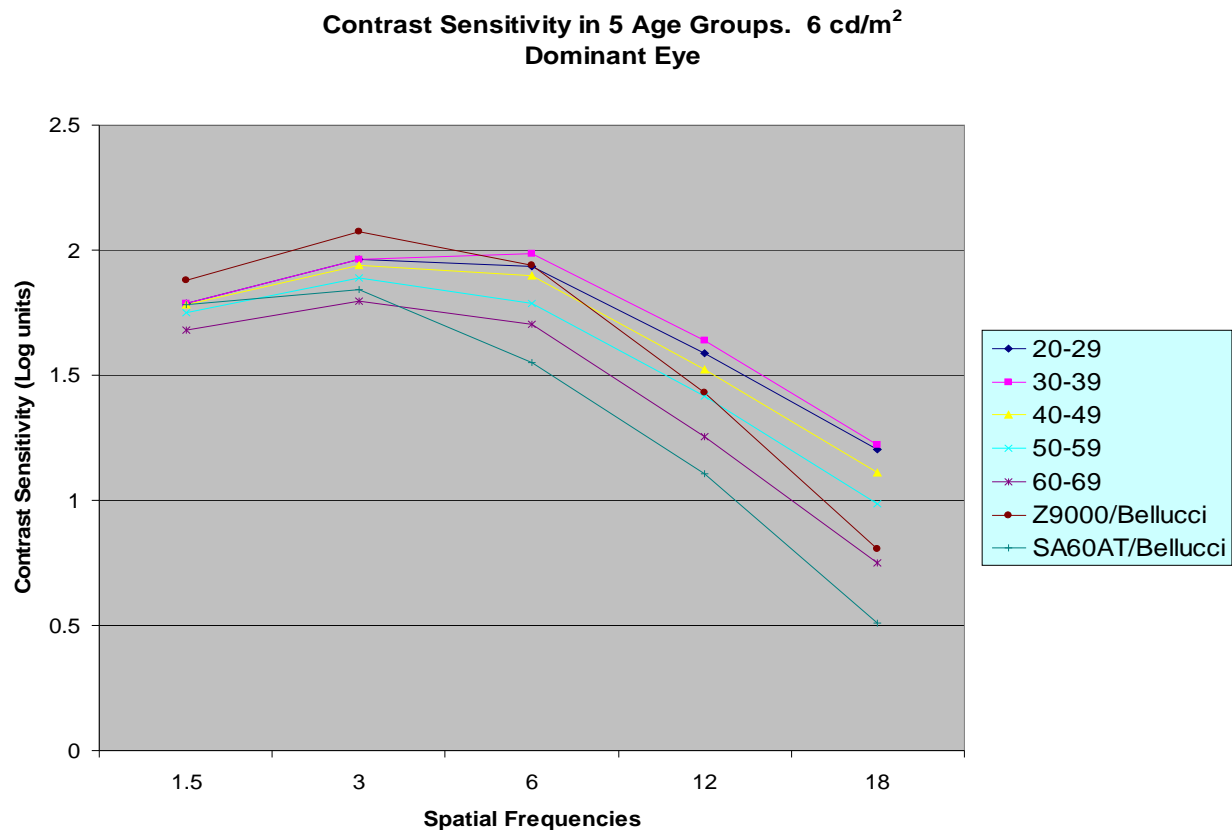


Fig. 13



**Fig. 14**

In a separate study conducted by Roberto Bellucci at the University of Verona, a similar outcome emerged when data from patients implanted with the Tecnis IOL was compared with data from healthy, normal subjects (Figure 14).<sup>33</sup> Bellucci randomly implanted 15 patients bilaterally with the Tecnis IOL and 15 patients with a comparator spherical acrylic IOL. His data showed peak contrast sensitivity in patients implanted with the Tecnis IOL slightly better than that of 20-30 year olds in a multicenter study of healthy, normal subjects conducted in the United States with the same testing protocol and equipment.

As advances in technology allow cataract and refractive surgeons to address higher order optical aberrations, the measurement of functional vision becomes increasingly critical as a gauge of our progress. Sine wave contrast sensitivity testing is assuming a prominent place in our evaluation of surgical modalities because it reflects functional vision, correlates with visual performance and provides a key to understanding optical and visual processing of images.

In the current era of presbyopia-correcting IOLs, toric IOLs and aspheric IOL technology, the practice milieu is changing. Informed consent takes on new meaning when the surgeon and the

patient decide together which IOL technology represents the best fit for a particular life style and its visual demands. Customizing IOL choice is no longer optional; it is essential to the practice of refractive lens surgery.

Because the positive spherical aberration of a spherical pseudophakic intraocular lens tends to increase total optical aberrations, attention has turned to the development of aspheric IOLs. As previously explained, these wavefront or aspheric designs are intended to reduce or eliminate the spherical aberration of the eye and improve functional vision as compared with a spherical pseudophakic implant. Three aspheric IOL designs are currently marketed in the United States: the Tecnis Z9000/2/3 IOLs (AMO, Santa Ana, CA), the AcrySof IQ IOL (Alcon, Ft. Worth, TX) and the SofPort AO IOL (Bausch & Lomb, San Dimas, CA). Other aspheric IOL designs not yet available in the United States also show promise for the reduction of spherical aberration.<sup>31</sup>

To review, the Tecnis IOL was designed with a modified prolate anterior surface to compensate for the average corneal spherical aberration found in the adult eye. It introduces  $-0.27 \mu$  of spherical aberration to the eye measured at the 6 mm optical zone. The clinical investigation of the Tecnis IOL submitted to the US Food and Drug Administration (FDA) demonstrated elimination of mean spherical aberration as well as significant improvement in functional vision when compared to a standard spherical IOL.<sup>32</sup>

The AcrySof IQ shares the ultraviolet (UV) and blue light-filtering chromophores found in the single-piece acrylic AcrySof Natural IOL. The special feature of the IQ IOL is the posterior aspheric surface designed to reduce spherical aberration by addressing the effects of over-refraction at the periphery. It adds  $-0.20 \mu$  of spherical aberration to the eye at the 6 mm optical zone. The SofPort Advanced Optics (LI61AO) IOL is an aspheric IOL that has been specifically designed with zero spherical aberration so that it will not contribute to any pre-existing higher-order aberrations.

Multiple peer-reviewed, prospective, randomized scientific publications have demonstrated reduction or elimination of spherical aberration with the Tecnis modified prolate IOL when compared to a variety of spherical IOLs.<sup>33, 34, 35, 36, 37, 38, 39, 40, 41, 42</sup> Data show that the mean spherical aberration in the eyes implanted with the Tecnis IOL is, in the words approved by the FDA, “not different from zero.” Studies have also documented superior functional vision with the Tecnis IOL. Subjects in the FDA monitored randomized double-masked night driving simulation study of the Tecnis IOL performed functionally better in 20 of 24 driving conditions (and statistically better in 10 conditions) when using best-spectacle correction with the eye implanted with the Tecnis IOL, as compared to best-spectacle correction with the eye implanted with the AcrySof spherical IOL.<sup>32</sup>

Data from the night driving simulation showed a significant correlation between reduction of spherical aberration and detection distance for the pedestrian target under rural conditions with glare (the most difficult target to discern).

More recently, peer-reviewed published clinical studies have also supported reduction of spherical aberration and superior functional vision with the AcrySof IQ when compared with spherical IOLs.<sup>43, 44, 45, 46</sup> In fact, the optical advantages of aspheric IOL technology have become fairly well accepted although some controversy remains in the areas of functional benefit as it relates to pupil size, IOL decentration, depth of focus and customization.<sup>47</sup> Some studies have shown little or no benefit of aspheric IOLs with smaller pupils<sup>42, 43</sup> while one laboratory study showed that the SofPort AO provides better optical quality than either a negatively aspheric or a spherical IOL under conditions of significant decentration.<sup>48</sup> One study has shown diminished distance-corrected near visual acuity, a surrogate measure for depth of focus, with the AcrySof IQ aspheric IOL as compared to the AcrySof SN60AT spherical IOL.<sup>46</sup>

Regarding customization of the aspheric correction, it has been suggested that achieving zero total spherical aberration postoperatively provides the best quality of vision. Piers and coauthors utilized an adaptive optics simulator to assess letter acuity and contrast sensitivity for two different values of spherical aberration. The first condition was the average amount of spherical aberration measured in pseudophakic patients with spherical IOLs. The second condition represented the complete correction of the individual's spherical aberration ( $Z [4,0] = 0$ ). The researchers found an average improvement in visual acuity associated with the correction of spherical aberration of 10% and 38% measured in white and green light, respectively. Similarly, average contrast sensitivity measurements improved 32% and 57% in white and green light. When spherical aberration was corrected, visual performance was as good as or better than for the normal spherical aberration case for defocus as large as  $\pm 1$  D. Therefore, these researchers concluded that completely correcting ocular spherical aberration improves spatial vision in the best-focus position without compromising the subjective tolerance to defocus.<sup>49</sup>

On the other hand, it has alternatively been suggested that providing  $Z [4,0] = +0.1$  micron of postoperative spherical aberration represents a better choice.<sup>50</sup> This line of reasoning originated from a study demonstrating that 35 young subjects with uncorrected visual acuity of 20/15 or better had a mean total spherical aberration of  $Z [4,0] = +0.110 \pm 0.077 \mu$ .<sup>51</sup> However, there is no logical basis to infer that the spherical aberration is responsible for the supernormal visual acuity. In fact, the authors of this study concluded that “The amount of ocular HOAs (higher order aberrations) in eyes with natural supernormal vision is not negligible, and is comparable to the reported amount of

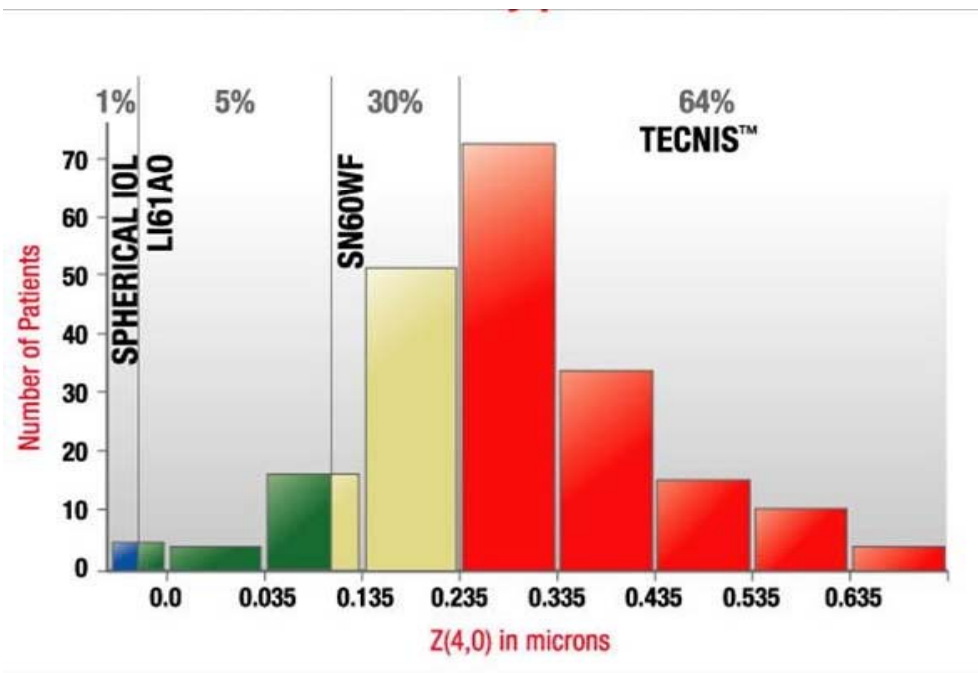
HOAs in myopic eyes.”<sup>51</sup> This conclusion is born out by a study performed by Wang and Koch demonstrating a mean total spherical aberration of  $Z [4,0] = +0.128 \pm 0.074 \mu$  in a series of 532 eyes of 306 subjects presenting for refractive surgery.<sup>52</sup> Nevertheless, Beiko<sup>50</sup> used the Easygraph corneal topographer (Oculus, Lynnwood, WA) to select patients with corneal spherical aberration of  $+0.37 \mu$ , thus targeting a postoperative total ocular spherical aberration of  $+0.10 \mu$  following implantation of the Tecnis IOL with  $-0.27 \mu$  (the Easygraph includes an optional software package that provides Zernike analysis). The selected patient group demonstrated significantly better contrast sensitivity than an unselected group of control patients under both mesopic and photopic conditions.

Recently, Beiko, Haigis and Steinmueller presented data from a series of 696 eyes confirming the mean corneal spherical aberration of  $+0.27 \mu$  used in the design of the Tecnis IOL.<sup>53</sup> They found a wide standard deviation of  $0.089 \mu$ , with a range from  $+0.041$  to  $+0.632 \mu$ , and significantly different corneal spherical aberration means in men and women. In some cases the corneal spherical aberration differed significantly between fellow eyes. The authors concluded that “individuals should be measured to determine their unique value when considering correction of this aberration.” In addition, they noted that keratometry and the corneal Q value do not correlate well with spherical aberration, and that therefore corneal spherical aberration must be measured directly with a topographer.

One method of proceeding with customized selection of aspheric IOLs involves the following protocol:

- 1) Preoperative testing to include corneal topography as well as axial length determination, anterior chamber depth, phakic lens thickness and corneal white-to-white diameter;
- 2) Application of a software package such as VOL-CT (Sarver and Associates, Carbondale, IL) to transform the topography elevation data into preoperative corneal Zernike coefficients, with special attention to  $Z [4,0]$ , fourth order spherical aberration at the 6 mm optical zone;
- 3) Application of an IOL calculation formula, such as the Holladay 2 (available as part of the Holladay IOL Consultant & Surgical Outcomes Assessment Program, Jack T. Holladay, Houston, TX) to determine correct IOL power for desired postoperative spherical equivalent;
- 4) Determination of desired postoperative total ocular spherical aberration and selection of IOL type.

For example, if the desired postoperative total ocular spherical aberration is zero and the preoperative corneal spherical aberration measures about  $+0.27 \mu$ , the Tecnis with  $-0.27 \mu$  would be selected. In general, the aspheric IOL that comes closest to providing the desired correction should be selected (Figure 15).



**Fig. 15**

Initial results of customizing the selection of aspheric IOLs have shown promise. In a series of 18 eyes of 12 patients with a mean preoperative corneal spherical aberration of  $+0.24 \pm 0.075 \mu$  and a targeted postoperative total spherical aberration of  $Z [4,0] = 0$ , the Tecnis IOL was selected for 10 eyes, the AcrySof IQ for 7 eyes and the SofPort AO for 1 eye. The overall mean postoperative total spherical aberration measured  $-0.0065 \pm 0.060 \mu$ , which is statistically not different from zero ( $p = 0.65$ ). For the Tecnis group, mean  $Z [4,0] = -0.019 \pm 0.061 \mu$ ; for the AcrySof group mean  $Z [4,0] = 0.0073 \pm 0.063 \mu$ ; for the SofPort eye  $Z [4,0] = 0.025 \mu$ .

In order to determine the feasibility of correcting preoperative corneal spherical aberration, we calculated the mean absolute error for each type of IOL. The mean absolute error is equal to the absolute value of the difference between the predicted total postoperative spherical aberration and the measured postoperative spherical aberration. The predicted postoperative spherical aberration is simply the preoperative corneal spherical aberration at the 6 mm zone plus the spherical aberration of the IOL implanted. In evaluating the results, allowance should be made for surgically induced spherical aberration; an accepted value for this quantity is  $0.03 \pm 0.17 \mu$ .<sup>54</sup> The surgically induced spherical aberration represents an estimate of the degree of variation one should expect in the postoperative  $Z [4,0]$  wavefront.

In the Tecnis group, the calculated mean absolute error was  $0.052 \pm 0.044 \mu$ ; in the AcrySof group the mean absolute error was  $0.052 \pm 0.033 \mu$ ; for the SofPort AO eye the absolute error was  $0.040 \mu$ . The overall mean absolute error for all IOLs was  $0.052 \pm 0.038 \mu$ . There were no statistically

significant differences in the mean absolute error among the different groups or between any group and the entire group.

Our results indicate that targeted postoperative spherical aberration can be achieved within a range very close to the limits of surgically induced spherical aberration. Future directions for research include expansion of this initial study and consideration of psychophysical measures such as contrast sensitivity to elucidate the real value of eliminating spherical aberration. It is important to realize that these psychophysical tests of functional vision are generally performed with best spectacle correction in order to exclude the effects of blur from test results. The ability to achieve superior functional vision with best spectacle correction reflects both the strength and weakness of wavefront-corrected IOLs. Given the state of the art of biometry and IOL power calculation it is not possible to achieve precise emmetropia in all eyes. Many pseudophakic patients find that their uncorrected vision is adequate for most tasks of daily living and therefore do not wear spectacles. The amount of defocus and astigmatism they accept may negate the pseudophakic correction of their spherical aberration. Nio et al noted in 2002, "Both spherical and irregular aberrations increase the depth of focus, but decrease the modulation transfer (MT) at high spatial frequencies at optimum focus. These aberrations, therefore, play an important role in the balance between acuity and depth of focus."<sup>55</sup> For some patients with adequate uncorrected distance acuity, the advantages of a bit more depth of focus may be worth a little loss of contrast. The ultimate expression of this trend is embodied in the multifocal IOL, which by its design reduces optical quality in order to enhance spectacle independence. The Tecnis Multifocal IOL, now in FDA monitored clinical trials, represents a conscious compromise between optical efficiency and functional vision on the one hand, and quality of life on the other.

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## GLOSSARY OF TERMS

Contrast – compare or appraise in respect to differences

Functional – performing or able to perform a regular function

Aberration - failure of a mirror, refracting surface, or lens to produce exact point-to-point correspondence between an object and its image

Spherical aberrations – aberration that is caused by the spherical form of a lens or mirror and that gives different foci for central and marginal rays

Wavefront – a surface composed at any instant of all the points just reached by a vibrational disturbance in its propagation through a medium

Mesopic – pertaining to nighttime luminance conditions

Fourier analysis – a mathematical technique that analyzes complex periodic wavelengths into a number of sine wave components

Sine wave grating – an alternating pattern of light and dark bars, mathematically derived

Spatial frequencies – an indication of the size of the bars used in sine wave grating

## FUNCTIONAL VISION

### *CE on the Internet Quiz*

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1. The crystalline lens in the aged varies from the youthful lens in that its spherical aberration has become more:
  - a. negative
  - b. positive
  - c. neutral
2. Based on information from clinical research, improvement in contrast sensitivity should enhance one's ability to:
  - a. read a book
  - b. see road signs at night
  - c. work at a computer
3. The term functional vision describes the impact of sight on:
  - a. vocational tasks
  - b. recreational pursuits
  - c. quality of life
4. A patient with loss of \_\_\_\_\_ frequency contrast sensitivity may be able to read 20/20 but be unable to see a truck in the fog.
  - a. high
  - b. middle
  - c. low
5. The wavefront-designed IOL has \_\_\_\_\_ spherical aberration optics.
  - a. negative
  - b. positive
  - c. neutral
6. The cornea's spherical aberrations \_\_\_\_\_ with increasing age.
  - a. become positive
  - b. become negative
  - c. remain stable
7. A large pupil:
  - a. produces less spherical aberration
  - b. produces more spherical aberration
  - c. has no effect on spherical aberration
8. Optic neuropathies generally cause contrast sensitivity loss at what levels?
  - a. low and middle
  - b. middle and high
  - c. higher
9. The age-related decline in contrast sensitivity is caused by changes in the spherical aberration of:
  - a. the crystalline lens
  - b. the retina
  - c. the cornea
10. Contrast sensitivity level testing can be compared best to testing of:
  - a. the muscular system
  - b. the auditory system
  - c. the digestive system

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3. Please read the following statements. Then, circle the number corresponding to the degree to which you agree with each statement.

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b. The information will be useful/relevant to me.	5	4	3	2	1
c. The material was presented at a level appropriate to my background and level.	5	4	3	2	1
d. Overall, I was satisfied with the article.	5	4	3	2	1

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