Thirty-four Challenges to Meet Before Excimer Laser Technology Can Achieve Super Vision

Isaac Lipshitz, MD

Two years ago, if someone had asked an ophthalmologist about higher order optical aberration of the eye, wavefront sensing, adaptive optics, or even super vision, probably the ophthalmologist would have been mute. Now, many clinicians are learning how the optical or surgical correction of higher order aberrations might achieve visual acuity that is better than that achieved by spectacles or contact lenses.

THE CHALLENGE

Advances in excimer laser technology for use in refractive surgery opened the theoretical possibility of achieving "super vision" by adopting approaches known for many years to the optical engineering community. But a question remains: Can excimer laser technology alone achieve these goals now, or in the foreseeable future? The current answer is clear: Not yet. We contend that even though excimer laser technology brought to our attention many new aspects in optics, it cannot bring us to the promised land of super vision.

In correcting higher order aberrations, minor changes count. Corneal surface changes must reach an accuracy of one micron; only one or two laser shots delivered in a slightly wrong position or incorrect timing will interfere with the desired result. We need absolutely perfect procedures to achieve the results we want.

I present here 34 challenges that must be met before excimer laser corneal surgery can achieve visual acuity that is better than conventional spectacles, contact lenses, and traditional refractive surgery.

THE CATEGORIES

These 34 challenges are divided into four main groups:

A. Inherent physiological differences and changes of the optical and biomechanical properties of different corneas

B. Uncontrolled optical changes during the healing process of the cornea

C. Technological limitations of surgical equipment

D. Uncontrollable surgeon-dependent variables

A. Ocular Challenges

There are inherent physiological differences and changes in optical and corneal biomechanical properties of different corneas that bedevil the goal of super vision.

<u>1. Changes in wavefront with age.</u> Wavefront measurement of the eye alters with age because of changes in the lens and cornea that occur over time. Even if we can achieve super vision at a certain time, new aberrations will appear subsequently with age.

<u>2. Changes of wavefront during accommodation (dynamic vision factor).</u> When the eye accommodates, the lens changes shape and that induces changes in higher order aberrations. Even if we achieve super vision for distance vision, when looking at near, newly induced higher order aberrations may occur.

<u>3. Effect of pupil size on higher order aberrations.</u> Change of pupil size—in light, dark, accommodation, convergence—dramatically affects vision. Constricting the pupil avoids the mid-peripheral higher order aberrations, increases the depth of focus, and even corrects lower order aberrations, so a patient may have aberration-free super vision with a very small pupil and very aberrated vision when the pupil size enlarges. In a 3-mm pupil, one need correct only the 4th order Zernike coefficient to achieve super vision, whereas for a 7-mm pupil, one will need to correct up to the 8th order Zernike coefficient to achieve super vision.

<u>4. Biomechanical differences among corneas before surgery.</u> Corneas differ considerably in their biomechanical properties. These differences depend

From the Ophthalmic Health Center, 40 Einstein St., Tel Aviv 46101, Israel. E-mail: lipshitz@netvision.net.il

on various factors such as patient age, corneal thickness, hydration, and collagen properties. There is no way to accurately characterize an individual cornea for its ablation properties. Thus, the effect of laser shots on a specific cornea is not precisely predictable.

5. LASIK flap biomechanics. Once a LASIK flap is created, the biomechanical properties of the cornea change dramatically depending on the depth of the incision, diameter of the flap, size of the hinge, location of the hinge, and uniformity of the flap. The higher order aberrations that are measured before creating the flap are used for calculating the laser treatment, but after the flap is created—even if it is returned to its place without ablation—there is a change in the wavefront measurement, and the calculations for laser application that were measured before the flap are incorrect. An unpredictable flap gives unpredictable corneal biomechanics, thus an unpredictable optical result.

6. Changes in tear film. Tear film optical properties in different eyes occur because of common pathologies such as dry eye and blepharitis. Damage to the corneal nerves varies with the type of microkeratome incision, hinge location, and depth of ablation. This will affect tear film production and distribution after LASIK. These tear film changes affect the aberration structure of the eye, since the tear-air interface is the most powerful refracting surface on the eye.

7. Changes in corneal thickness after laser surgery. The change in corneal thickness after laser surgery affects the tear film, the biomechanical properties of the cornea, the healing process, and the mechanical strength of the cornea. These effects cannot be evaluated before surgery and thus unpredictably affect the optical results of the laser treatment.

8. Changes of wavefront during cycloplegia. Most measurements of wavefront are taken through dilated pupils after cycloplegia and most higher order aberrations correspond to the corneal midperiphery. When the pupil constricts back, the wavefront measurements change significantly, so the preoperative mydriatic measurements are not valid for determining the results under normal physiological conditions.

9. Variation of ablation rate in different depths of the cornea. The water content of the cornea increases from anterior to posterior and differs among eyes, so the ablation rate per pulse changes at different depths for different eyes. Thin corneas (eg, from prolonged soft contact lens wear) have a lower water content so they ablate more for each laser shot.

10. Variation in corneal thickness in different meridians. Usually the cornea is thinnest in the inferior or inferotemporal area, probably because these areas are dryer (they get less tears), hence the ablation rate is higher at these locations compared to others, and this may create an effect of coma on postoperative aberrometry.

B. Uncontrolled Optical Changes During the Healing Process

11. Corneal epithelium wound healing. After changing the corneal curvature with the laser, and as a result of the epithelial injury by the microkeratome or sponge drying, the epithelial cells regenerate over the treated area, changing the refractive power. The amount of epithelial hyperplasia is different from eye to eye and in different areas of the cornea. One layer of epithelial cells is 5 to 10 µm thick, enough to dramatically change the higher order aberrations.

12. Corneal collagen wound healing. Collagen wound healing varies among eyes. In addition, changes in stromal collagen after LASIK depend on the depth of ablation, the incision and ablation profiles, and the newly created biomechanical properties of the cornea.

13. Effect of corneal biomechanics after surgery. Individual corneas have different biomechanics—even more after surgery. Change in the biomechanical properties of the cornea after LASIK, such as the retraction and steepening of stromal lamellae at the edge of the bed, alter the optical properties of the cornea, changing the aberration structure of the wavefront.

C. Technological Limitations of Surgical Equipment

14. Eye positioning during preoperative measurement and laser treatment. Optical axis alignment, refraction, topography, and wavefront testing are measured when the patient is sitting. The exact head position (tilt, chin up or down, etc.) is not fixed for each of these measurements. When the patient lies down, one can never be sure that the supine head and eye positions are exactly the same as they were when measurements were taken in the upright sitting position. Furthermore, for accurate placement of wavefront-guided laser treatment, the various instruments must all be in register.

15. Accuracy of laser ablation. The exact amount of corneal tissue removed with each laser pulse changes continuously. Among other things, it depends on room humidity and temperature, quality of delivery system optics, and pulse energy. The energy output of the laser is measured as an

average of many laser pulses, but when treating higher order aberrations, we depend on very few pulses, sometimes even one, at a very specific location.

16. Microkeratome accuracy and profile. At a specific setting (eg, 160 µm), microkeratomes cut flaps of varying thickness—varying among manufacturers, among instruments, among eyes, and at different regions in a single flap. The thickness depends on many variables, including the diameter of the microkeratome incision, blade quality, corneal curvature, surgical technique, microkeratome design, corneal diameter, corneal biomechanical properties, corneal hydration, and environmental parameters. Variable flap thickness may influence higher order aberrations.

17. Tracking the location of the laser beam. Accuracy of tracking should not be confused with the speed of the sampling rate. One can measure the position of the eye 4000 times per second but after getting the measurement, the mechanics and optics of the laser must adjust themselves exactly to deliver the laser energy to the exact predetermined topographical location on the cornea. The optical alignment and mechanical adjustment take time (much more than the sampling) and there will always be a critical delay between measurement alignment and delivery. For example, a 10-millisecond latency allows the normal eye to move 11 to 19 µm.

18. Decentration. Laser alignment can be done on the optical axis, on the geometric axis, or on the pupillary axis (which is not in the center of the cornea). All these minor variations affect higher order aberrations, especially the asymmetrical aberration known as coma.

19. Accuracy of wavefront sensors. There are several ways to measure the wavefront entering or leaving the eye. Each method works differently, has a different resolution capability (number of points measured per cornea), and different algorithms to construct the wavefront—producing different results. For example, when a patient suffering from keratoconus was measured by six different wavefront analyzers during an ophthalmology meeting, only one detected the keratoconus.

20. Computer programs for the laser. The results of aberrometry, as well as other data such as refraction, corneal diameter, and topography, must be entered into the software that directs the laser. The current capability of computer programs to integrate this enormous amount of data and to give to each piece of data the exact value required by the laser is questionable. For different patients, each piece of information may have a different influence on the refractive outcome. For example, in an eye with high astigmatism, the wavefront measurement may not be as important as the corneal topography.

21. Accuracy of the laser. Two instruments manufactured by the same company may work differently. Each laser changes its pulse energy continuously when in use, and the variation may be greater among lasers made by the same company. We have two identical models that work differently and we use different nomograms for each one.

22. Consistency of one laser. The laser pulse energy changes all the time, so the instrument calculates and uses an average energy. When we finish a procedure, the laser works slightly differently than at the onset, and it changes even more when doing multiple procedures. So, requiring exact energy doses to the cornea to correct higher order aberrations is a difficult standard to meet.

23. Chromatic aberrations are not detected by aberrometers. All wavefront analyzers use monochromatic light, but real life is polychromatic and multiple wavelengths cannot be measured by current wavefront machines. The wavefront for a certain eye changes significantly when it is measured using different wavelengths of light, so how can we correct vision across the entire visible spectrum of light by using machines that measure using only one wavelength?

24. Location and shape of wavefront measurements. Most aberrometers take measurements at the level of the entrance pupil but the correction by the laser is done on the corneal surface, some 3 to 4 mm away, which may induce some inaccuracies in wavefront-guided corrections. The wavefront is detected as a plane but the laser works on a curved cornea. Wavefront is measured as a planar surface at the exit pupil, but the laser correction is done on the curved corneal surface, which is aspheric and is different for each eye.

25. Objective aberrometers measure only the optics of the eye. Only one or two subjective instruments include the influence of neural processing and the visual cortex. Vision is complex because it involves the patient's perception at the visual cortex. This influence on surgical outcome is not known; perfect optics do not assure perfect vision, because they do not take into account the cortical influence. But, maybe perfect optics are all we can aim for as surgeons.

D. Uncontrollable Surgeon Variables

26. Dryness of the ablation surface. Control of stromal hydration is crucial for accurate ablation, but we still don't have any method for measuring

exactly the amount of moisture on the stromal surface before ablation, or the change of surface hydration during ablation, which depends not only on the corneal properties that cannot be measured, but also on the number, frequency, and pattern of laser shots.

27. Environmental issues during surgery. We can control humidity and temperature in the operating theaters, but we cannot control them exactly at the stromal surface of the cornea-laser interaction. The temperature there changes constantly due to the heat generated by photoablation and by the plume of ejected tissue fragments. The humidity in the area between the laser exit and the cornea cannot be accurately controlled and variation may alter the amount of tissue removed with each pulse. For instance, if the surgeon breathes deeply and rapidly during surgery, the humidity and temperature at this crucial area may change.

28. Retinal problems of aberration-free optics. We still don't know if directing all the rays of light on the fovea—which is what we are going to do if we want to create super vision—will cause thermal or toxic damage to the retina. Maybe that's why there are optical aberrations in our eyes.

29. Possible worsening of visual performance with inaccurate surgery. Using current technology, the increase in higher order aberrations after LASIK has been well documented, especially spherical aberration and coma. Aberration-directed surgery seeks to reduce these. But surgical complications can also disrupt the final wavefront, seen as striae, diffuse lamellar keratitis, free cap, and epithelial ingrowth.

30. Effect of enhancement procedures on the wavefront. Currently, we have an enhancement rate of 5% to 25%, which is done only for lower order aberrations. If we expect to correct many higher order aberrations, a considerably higher number of reoperations may be needed. But, each enhancement procedure has its own effect on the total higher order aberrations because of lifting and repositioning of the flap.

31. Positioning of the flap after ablation. Even though the surgeon usually marks the cornea before the microkeratome incision, we can never be sure that the exact original position of the flap on the cornea is achieved. Only a few microns of change in flap position may disrupt the planned correction of some higher order aberrations.

32. Flap edema after ablation. The flap becomes variably edematous during the procedure depending on the length of the procedure and the surgical technique, so that when the flap is put back on the bed, it has a different thickness, shape, and size, which vary during deturgesence.

33. Curvature of the flap and bed do not fit perfectly after ablation. After removing tissue from the bed, the ablated surface is flatter and the flap is steeper (in myopia). This can cause wrinkles in the center, which disrupt the wavefront.

34. Irreversible procedure. Excimer laser surgery is irreversible, so that if some of the aforementioned problems prevent the super vision result, the original condition of the eye cannot be restored.

CONCLUSION

Although some of these challenges have a high toll on wavefront measurement and laser surgery, and occur frequently, others have a lower effect, and there is variable influence among individual patients. The total impact of these 34 factors is considerable in most eyes.

We can achieve very good uncorrected visual acuity in some of our patients. In an informal survey in our office, 15% of patients had uncorrected visual acuity of 20/15 or better after standard spherical and astigmatic correction. These are patients who would have low visual benefit from correcting their higher order aberrations. The questions we want to answer here are: Can we predict before surgery if a certain patient will achieve super vision, and can we consistently achieve super vision in most of our patients? Taking into account the multiple challenges to overcome, we cannot. Current excimer laser technology and foreseeable developments will not allow us to consistently correct our patients' vision better than that which can be achieved with spectacles or contact lenses. Yes, we may accidentally achieve it for a low percentage of patients, but to predict it for a certain patient, we need to eliminate or considerably reduce higher order aberrations. Refractive surgery—especially LASIK—must overcome many challenges to reach this goal.