Principles of Ray Tracing Aberrometry

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ABSTRACT

PURPOSE: Of all transforms of an eye, aberrations are significant when higher visual acuity is to be achieved. Ray tracing aberrometry developed by the Institute of Biomedical Engineering (Kiev) and first tested at the Vardinoyannion Eye Institute of Crete is a promising technique for eye refraction aberration and refraction mapping.

METHODS: The technique uses measurement of the position of a thin laser beam projected onto the retina. The beam is directed into the eye parallel to the visual axis. Each entrance point provides its own projection on the retina. A set of entrance points forms a set of projections. From these data, a refraction map is reconstructed as well as a point spread function of the eye. The total time of scanning over the whole aperture of the eye is within 10 to 20 ms and depends on the number of test points at the eye entrance, as well as on the number of independent measurements in each point. Configuration of the scanning pattern can be chosen by the operator. It may contain 60 to 400 points, each checked 1 to 5 times.

RESULTS: Preliminary studies showed high reproducibility of results. Twenty pseudophakic eyes were subjected to 30 consecutive measurements each. Ninety-five percent of all measured values were within ±0.20 D of declination from the mean.

CONCLUSIONS: Ray tracing aberrometry is a flexible technology for eye investigation. It can be adapted to any laser technique of vision correction Its further development should be oriented on laser-linked applications of the refraction driven refractive surgery. [*J Refract Surg* 2000;16: S572-S575]

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V. Molebny, I. Pallikaris, and Y. Wakil have patent rights on the technology of ray tracing aberrometry.

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Functions of the human eye (how it performs) can be represented as a set of transforms—a series of components, eg, Zernike polynomials. Some of these components are related to the principal functions of vision: (1) transforming of a spherical wavefront at the entrance of the eye into a plane surface (accommodation); (2) transforming of the plane wavefront corresponding to a parallel beam into a wavefront of a converging beam (image focusing on the retina). Other components are aberrations and human optics introduced into the process of vision. The physical equivalent for the polynomials or the groups of polynomials can be phase transparencies, which carry out corresponding transforms.[1]

Light aberrations in the eye are the result of optical nonhomogeneity of eye media and local irregularities of the optical surfaces of the eye. These aberrations are specific for each individual. They are the main factor limiting the acuity of vision originating from imperfections in the optical system of an eye. Aberration or refraction maps, measured with special instrumentation, can be used for correction of vision to achieve higher visual acuity.

METHODS AND INSTRUMENT

Numerous techniques are known for measuring the mean value of optical power of an eye.[2] Our objective was to develop a new, fast, noninvasive method to measure the optical properties of the eye including defocus, astigmatism, spherical aberration, and coma. Other techniques for accomplishing the same purpose include the Tscherning approach of projecting a regular structure on the retina and analyzing its distortions[3], the Hartmann-Shack method with lenslet array followed by multielement sensor[4], and the spatially resolved refractometer with its subjective alignment of the beams projected into the eye.[5]

Ray tracing aberrometry, described recently[6], uses measurement of the position of a thin laser beam projected onto the retina. The beam, 0.3 mm in diameter, is directed into the eye parallel to the

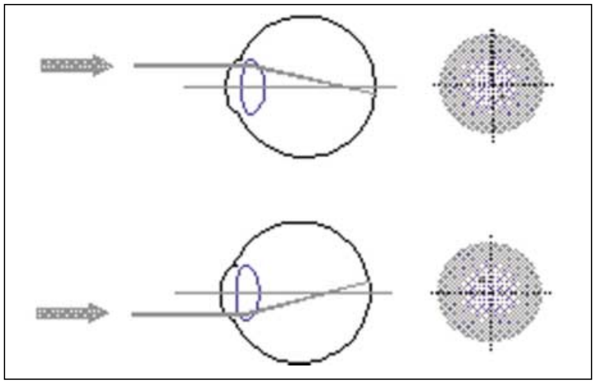

Figure 1. Projecting a thin laser beam on the retina.

visual axis. Each entrance point provides its own projection on the retina (Fig 1). A set of entrance points forms a set of projections (Fig 2).

We use a 10 mW diode laser (wavelength 650 nm), displacing the laser beam over the entrance aperture of an eye and keeping it always parallel to the visual axis. This procedure is performed with the acousto-optic deflector and corresponding forming optics. The light spot from retina is imaged on the position sensitive detector (PSD) by the detector objective lens (Fig 3).

The position sensitive detector measures the transverse declination of the laser spot on retina magnified by the optical system “eye-detector lens” (retina and detector plane are optically conjugated). In this way, transverse aberrations of the eye optics can be calculated, as well as wavefront aberrations. In the process of beam displacement over the eye aperture, we get the data on transverse aberration for each point of beam entrance into the eye, thus enabling the reconstruction of a two-dimensional distribution. Assuming the eye is standard (we use Listing's eye model), one can derive spatial distribution of spatial power over the entrance aperture. Distribution corresponding to the declinations from emmetropia is called a refraction map. From these data, point spread function is also derived (Fig 4). The data obtained with the instrument also permit calculation of the ablation map (distribution of the depth of the tissue to be ablated to achieve the required correction of vision).

The Tracey ray tracing aberrometer contains a CCD video camera and a special target (fixation point) for aligning the eye and the instrument. Optical schematics correspond to the recommendations of the OSA working group.[7] Preprocessing electronics prepares the data from the position sensitive detector for transferring into the computer. An accommodation target enables examination of accommodative functions of the eye. The total time of scanning for the entire aperture of the eye is within 10 to 20 ms and depends on the number of test points at the eye entrance, as well as on the number of independent measurements in each point. Configuration of the scanning pattern can be chosen by the operator with the computer software, and contains 60 to 400 points, each checked 1 to 5 times. The default is 64 points, checked 5 times.

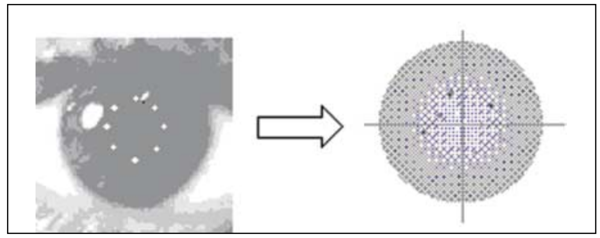

Figure 2. Scanning over the eye aperture.

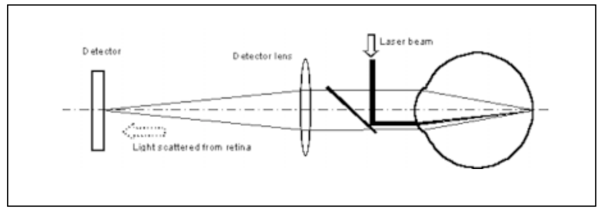

Figure 3. Imaging the laser spot from retina.

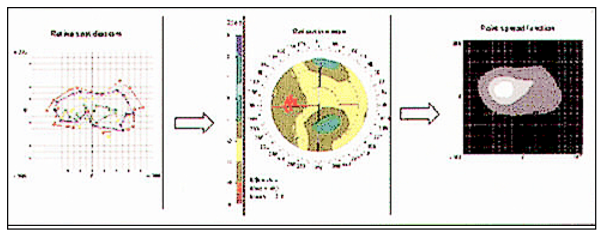

Figure 4. Derived refraction map and point spread function from the retina spot diagram.

The following procedure of information processing is applied. Aberration function is approximated from the measured retina spot diagram using the method of least squares. Zernike polynomials are used to describe wave aberration function. Aberration parameters and other characteristics are calculated from the aberration function. Spline interpolation is involved to better restore the aberration function in the central zone of the eye.

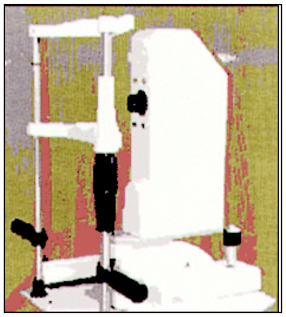

Figure 5. Side view of the Tracey ray tracing aberrometer.

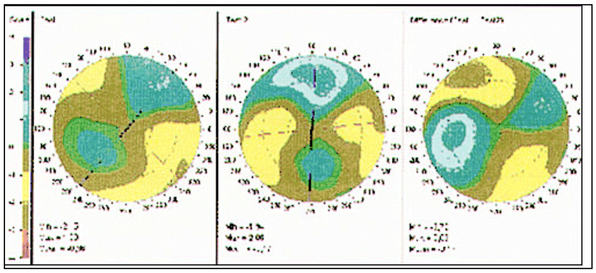

Figure 6. Comparison of the refraction maps with TraceyWorkStation software.

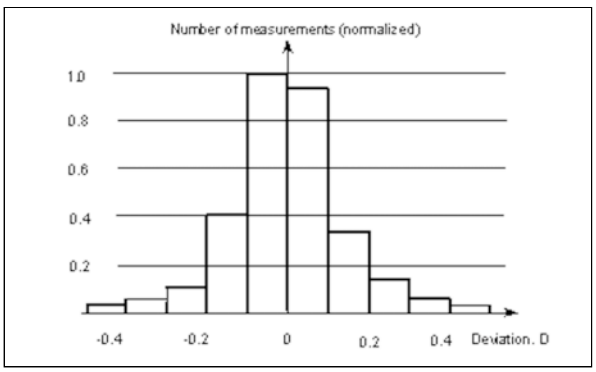

Figure 7. Reproducibility of measurements with Tracey aberrometry in 20 pseudophakic eyes.

The early Tracey configuration had a measurement range of ±3 diopters (D) from emmetropia. Higher ametropia was examined by inserting standard trial lenses into a special receptacle of the instrument. This measurement range was not a restriction of the method, so a new modification of Tracey does not require any trial lenses for compensation of ametropia (Fig 5). Wider measurement range is achieved due to two crossed linear arrays for position sensing instead of the initially used quadrant detectors.

Three software packages supplement the instrument: (1) TraceyScan provides the measurement procedure, (2) TraceyWorkStation provides analysis after measurement, comparisons, etc., and (3) TraceyService provides service for the instrument. An example of the comparison of two measurements for the left and the right eye of the same patient with the TraceyWorkStation software is shown in Figure 6.

Several problems were overcome in developing the technology of ray tracing aberrometry. One of them was connected with incessant eye movement. This difficulty has been overcome by fast beam scanning with an acousto-optic deflector that reduced the time of eye irradiation, as well as by using the technique of video tracking, permitting irradiation of the eye only during time intervals when the visual axis of the eye and the optical axis of the instrument are properly aligned.

PRELIMINARY EVALUATION OF REPRODUCIBILITY

The best way to evaluate the reproducibility of measurements is to make point-by-point comparisons of a series of refraction or aberration maps with some reference, and constructing a two-dimensional distribution for each set of measurements. It is understood that reproducibility of refraction measurements will be evaluated in diopters, aberration in micrometers. For preliminary estimates, we chose simplified comparisons of amounts of astigmatism for the sets of distributions, with subsequent statistical processing.

These preliminary clinical trials with Tracey included 20 pseudophakic eyes (to exclude refractive changes related to accommodation) with clear corneas and no visible fundus irregularities. An intraocular lens was centered and aligned in all eyes. Twenty-five to thirty consecutive measurements of each eye were performed to test instrument reproducibility. Head positioning and eye alignment were performed separately for each examination. The results are shown in Figure 7, where about 60% of all measurements showed reproducibility better than 0.10 D, and about 95% better than 0.20 D.

We evaluated also the same parameter in different zones of the entrance aperture. In accordance with simple geometry considerations, the smaller zone in the center of the pupil, the lower the reproducibility. For example, for the 0 to 6 mm zone, a standard deviation (SD) of 0.11 D was obtained; for the 0 to 3 mm zone, SD was 0.15 D.

DISCUSSION

To verify the described principles of ray tracing aberrometry, an instrument was developed and tested in a clinical setting. Reproducibility of measurements demonstrated the instrument's aptitude for the technologies of vision correction. The technique is flexible and compatible with the technologies of corneal topography. The next steps in its development will provide the instrument linkage to the operating lasers and higher accuracy due to additional data obtained with the instrument (axial eye length, curvature of the cornea, etc.)

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