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MULTIMERIDIAN PHOTOREFRACTION: A TECHNIQUE FOR THE DETECTION OF VISUAL DEFECTS IN INFANTS AND PREVERBAL CHILDREN

A significant percentage of the child population suffers from visual anomalies such as strabismus ("crossed eyes") that predispose to amblyopia ("lazy eye"). Undetected and untreated, these abnormalities can severely, and perhaps irreversibly, impair a child's cognitive and motor development. Consequently, an efficient screening process capable of detecting visual defects in the first two years of a child's life has been the subject of several investigations in ophthalmology during the past decade. One promising technique is photorefraction, which was first described in the early 1970s. The Applied Physics Laboratory and the Department of Ophthalmology at the Johns Hopkins Medical Institutions have collaborated in a two-year effort to identify and develop techniques based on photorefraction for the visual screening of young children. This article briefly discusses visual screening concerns and photorefractive theory and techniques. Difficulties associated with the measurement of visual defects using conventional photorefractors are identified, and the Laboratory's efforts to design two photorefractors intended to overcome the limitations of previous instruments are described along with the operating principles of the two prototypes. An introduction to laser retinoscopy is also presented. Research on a more comprehensive device—a multimeridian laser retinoscope—is under way.

INTRODUCTION

Amblyopia, strabismus, or a combination of both disorders afflicts approximately 5% of all children.[1,2] (See the glossary in the boxed insert for definitions of ophthalmic terms used throughout this article.) Amblyopia is a reduction in visual acuity resulting from abnormal ocular development and usually leads to a permanent loss of vision. Unfortunately, the likelihood of successfully treating this condition decreases with age. A neurocompensatory process is believed to occur that results in formation of abnormal neuronal connections and thus limits the degree of visual maturity, which normally is attained between ages three and five years.[3]

The precise causes of amblyopia are unknown, but binocular asymmetries such as strabismus, anisometropia, or media opacities are predisposing factors.[2] These binocular asymmetries in themselves can retard perceptual-motor development.[4] Consequently, a screening technique capable of reliably and efficiently detecting these visual defects early in life has been the subject of several studies in ophthalmology throughout the last decade. This concern is underscored by the American Academy of Ophthalmology, which considers adequate screening essential for maintaining good vision health in infants and preverbal children.[2]

Screening infants and young children under the age of two years is difficult, as they cannot readily comprehend instructions or articulate visual acuity information. Standard techniques to measure refractive errors, such as autorefraction and retinoscopy, cannot be used with young children because of difficulties with alignment and poor control of accommodation. Precise alignment and fixation during infant examination are quite challenging even for skilled practitioners. The proximity of the examiner and the paraphernalia used during these procedures tend to unsettle most young children. In addition, the administration of cycloplegics to paralyze accommodation and produce mydriasis is controversial because of concerns over adverse reactions. At a minimum, cycloplegia can antagonize children just as their cooperation is most needed.

A screening alternative to autorefraction and conventional retinoscopy must have enough specificity and sensitivity to provide the examiner with a reliable diagnosis. The presence or absence of a particular visual defect needs to be indicated with high confidence (specificity) to reduce false alarms and, more importantly, to eliminate the interpretation of abnormal results as normal. In addition, the severity of a visual defect needs to be measured precisely to permit reasonable characterization (sensitivity). Finally, to be acceptable, screening methods require simplicity of operation, adaptability to various environments, the capability of making rapid assessments, and relatively low implementation costs. Photorefraction, which was first introduced in 1974, is one technique identified during our study that satisfies these criteria.

GLOSSARY OF OPHTHALMIC TERMS

Accommodation: The process of adjusting the eye's focus for relatively short distances using the suspensory ligaments attached to the crystalline lens.

Amblyopia: A visual condition commonly referred to as "lazy eye" in which visual acuity declines because of abnormal ocular development (partial loss of sight without discoverable lesion in eye structure or optic nerve).

Ametropia: Any abnormal refractive condition of the eye in which images fail to focus on the retina (hyperopia, myopia, or astigmatism).

Anisocoria: Unequal pupil sizes when both eyes are subjected to the same conditions.

Anisometropia: A disparity in refraction between the two eyes.

Artificial eye: A simple device that has an objective mounted to a cylindrical cavity. The reflectivity of the inner back wall opposite the objective simulates the human retina. Various amounts of myopia or hyperopia can be set by movement of the objective with respect to this back wall.

Astigmatism: A condition in which a variation in refractive power exists in the different meridians of the eye. The meridians of maximum and minimum power, the principal meridians, are 90° apart in regular astigmatism. The optical effect is to cause two points of defocus to form in the eye. Astigmatism may be compound myopic (the principal meridians are both myopic in error), compound hyperopic (the principal meridians are both hyperopic), simple myopic (one principal meridian is myopic and the other emmetropic), simple hyperopic (one principal meridian is hyperopic and the other emmetropic), or mixed (one principal meridian is myopic and the other hyperopic). Astigmatism is corrected with a sphero-cylindrical lens, the cylinder axes of which are aligned with the eye's principal meridians.

Autorefraction: A technique for determining refractive error with a high degree of accuracy. Autorefraction may be either subjective or objective. In subjective autorefraction, the patient adjusts the focus of the autorefractor until maximum clarity is attained in each eye. In objective autorefraction, the autorefractor measures the refractive state of each eye using the principles of retinoscopy, and thus the active participation of the patient is not required.

Autorefractor: An instrument used to perform autorefraction.

Conjugate points: Two points in space that are joined together through optical object–image relationships.

Cornea: The transparent membrane of the eye; the outer coat of the eye having more curvature than the sclera. The curvature of the cornea is responsible for two-thirds of the eye's refractive power.

Cycloplegic: A drug administered in drop form that is used to paralyze accommodation (cycloplegia) and that secondarily produces dilation of the pupil. A typical agent used for children is 1% cyclopentolate.

Dilation: An enlargement of the pupil.

Diopter (D): The unit defining the refractive power of a lens. It is simply the reciprocal of its focal length given in meters. A one-diopter (1-D) lens is a lens with a focal length of 1 m. If a lens is divergent, its dioptric power is negative; if a lens is convergent, its power is positive. For calculation purposes, lens diopters are determined using $100/f$, where f is the focal point of the lens given in centimeters. A prism diopter (Δ) represents a 1-cm deflection at 1 m.

Eccentricity: Literally means proceeding from the center. An eccentric photorefractor is one in which the light source is located to one side of the camera's aperture.

Emmetropia: A normal refractive state in which light rays come to a focus on the retina.

Esotropia: A constant deviation inward of one eye commonly referred to as internal, or convergent, squint.

Exotropia: A constant turning out of one eye.

Far point plane: The object plane conjugate to the retina when the eye is not accommodating.

Heterophoria: A misalignment of the eyes when one eye is occluded. This condition is a temporary, normal response and is not considered serious.

Heterotropia: A misalignment of the eyes at all times.

Hyperopia: A refractive error in an eye that is not accommodating in which an image would come to a theoretical focus behind the retina because the length of the eye is too short, thus placing the lens too close to the retina. This condition is also known as hypermetropia and is commonly referred to as farsightedness.

Isotropic photorefraction: On-axis photorefraction in which the light source is located on the optical axis in line with the camera and subject. This technique requires multiple images at different camera-to-subject lengths.

Medial opacities: Areas of the ocular media impervious to light. The term usually refers to an opaque spot on a normally transparent structure such as the crystalline lens.

Mydriasis: A dilated condition of the pupil.

Myopia: A refractive error in an eye that is not accommodating that produces an image in front of the retina because the eye is too long, thus placing the lens too far from the retina, or because of a change in the eye's refractive components. This condition is also commonly referred to as nearsightedness.

Pupil: The aperture of the eye through which light enters; the orifice located at the center of the eye's iris.

Retina: The inner nervous tunic of the eye. A thin (0.02-in.) layer of light receptor cells (cones and rods) that cover the inner surface of the choroid. (The choroid is the tough sclerotic inner wall that is well supplied with blood vessels and pigmented with melanin.)

Retinoscope: An instrument used to perform retinoscopy.

Retinoscopy: A method of objectively determining refractive errors of the eye. A light source is moved transversely in front of the eye, and the direction of movement of the reflected light (the red reflex response) from the retina and the associated shadow indicate the type of refractive error if present. A highly skilled practitioner is required to ensure accuracy.

Scotopic: Denotes a condition of dim light in which only the retinal rods are used as light receptors.

Strabismus: A visual defect in which a lack of parallelism exists between the visual axes of the eyes ("crossed eyes"). (Refer to **esotropia**, **exotropia**, **heterophoria**, and **heterotropia**.)

Tropia: A misalignment of the eyes.

PHOTOREFRACTION

Background and Principles of Operation

Photorefraction encompasses a family of techniques that use the reflection of light from the retina to determine the eye's optical performance.[5] The origin of this retinal reflection, termed the "red reflex," has been well characterized and verified experimentally.[6] Photorefraction using a photographic approach was first introduced by Howland and Howland in the early 1970s.[7] Kaakinen,[8,9] using this technique, described an off-axis photographic (eccentric) method for detecting myopia and hyperopia, and photorefractive instruments developed throughout the 1970s and 1980s were based on this design.

In eccentric photorefraction, light from an optical flash positioned next to the aperture of a camera lens is used to probe a subject's eyes. The subject is induced to fixate on the light source, and a flash exposure is then taken. Light from the flash enters the pupils and, after reflection from each retina, is returned to the source, where it is collected by the camera as shown in Figure 1. In this way, the refractive state of each eye can be determined objectively at a distance of one to two meters. If an eye is emmetropic, most of the reflected light will be returned to the source; no light will be intercepted by the camera lens as shown in Figure 1A. Thus, the pupil of an emmetropic eye will appear uniformly dark in the photographic image. For a myopic eye, light entering the eye will come to a focus before striking the retina. An extended (blurred) image will be formed at the retina and reflected back toward the source. If sufficient myopia exists, this reflected light will diverge enough to allow a portion of the returning light to enter the camera lens (see Fig. 1B). The photographic image formed by the myopic eye will be characterized by a bright crescent in the pupil on the same side as the offset of the light source. When the refractive state of an eye is hyperopic, light within the eye will theoretically be focused at a point behind the retina, and the divergent light will be reflected from the retina through the lower part of the pupil. Thus, for a hyperope, the crescent will be observed in the pupil on the side opposite the offset of the flash (see Fig. 1C).

The optics of crescent formation are geometrically depicted in Figure 2 for both myopic (Fig. 2A) and hyperopic (Fig. 2C) eyes, and Figure 2B illustrates a typical crescent for a myopic error as it appears to the cam-

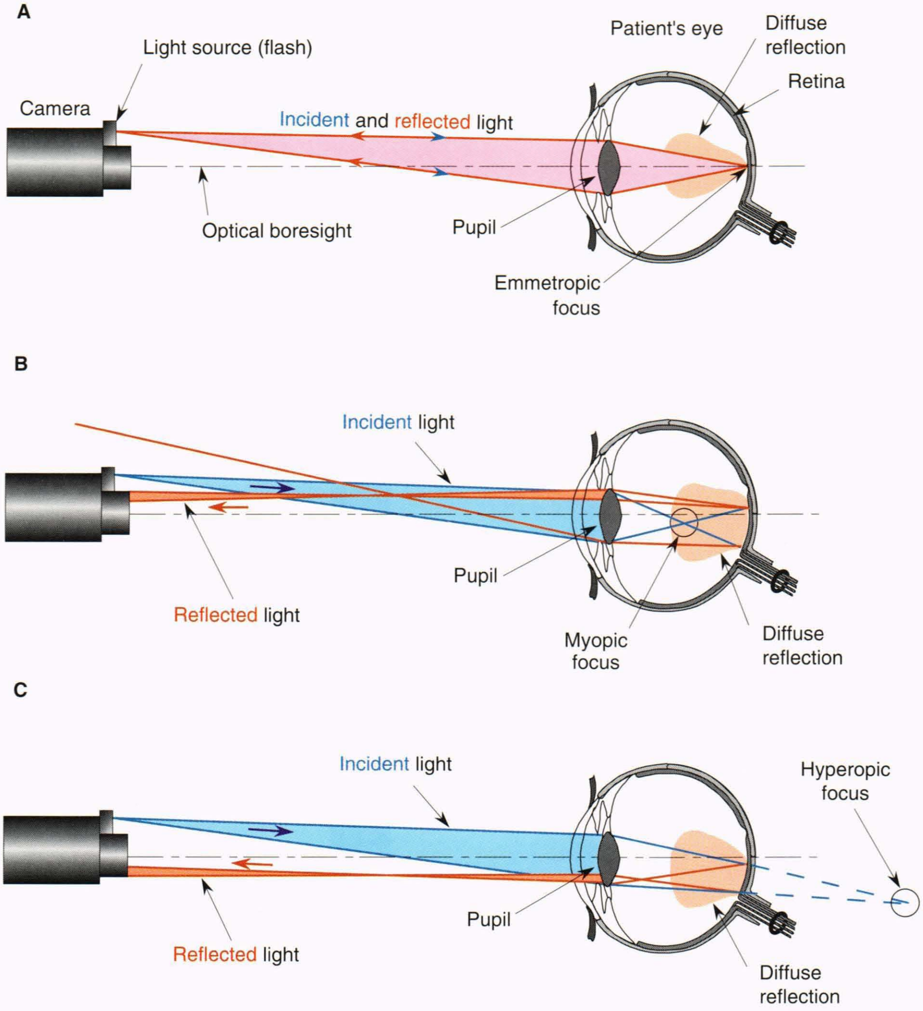

Figure 1. Schematic illustrating the principles of photorefractive measurements. A light source and an observing camera are collocated. Light intercepts the subject's eyes, which are fixated on the camera and light source, and is reflected off the retina toward the camera. If a refractive error exists in either eye, the reflected light will diverge sufficiently to allow a portion of the returning light to enter the camera lens and be imaged as a crescent. **A**. For an emmetropic eye, the reflected light is returned to the light source, and no crescent structure is observed by the camera. (The flash and the retina are conjugate points.) **B**. For a myopic eye, a portion of the reflected light intercepts the camera lens, and a crescent will be seen in the pupil on the same side as the light source in the photographic image of the eye. **C**. For a hyperopic eye, a crescent will be imaged in the pupil on the side opposite the light source.

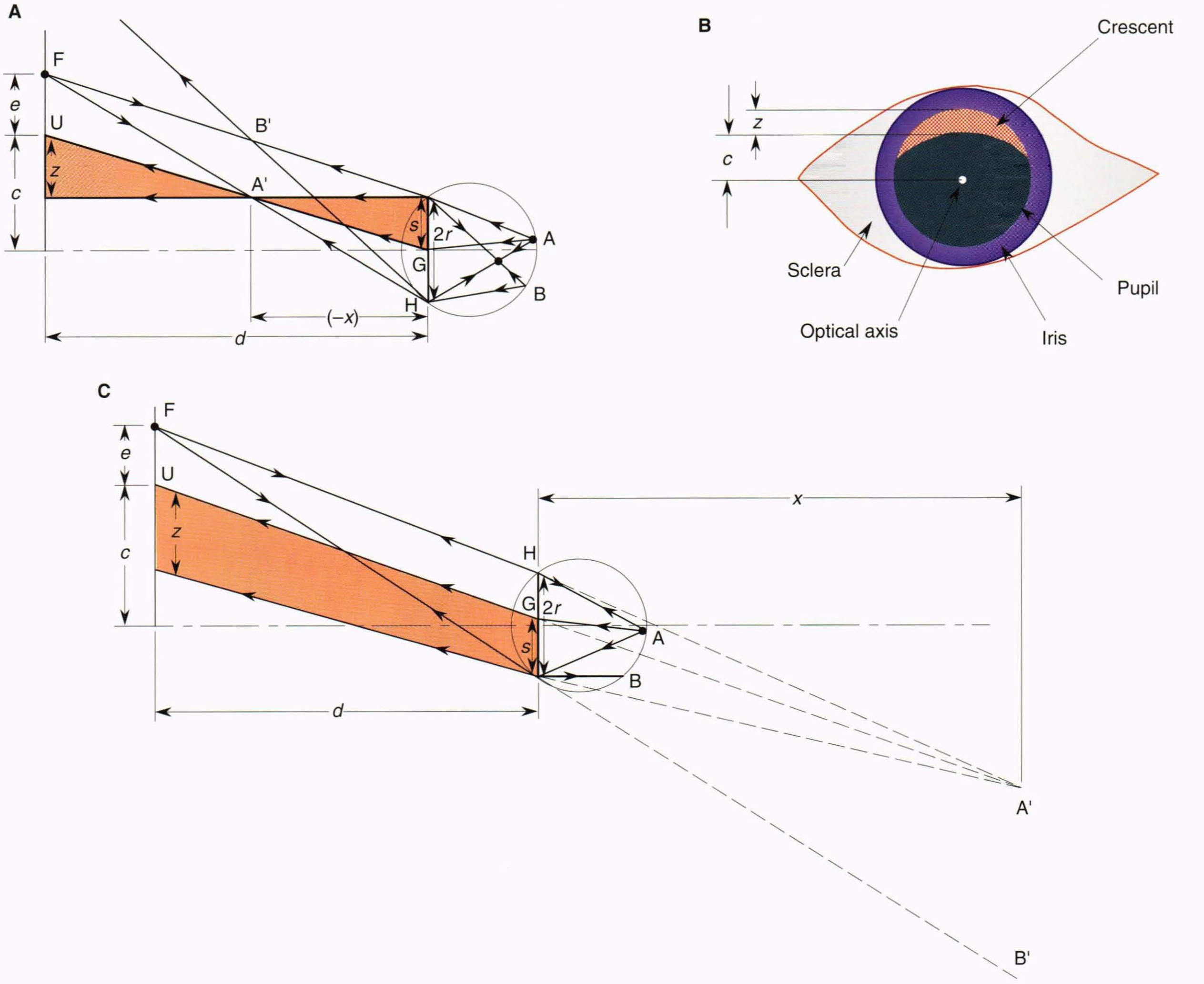

Figure 2. **A**. Crescent formation with a myopically defocused eye. A flash source F is eccentrically positioned a distance *e* above the extreme edge U of a camera lens. The eye is a distance *d* from the plane containing the flash source and the aperture of the camera (radius *c*). The eye is myopically focused with respect to this plane. Light from the flash enters the eye, is imaged in front of the retina, and forms a blurred image on the retina at AB. In turn, an aerial image A′B′ of this retinal pattern is formed at the far point plane of the myopic eye. If the eye is sufficiently myopic, the light returning from this image will diverge sufficiently that a waist of rays (denoted by *z*) will enter the camera aperture. As shown by the shaded region, these rays define a crescent of finite width *s* in the plane of the pupil. The following geometrical relation can be derived from a consideration of the similar triangles FA′U and GA′H. (Sign convention dictates that *x* is a negative value, whereas all other parameters are positive.)

$$\frac{2r - s}{-x} = \frac{e}{d - (-x)}$$

The crescent appears on the same side of the pupil as that to which the flash has been offset. **B**. The image of a myopic eye as it appears to the camera. **C**. The eye is focused hyperopically with respect to the camera. A virtual image A′B′ of the retinal image is formed behind the eye at the far point plane. A waist of rays (*z*) enters the camera aperture. A crescent of width *s* will appear in the plane of the pupil in a position opposite to the offset of the source. The following geometrical relation can be derived from similar triangles FA′U and HA′G.

$$\frac{2r - s}{x} = \frac{e}{d + x}$$

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era.[10] In Figures 2A and 2C, x denotes the distance in centimeters from the cornea to the far point plane (the focal length), which is the object plane that is in conjugate focus with the retina when the eye is not accommodating. If the far point plane of a myopic eye is 25 cm in front of the eye, for example, objects beyond this distance will be myopically defocused, and a diverging lens (a lens of minus power) must be provided to bring light rays from objects beyond 25 cm into focus on the retina. The degree of refractive error is expressed in diopters (D) calculated as $100/x$. Thus, if a myopic eye's far point is at 25 cm, the amount of myopia is 100/25 or −4 D. The value is negative because a diverging lens must be used so that images beyond the far point will be moved back into focus upon the retina.*

The far point plane for a hyperopic eye (Fig. 2C) theoretically exists behind the retina, and the focal length x is therefore measured from the imaginary far point plane behind the eye to the cornea. Since a converging lens is required to move images forward to the retina, dioptric values for correcting a hyperopic error are expressed as positive numbers.†

As defined in the equation for Figure 2A, crescent width s is related to the refractive error in diopters ($A = 100/x$, where x is the distance from the far point plane to the front of the eye in centimeters) through pupil size $2r$, flash eccentricity e, and camera-to-subject working distance d for a myopic eye by

$$s = 2r - \frac{e}{d(-A - 1/d)} .$$

A minus sign precedes A because dioptric values for myopia correction are negative. The same equation is used for calculating crescent width for a hyperopic eye, but the denominator is changed to $d(A + 1/d)$ because dioptric values are positive for a converging lens. For a crescent to be visible, the refractive error must exceed a critical magnitude (the dead zone). If $2r$, e, and d are held constant, the crescent width s will expand rapidly as the refractive error in diopters increases until a critical value is reached at ±5 D, beyond which changes in crescent width become less perceptible.

Advantages

Clinical reports[2,3] indicate that sufficient accuracies have been obtained using eccentric photorefraction. To acquaint our team with photographic photorefraction, the refractions of several children were measured using a commercially available photorefractor, the Otago Photoscreener,[11] and the images obtained are presented in Figure 3. The photorefraction results were then compared with retinoscopic findings for the same children. A high correlation was observed between the characterization of visual errors using the Otago instrument and the results obtained with the more time-consuming method of retinoscopy.

Aspects of binocular asymmetries have been adequately detected and measured using eccentric photorefraction, for both eyes are observed simultaneously. Among the asymmetries that can be evaluated are anisometropia, anisocoria, and differences in medial opacities. (Anisometropia can be detected by observing differences in crescent size and position. Differences in pupillary diameters are diagnostic of anisocoria. Size or position differences in medial opacities can also be detected by comparing the brightness of the red reflex from the two eyes.)

Other photorefraction techniques exist such as orthogonal photorefraction and isotropic photorefraction.[11–15] Schaeffel et al.[12] describe an infrared photoretinoscope that permits repeated measurements in dim ambient light without distraction of the subject or constriction of the pupil. A correction is necessary when performing infrared photorefraction because a refractive error is introduced by chromatic aberration. The infrared offset error causes a refraction to appear 1.0 to 1.5 D more hyperopic as compared with the visual spectral response.

Limitations

Despite the apparent success of existing methods, why has photorefraction not been universally accepted as an approach to visual screening? Two fundamental impediments to the widespread acceptance of photorefraction as a mass screening tool are measurement insensitivity and lack of overall cost-effectiveness because of the complexity involved in obtaining and analyzing data.

Given the geometric restrictions on the size and placement of the light source in eccentric photorefraction, refractive errors are evidenced only over a relatively limited range. Refractive errors must typically exceed the dead zone to result in crescent formation as previously noted. In addition, once ametropias exceed ±5 D, measurement accuracy is lost.[10]

Photorefractors currently in use are single-axis devices that are completely insensitive to astigmatism with a principal meridian parallel to the axis of the flash. One study[16] found single-axis photorefraction to miss 25% or more of cases with ametropia of less than 4 D, and the type of error was not indicated because of a lack of emmetropic controls. In the presence of astigmatism, multiple single-axis measurements are required along three separate meridians simultaneously to fully characterize its extent.

Sensitivity is also adversely affected by the wide amplitude of accommodation of infants and preverbal children. If accommodation is not controlled, latent hyperopia can go undetected and false diagnoses of myopia

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*Note that the refraction measured from the cornea is not equivalent to the power of a spectacle lens required to neutralize the ametropia. When the power of a spectacle lens required to correct a refractive error is calculated, x is measured from the far point plane to the surface of the corrective lens. If a corrective lens is positioned 15 mm before an eye, the focal length for a lens needed to correct a 4-D myopic error is 25 cm − 1.5 cm or 23.5 cm, which means that the required lens power is 100/23.5 cm or −4.25 D.

†The lens power required to correct hyperopia decreases as the distance between the eye and the spectacle lens increases. For example, if a hyperopic eye with a far point plane located 25 cm behind the cornea, which is equivalent to a 4-D error, were corrected by a lens placed 15 mm in front of the eye, a +3.75-D lens would be used, as the distance [1.5 cm + 25 cm] from the surface of the lens to the far point plane is 26.5 cm.

can occur.[17] The usual method employed to suppress accommodation is to make several measurements while the child fixates on multiple distances. Most photorefraction techniques, however, require cycloplegia to provide sufficient sensitivity by inducing mydriasis and to control accommodation. Sensitivity of photorefractive techniques to pupil size $2r$ can be understood by using the equation given in the previous section. The larger the pupil, the greater the sensitivity. This relationship is also demonstrated in Figure 3. One study[17] found that the capability to detect refractive errors between 1 and 2 D through photorefraction increased from 62% to 95% with dilation. Although cycloplegia improves refractive error sensitivity, it decreases the ability to detect strabismic deviation.[18] Cycloplegics also have the potential of causing allergic reactions, and additional time and care are required to administer eye drops for the test procedure.

Photographic means have been used to acquire and display measurement data, but film processing and operational procedures involve excessive turnaround time. Although the introduction of cameras based on charge-coupled devices (CCD's) has expedited processing, obtaining and analyzing data remain complex processes. Sophisticated training is a prerequisite for interpreting photorefraction images, since measuring crescent structure parameters is not straightforward and is a process prone to error. If screening is to be performed efficiently, measurement and evaluation need to be conducted in less than ten minutes.

Eccentric photorefraction permits the eye's refraction to be approximated objectively at a predefined distance of one to two meters, but the subject must fixate on the light source for incident light to reach the eyes and be reflected to the photorefractor. Securing the cooperation of infants and young children for such a procedure is obviously a formidable task.

Despite the problems inherent in single-axis eccentric photorefraction, ample evidence exists that photorefraction is an extremely promising vision screening technique. Comparison of photorefractor results with retinoscopic findings yields a correlation greater than 0.8 with achieved sensitivities and specificities of 93% and

Figure 3. Photographs taken with a commercially available photorefractor of the eyes of three subjects in dilated and undilated states for comparison. The panels on the left are the images of undilated eyes, and the panels on the right show the dilated eyes of the same subjects. **A**.The subject is corrected by glasses for hyperopia and strabismus. Note the lack of a red reflex. **B**. When the eyes shown in A are in a dilated state, a small refractive error in the left eye becomes apparent as shown by the red reflex crescent. **C**. The subject appears to be an emmetrope given the absence of crescents. **D**. The eyes of the apparent emmetrope are shown in a dilated state. Crescents appear in both eyes that reveal refractive errors of +1.75 D in the right eye and +1.00 D in the left eye. **E**. The subject is strabismic in the left eye. No reflex is seen from the fixating eye, whereas the left eye reveals an off-centered corneal reflex (white spot at bottom of pupil). **F**. When the eyes of the strabismic subject are dilated, strabismus and a hyperopic refractive error in both eyes (+4.5 D for each eye) are revealed from the crescent patterns.

82%, respectively.[6,10] Photorefraction was therefore chosen as a point of departure for APL's effort to develop a technique suitable for the mass screening of young children's vision.

The overriding objective of our study is to enhance refraction sensitivity by attempting to narrow the dead zone, compensating for accommodation, and implementing a workable approach to making measurements along multiple meridians to assess astigmatism. To reduce the complexity of operation and data analysis, computerized approaches to image feature identification, extraction, and measurement have been developed and are continuing to be explored. Infrared monitoring techniques were adopted to permit the procedure to be performed in a dimly lit area, which should eliminate the need for medication-induced dilation, for dilation in children occurs in three to six seconds under scotopic conditions.

Two very different techniques have been explored thus far during the study. The first was a multimeridian system that used three separate flash units with a CCD camera.[19] A prototype device was assembled, and testing was conducted using an artificial eye. The testing revealed fundamental limitations with the light source geometry. To overcome these deficiencies, a second technique was devised using a linear CCD detector array with a scanning laser system as the light source. The development of hardware to evaluate this approach is ongoing.

MULTIMERIDIAN PHOTOREFRACTION

A multiple-imaging photorefractive system was envisioned to screen very young children successfully for significant refractive errors, including astigmatism and strabismus. A prototype using this concept and designed to record three sets of crescents simultaneously along three different meridians spaced 120° apart was fabricated. The three measurement axes make it possible to detect astigmatism in any meridian without ambiguity. Images are required of both eyes in each of the three meridians being tested for the technique to work properly. Obviously, crescent image information is required from both eyes, but simultaneous imaging of the eyes is even more important to provide information on binocular anomalies such as strabismus and anisocoria. (Strabismus is diagnosed and characterized through corneal reflections. Anisocoria is identified by examining the pupillary images directly.)

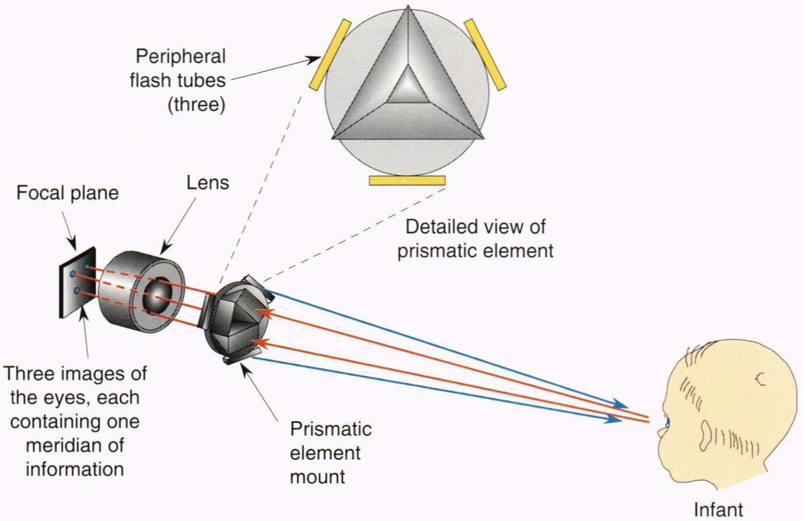
An exploded view of the prototype multimeridian photorefractor is shown in Figure 4. Three identical right-angled prisms, each with a separate flash unit, are located in front of the camera lens. The dispersive power of these prisms was selected to provide adequate image separation to facilitate interpretation. (Crescent width dimensions for six images similar to the one shown in Fig. 2B need to be measured; if overlapping occurs, this could be quite challenging for the operator.)

The images were formed using a CCD camera (electronic focal plane) to permit image processing by computer. The flash units and CCD frame grabber required synchronization so that eye blinking or head motion would not prevent useful images from being obtained. To this end, three successive images were determined sufficient to obtain at least one good image, which required an acquisition period of about 100 milliseconds. To accomplish the required synchronization, the camera was placed under control of a microcomputer, and an external control circuit was assembled to coordinate image acquisition with the firing of the flash units. The operator used this control circuit at the appropriate times to signal the computer to acquire images.

The need for a cycloplegic to induce dilation was obviated by testing in a dimly lit area. Using an infrared flood beam and an infrared monitor, the operator could observe the child to determine when to acquire the images.

To eliminate loss of measurements residing in the dead zone, two cameras were used, each at a different camera-to-child distance. When one camera of the system was operating in its respective dead zone, the other camera was able to make measurements. Analyses were performed to determine the appropriate working distances and how best to integrate the two cameras.

Figure 4. Multimeridian flash photorefractor. The first prototype developed used three right-angled prisms to enable three images of the subject's eyes to be obtained simultaneously to measure any astigmatism completely.



Measurements obtained with our multimeridian photorefractor demonstrated the advantages of this device over commercially available photorefractors. The principal advantages are the elimination of measurement ambiguities when evaluating astigmatism and an improvement in the reliability of data collection. Interpretation of the acquired images using an artificial eye indicated detection of refractive errors greater than ±1 D with inaccuracies as low as ±0.5 D.

Well-defined linear sources of light are necessary for this technique to provide accurate refractive error measurement. In an attempt to meet this need, the flash elements were mounted into special brass housings. Each housing had a 3-mm-wide longitudinal slit from which the light source emerged. Unfortunately, the images collected were marred by an insufficient luminance profile. Delineation of the brighter crescent from the darker pupil was not easy or repeatable.

The design was repeated using 0.5-mm-diameter fiber optics. Although the luminance profile at the image increased, the contrast was considered insufficient for ideal measurements. Accuracies required for refractive measurements range from 0.25 to 0.5 D; however, the multimeridian photorefractor could not measure refractive errors below 0.5 D.

The design parameters of the photorefractor were revised to investigate the measurement limitations further. Although data quality improved through trial and error, two fundamental difficulties remained with the use of the prismatic approach.

First, optimum slit width for the light source was found to be directly related to the magnitude of the refractive error. This relationship required that multiple measurements be taken over a range of slit widths to ensure accurate readings. The second difficulty was that the prismatic measurement data required rather complex processing to extract error information. A practicable solution to the problem was expected from previous work in medical imaging, but even the raw images using the linear light version (fiber-optic sources) presented unacceptable crescent-to-dark image contrast. With such low contrasts, continued unsatisfactory results were expected.

In summation, the multimeridian photorefractor could measure small refractive errors reasonably well but not to the level of sensitivity required. This design was abandoned because of its inability to measure small errors and because the resulting data consisted of complex crescents that do not lend themselves readily to computerized analysis.[20] It became apparent that another means of estimating refractive error was necessary.

LASER RETINOSCOPE

A second approach to measuring refractive error using the principles of retinoscopy was identified. Instead of an incoherent light source, this approach uses a 1-mm-diameter beam from a laser diode to produce the reflex. The design is basically a one-pass system, and incident light does not undergo any measurable refraction. Two advantages over the multimeridian photorefractor are realized. First, only one lens, the eye, is in the optical path. Second, the design employs the principles of retinoscopy—a widely accepted technique to measure refractive errors directly. Laser retinoscopy, however, may not yield the accuracy of standard retinoscopy, for no attempt is made to neutralize the ametropia with corrective lenses. Figure 5 illustrates a preliminary design of this device.

For clarity, note that Figure 5 presents the laser retinoscope concept using one eye. For two eyes, the incident laser beam is split by a two-sided scanning mirror to form a beam for each eye simultaneously. The angle of the two-sided mirror is determined by the working distance and separation between the pupils. Two focal plane assemblies are used to acquire the returning light from the eyes.

The lens of the eye presents itself as a flat surface when intercepted by the small-diameter laser beam. Losses from beam spreading are minimized, since the refracted beam continues towards the retina undeviated. After the incident laser beam is diffusely reflected by the retina, the return beam (reflex) fills the eye's lens. When the eye is emmetropic (Fig. 5A), the scanning mirror will obscure the beam and prevent it from reaching the CCD detector. Thus, the output from the detector will remain constant. For a myopic eye (Fig. 5B), a portion of the defocused reflex will bypass the scanner and will reach the detector to produce an output proportional to the degree of the error. (The mechanism for detecting hyperopia is similar.) To quantify the refractive error and to determine whether it is myopic or hyperopic, the temporal response from the CCD based on a scanning cycle must be processed. For each detector output, a corresponding position of the laser beam is indicated.

In testing actual eyes, scattering and multiple reflections of the laser light are expected at each interface (especially at the cornea). In addition, a level of constant detector output will exist because of electronic biases. Therefore, the signal level from the CCD is not expected to measure true zero for an emmetropic eye. Instead, a relatively small constant signal resulting from a combination of systematic and temporal responses correlated to the scanning position is expected. The reflex signal from an ametropic eye sufficiently exceeds the signal from these interfering sources, however.

SOFTWARE CONTROL AND PUPIL-TRACKING SUBASSEMBLY

In tandem with the development of photorefractor hardware, software was designed to control hardware and to manipulate images. Control of frame grabber hardware for alignment and data acquisition was required for both designs. Software was developed for use with the multimeridian photorefractor to maintain synchronization between the flash units and the frame grabber. A triggering signal generated by a simple, retriggerable monostable multivibrator circuit was the controlling principle for this software.

A tracking device is currently being integrated into the laser retinoscope. An idealized scanning mirror that rotates about one axis is shown in Figure 5; however, to

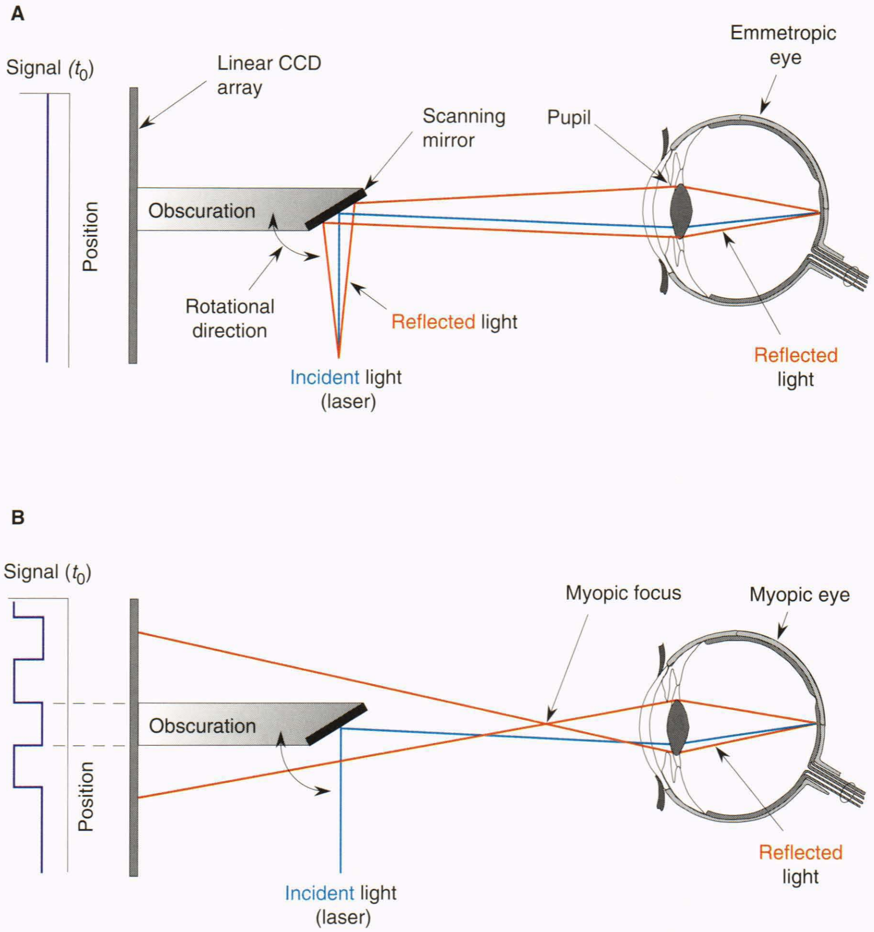


Figure 5. Schematic illustrating the principles of laser retinoscopy. The signals shown are for a particular orientation of the scanning mirror occurring at time t_0. **A**. Emmetropic eye. Laser illumination is directed to the subject's eye. The scanning mirror completely blocks the returning laser light reflected from the retina and prevents it from reaching the CCD detector. The resulting output from the focal plane signal remains constant. **B**. Myopic eye. The returning laser light spills past the scanning mirror and produces an output at the CCD detector proportional to the extent of the myopia.

permit maximum freedom for the child during testing, an elevation-azimuth table capable of 100°/s angular rates has been designed. Figure 6 illustrates this hardware. To provide table steering commands, an infrared camera is used to image the child, and the video signal is fed into a tracking processor. (This replaces the operator's monitor used with our multimeridian photorefractor.) Once the child is imaged, the tracker generates the necessary steering commands to direct the laser beams to the pupils via the scanning mirror. The tracker maintains the beams on the pupils by responding immediately to changes in the child's position.

To avoid the resolution problems that could occur with finite-step motors, direct current servomotors were selected for the design. The steering element is mechanized by worm-drive tables capable of high-precision positioning and minimal backlash.

Software was also developed for the multimeridian photorefractor to perform pattern analyses on the two-dimensional images to determine the presence of crescents. These complex two-dimensional patterns required substantial image processing for crescent identification and quantization of refractive error (see Figs. 2B and 3). The laser retinoscope, in contrast, presents relatively simple signal patterns for analysis that require time–position correlation (see Fig. 5).

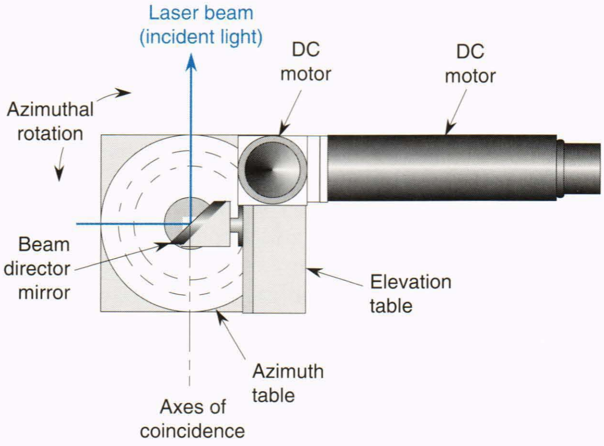


Figure 6. The two-table servomechanism enables the beam-steering mirror to direct the laser beam to a dynamic target. Angular velocity associated with this table is 100°/s in either azimuth or elevation.

Actual data processing using the laser retinoscope has yet to occur, as final assembly of this device has not been completed. A laboratory setup has been assembled, but only very preliminary data have been obtained.

SUMMARY

A prototype multimeridian photorefractor was assembled, and tests of the device were performed using an artificial eye. Although acceptable measurement capability was demonstrated, limited precision precluded using this approach for mass screening. Laser retinoscopy, on the other hand, is a technique that presents the advantages of operating ease and cost-effectiveness. The minimal operator experience required and the low system costs appear to make this technique an effective tool for the mass screening of infants.

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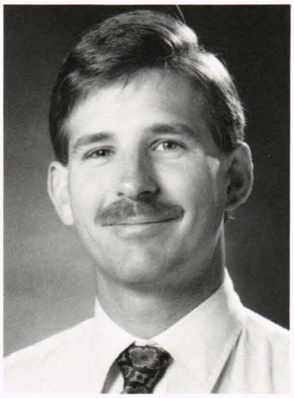

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