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Abstract

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In Vivo Measurement of the Sagittal Depth of the Anterior Corneal Surface

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IN VIVO MEASUREMENT OF THE SAGITTAL DEPTH OF THE ANTERIOR CORNEAL SURFACE

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Date : . . . . 5 Feb 1979 . .

Introduction:

Historically, many methods have been used to objectively estimate the corneal curvature. The ancients attempted to observe the relative sizes of familiar objects reflected in the cornea. Scheiner, in 1619, used a similar technique when he compared the separation of slats in a window frame as reflected from the anterior corneal surface with the reflections in glass balls of known diameter. Although Levene (1965) credits Goode with the invention of the keratoscope (using a small luminous square as a target), Placido, in 1870, devised the instrument which bears his name and which was the forerunner of the modern photokeratoscope. (Levene, 1965; Mandell, 1961).

Mandell (1960) credits Ramsden with the development of the essential features of the modern ophthalmometer: the object, the doubling device, and the magnifying device. Purkinje apparently made the first estimations of corneal curvature with the Ramsden instrument (Levene, 1967). In 1854 Helmholtz applied the principle of doubling to the modifications performed by Valentin, Cramer, and Sneff upon the Ramsden instrument and produced the keratometer or ophthalmometer.

At one time Placido placed a camera behind the peephole of his Disk and photographed the cornea; he was unable to analyze the results in any meaningful way (Bibby, 1972). It was left to Gullstrand, in 1896, to construct a photokeratoscope and, using his mathematical talents, to analyze the photographic data in terms of corneal curvature (Levene, 1965).

Corneal and Ocular physiology impose four limitations on all topography-measuring systems:

(1) The cornea is an aspheric reflecting surface of variable thickness; it cannot be accurately described as spherical.

(2) Small eye movements (rapid micronystagmus) make photography with long exposures difficult.

(3) The brow, cheek, and nose limit the placement of instruments very near the cornea.

(4) Traumatized or diseased corneas with irregular and diffuse reflecting surfaces do not produce a clear image of a target object.

Placido's Disk has no method of compensating for micronystagmus. Furthermore, it projects a flat object onto the cornea over a large area, resulting in an aplanar image. Photography of this image is difficult because all the rings cannot be brought to a crisp focus; when one triesto compute corneal curvature on the basis of photographic data, a lack of definition in the blurred rings introduces considerable error. When the flat target of the Placido's Disk was photographed and the results analyzed, Blair(1960) found errors of 0.05 mm in 45% of the readings and as high as 0.1mm to 0.18mm in 10% of the readings. (These were measured on spherical steel balls of known radius.) When the target is constructed so as to produce a flat image, the accuracy improves as indicated by Ludlam(1967) and Knoll(1961). However, Knoll found accuracy uncertain above o.20mm and Ludlam reported

±1.00D error from Knoll's instrument. Mandell(1969) attempted to reduce the error by assuming an eccentricity of 0.48 for the central cornea and subtracting the error obtained from this elliptical model from the data for each photokeratogram. Clark(1972) used this method in an autocollimating photokeratoscope and obtained standard deviations of $1x10^{-3}$ of the measurement. Townsley(1967) reported a photokeratoscope with a ring configuration which produced a virtual image in a flat plane; he reported measurements made on the enlarged photograph to a precision of 0.001" with a magnification of 4.57. After development by the Wesley-Jessen Company, Prechtel and Wesley(1970) reported that:

> "The maximum distance from any computed point is 0.0007mm .... 2½ Newton rings (λ= 2570nm)."

Townsley (1974) reported that the Wesley-Jessen Mark III Photo-Electronic Keratoscope possessed repeatability of 0.025mm or 0.005mm at the cornea with target ring error of ±0.0125mm or ± 0.0025mm at the cornea.

Because the Placido's Disk is held in the hand, tilting may cause additional errors (Levene, 1962). Although the Placido's Disk is useful for qualitatively assessing large amounts of corneal astigmatism and surface irregularities, it cannot be seriously considered when quantification of the corneal topography is desired.

The photoelectronic keratoscope, previously described, is an extremely accurate method of analyzing corneal curvature. Problems inherent in the photokeratoscope are: inaccuracy in centering, inaccuracy of alignment(coaxial), loss of resolution due to graininess of film, and lack of stability of the film emulsion and/or backing. (Ludlam,1967). The Wesley-Jessen System 2000 PEK has solved most of these difficulties; a coaxial alignment focus (centered dot) with depth of field of 0.10mm is provided with focus occuring in only one meridian. Lithography film having high contrast, good stability, and high resolution is employed; the resultant photograph is a transparency which can be easily magnified. More importantly, the System 2000 PEK does not assume sphericity of the corneal surface; a sophisticated system of conic sections has been devised to describe a model for corneal topography (ElHage, 1972). A short exposure time prevents micronystagmus from causing blur and a large portion (9mm) of the cornea is sampled in 0.5mm increments (Bibby, 1976).

The ophthalmometer estimates the corneal curvature according to the assumption that the cornea is spherical. Inaccurate results are obtained when measuring the corneal periphery because the keratometer's large sampling area (3mm diameter in the Bausch and Lomb Keratometer) averages irregularities and radius changes within the chord diameter, giving only approximate values. Mandell(1962b) also showed that smaller mires increased the difficulty of finding the endpoint. Mandell(1962a) has published a table of corrections for use in peripheral keratometry but Ludlam(1969) has showed that Mandell's approach is complicated by many measurements and also by centering the unfocused mires on the keratometer cross-hair.

Other problems inherent in the ophthalmometer design are accurate focusing of the eyepiece, precise centering of the central mire and cross-hair over the apex of the cornea, and determination of the endpoint. Since a certain value for the index of refraction of the cornea is assumed from experimental data, equally reliable measurements cannot be made for all corneas. Furthermore, surface irregularities in the cornea make accurate measurements impossible because the mire images become badly blurred and distorted.

Profile measurement has been attempted as a means of quantifying corneal curvature. McMorris(1971) and Nolan(1968) claim success in matching corneal profiles to templates but their accuracy was less than 1.00D in the best cases when compared to ophthalmometer readings taken from the same corneas. This system has many possible errors due to camera placement, image stability and film resolution, skill of operators at matching the template to a slightly blurred photographic image under a microscope, and lack of reproducibility of results. Many opportunities for human error make this method an undesireable clinical tool and a laboratory curiosity.

The cornea may be anesthetized and dusted with white talcum powder. Stereo photographs may be taken of the cornea and analyzed in a manner similar to that used for determining ground contours from aerial photographs. Bonnet and Cochet(1962) found relative height with accuracy of ±.0.03mm. This small distance error becomes a large dioptric error when the radius is computed and converted to the dioptric equivalent of the keratometer reading. The authors themselves noted difficulties in correct positioning of reference points on the cornea and interpretation of the lines with regard to numerical topography; both arose from human error. Furthermore, they emphasized the difficulty of obtaining distortion free objectives and of accurately constructing the stereo camera so its major reference points coincided with those of the "restitutor", the device used to interpret the photographs. Clark(1973) also notes inconsistencies in Bonnet's work; Ryzyakowski(1954) emphasizes the dependence on human stereopsis in earlier stereogrammetry of the eye using hand-assisted reconstruction. Although this technique is of little value in accurately estimating corneal curvature, it could be used in the fitting of scleral lenses.

Theoretical:

When the cornea is considered as a curvilinear surface S, the sagittal depth s corresponds to the distance between the plane P normal to the surface gradient vector $\vec{N}$ at the apex A of the surface and the plane P' which is parallel to plane P and contains line C connecting the points p and p' located on S. The line C is often called the chord and the distance $\overline{p\,p'}$, the chordal width or chordal diameter.

When an incident ray of light R whose path is parallel to the vector $\vec{N}$ strikes a point on S (S is partially reflective) other than the apex it will be reflected at an angle (α) to N where $\alpha = 0$, as illustrated in Figure 1.

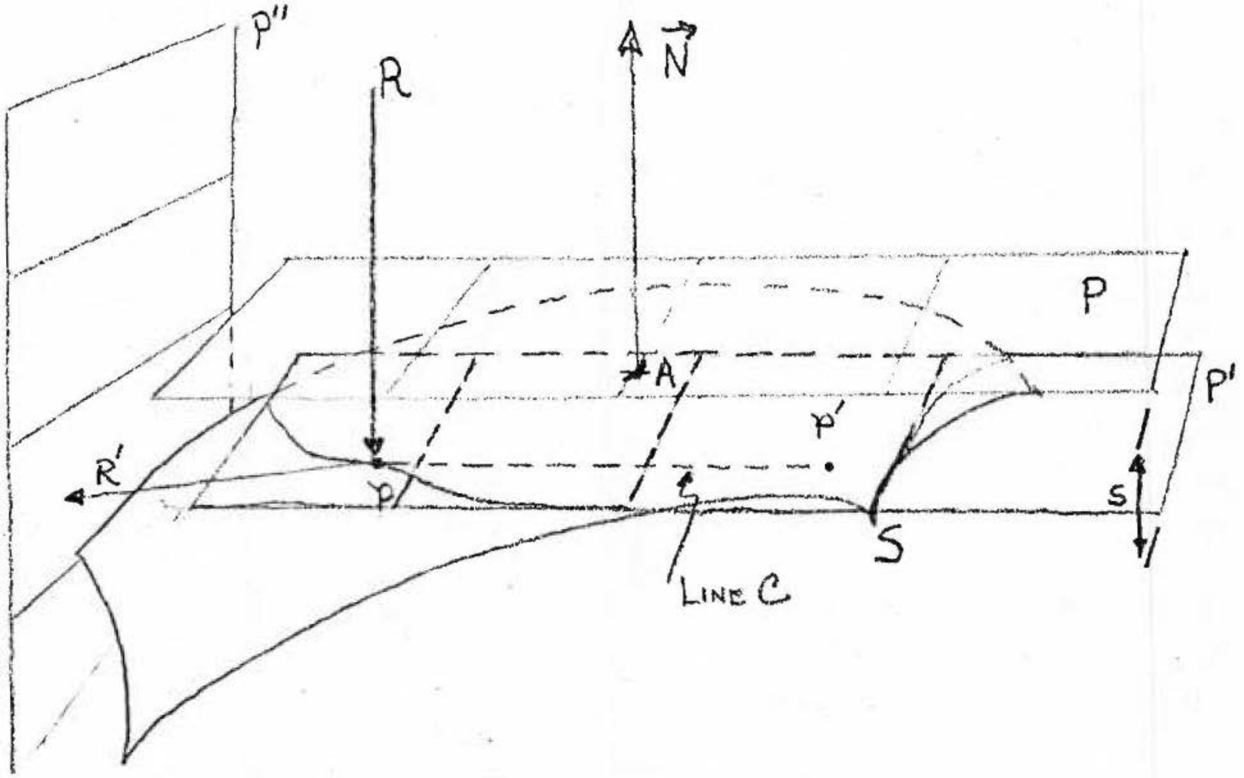

Figure 1. Relationship of the Principal Reference Planes to the Curvilinear Surface S.

A device capable of measuring light intensity (photodetector) is placed at the intersection of ray R' and a plane P" which is parallel to plane P and perpendicular to plane P'. P" is perpendicular to R' and R' intersects P" at point x, as illustrated in Figure 2.

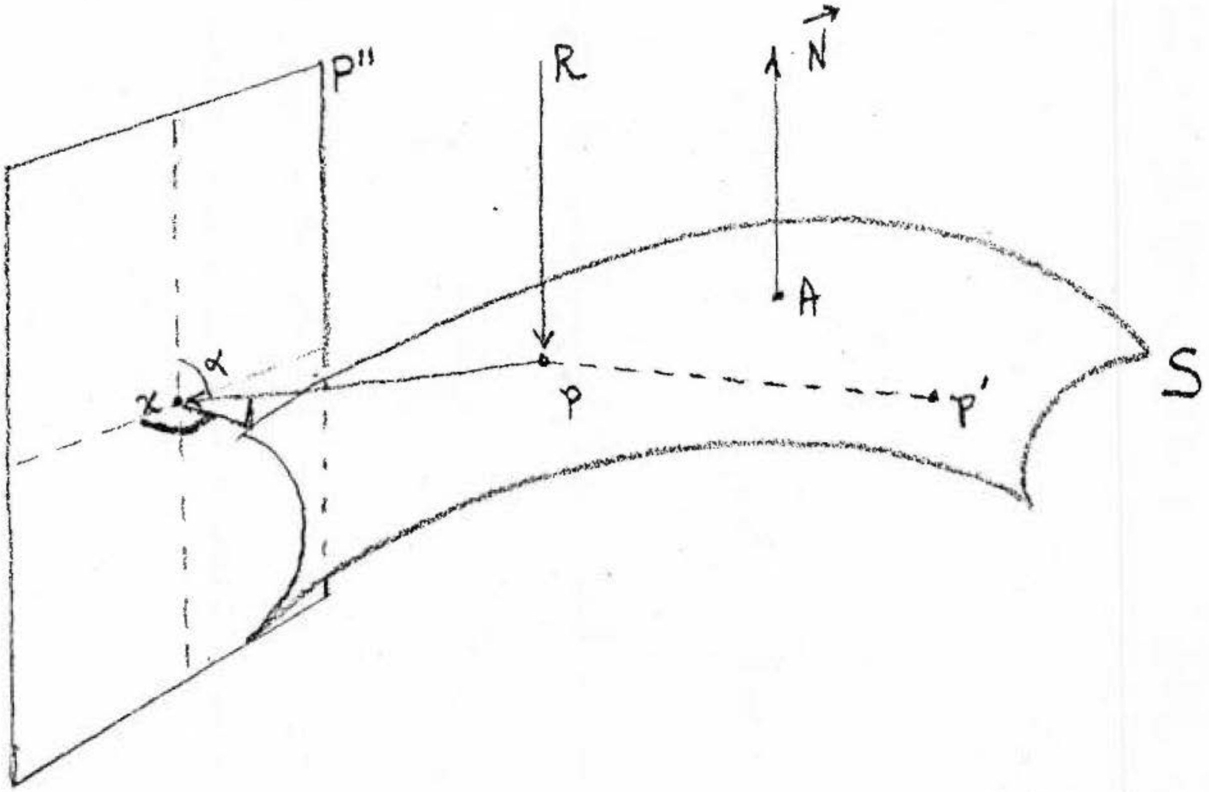

Figure 2 — Geometric Relationships of Incident and Reflected Rays and Surface S

When the ray R is reflected from the apex, R and R' will be coincident and a photodetector placed in the path of R' will measure light intensity as $I = I_0$.

From Figure 3, a is the shortest distance from p to P"; d is the distance along the vector $\vec{N}$ between the origin of R and apex A when R is coincident with $\vec{N}$. The distance between the point o on P" and point p is called a; c is the shortest distance between points o and x. When a line intersects plane P" at a distance above o equal to the sum of the distances d and s, the point of intersection is called point r; h is the distance between r and x.

The sagittal depth is computed as follows:

From the cosine law of illumination,

$$I = I_0 \sin \alpha \ .$$

Also, from Figure 3 and trigonometry,

$$a = c \tan \alpha \ .$$

Since a, h; and I are directly measureable variables,

$$c = a\ (\cot[\arcsin(\ I/I_0)]).$$

From Figure 3,

$$e = h - d$$

and

$s = c \quad (e = 0)$ when $d = h = a$, all a.

$s = e - c$ when $d < h < a$, $a > d$
and $d \leq h > a$, all a.

$s = c - e$ when $d > h \geq a$, $a < d$
and $d > h < a$, all a.

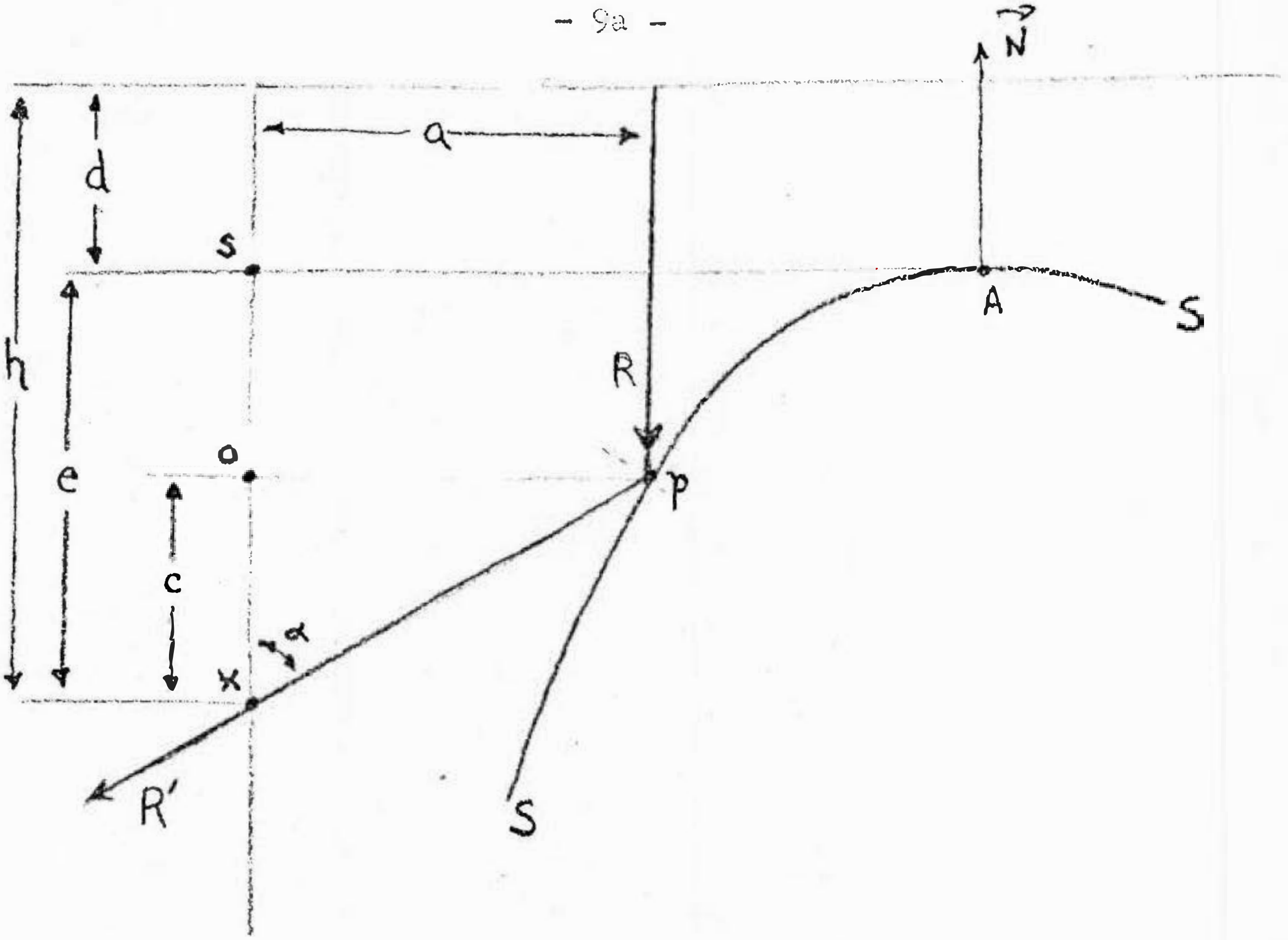

Figure 3. Cross-sectional View of the Reflected Ray in Relation to Important Variables.

Observations and Discussion:

This new method for estimating sagittal depth of a curvilinear surface can be used to measure the sagittal depth of the *in vivo* cornea. A matrix of photoemitters and photodetectors can be used in conjunction with a digital computer to produce a collimated beam of light whose origin and endpoint (x) can be measured directly; the computer is used to keep track of the position in the matrix corresponding to the emitter or detector. The smaller one makes the detectors, the higher the resolution one can achieve when measuring the exact position of the point x. The operator does not need to focus the instrument to obtain distance d -- the photoemitters whose beams are parallel to plane P will energize the emitters at the same height as the apex when the beams are no longer obstructed by the surface (when the paths of the beams are in plane P). All positional measurements are, therefore, made automatically and are independent of human error.

Listed below are advantages of this new method of measuring sagittal depth and charting the topology of the cornea:

(1) The sampling area is essentially a point of light whose dimensions are limited only by diffraction. The error due to linearization over a large area, as in the ophthalmometer, is made negligible.

(2) Because the scanning of the cornea is rapid due to the low risetime of the photoemitters and the speed

of the computer's circuits, the measurements are not affected by micronystagmus.

(3) Since there are no human operator - assisted functions, focusing of eyepieces, looking at targets and making alignment discriminations are a thing of the past and human error is eliminated.

(4) The true corneal topography can be charted since the data set is not fitted to a spherical model, as in the ophthalmometer, or a conic-section model, as in the PEK.

(5) The placement of the measuring device near the cornea need not be hindered by the orbital bones because the device can be made very small. This would make such an instrument ideal for evaluation of corneal contour immediately after ocular surgery.

(6) The sagittal depth is a parameter common to any curvilinear surface. Since it can be measured by the method described above and since this measuring technique may be extended to charting the surface of a contact lens, it is ideally suited for use in contact lens practice. Therapeutic lenses can be fit to damaged corneas because the measurement of the sagittal depth is not contingent upon a clear mire image. Thus, the progress of corneal ulceration and the development of keratoconus can both be recorded using this method.

The realization of this novel method has its limitation only in the construction of the emitter-detector matrix. Accuracy can only be achieved with high resolution; a small error in intensity measurement can lead to a large error in the final result; it is from intensity readings that the angle of incidence is derived. Furthermore, if the incident ray is reflected from a rough surface, the pattern of incidence will be very wide. A possible solution to the problem of the accurate location of point x is to use the computer to perform an averaging operation upon each data set for each reading to find the projection of R' to intersection with P", thereby locating x.

Conclusion:

A novel method for measuring the sagittal depth of a curvilinear surface has been presented and its application to measuring the sagittal depth of the cornea has been discussed. It has been shown that this method would reduce human error associated with such measurements; it is hoped the error would be negligible. Furthermore, applications in the ophthalmic practice have been discussed and it has been shown that this method would be useful in the fitting of contact lenses and the charting of diseases of the anterior corneal surface.

The technical realization of this idea is discussed and will be left to future investigators. Although construction of such an instrument would be inexpensive it would consume much time and effort.

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