Purpose. To study age-related changes in the refractive index distribution of the human ocular lens.

Methods. Biometric data collected on 48 eyes in subjects ranging in age from 19 to 31 years and 48 eyes in subjects ranging in age from 49 to 61 years allowed estimation of a single parameter related to the refractive index distribution of the crystalline lens. The authors selected a gradient index model of the lens characterized by a fixed index at the lens center, a somewhat lower fixed index at the surface, and a continuum of index values between center and surface depending on a single parameter, $\beta$. This parameter was evaluated for each of the two age groups.

Results. The distributions of the gradient index parameter $\beta$ for the two age groups were found to be statistically well separated. On average, the older group was found to have an index gradient that was flatter near the lens center and steeper near the surface, implying a lower refractive power of about 2 D for representative lens surface curvatures.

Conclusions. It has been observed that surface curvatures and thicknesses of the ocular lens increase with age, whereas other ocular dimensions apparently do not change, implying a trend toward myopia. This trend has not been observed. The authors' results are consistent with and strongly in support of the hypothesis that subtle index changes in the aging lens compensate to a large extent for changes in surface curvatures. Investig Ophthalmol Vis Sci. 1995; 36:703-707.

Measurements on extracted crystalline lenses of humans and animals demonstrate conclusively that the refractive index decreases significantly from the center of the lens to the surface. Thus, this gradient in refractive index must be taken into account if one is to understand thoroughly the optics of the crystalline lens. Although there is agreement on general characteristics of this index gradient, many questions remain concerning its details as well as its visual consequences.

We have investigated an interesting related question. What is the role of the index gradient in the changing optics of the aging crystalline lens? The lens grows throughout life. In adults, it becomes progressively thicker and acquires steeper surfaces. Because other dimensions of the eye change little with age, one naturally predicts an increase in lens power and a tendency toward myopia in the older eye. That this does not happen has sometimes been called the "lens paradox." How might this paradox be resolved? An hypothesis that the index gradient of the lens develops in such a way that lens power changes less with age than might be predicted based only on changes in surface curvatures has been put forward by Pierscionek. We have tested this hypothesis by taking measurements on 96 eyes divided into younger and older subgroups. Our data allow us to estimate the refractive index variation for each eye within a particular lens model. We find a significant difference in the variation of the lens index between the two age groups. This result is completely consistent with and provides strong support for the hypothesis.

METHODS

Two balanced age groups were selected to avoid overlap. The younger group ranged in age from 19 to 31 years; the older group ranged in age from 49 to 61 years.
years (mean, 22.1 years), and the older group ranged in age from 49 to 61 years (mean, 53.9 years). Within each group, a quota sampling technique was used to obtain a balanced proportion of subjects in the three refractive categories—those with myopia (equivalent sphere \( \leq -0.62 \) D), those with emmetropia (equivalent sphere between +0.87 D and -0.50 D), and those with hyperopia (equivalent sphere \( \geq +1.00 \) D). An equal number of male and female subjects was assigned to each refractive category to balance possible gender differences. Volunteers were recruited from the staff and student population of the University of Auckland and from the general public. Research followed the tenets of the Declaration of Helsinki, informed consent was obtained from each subject, and the protocol of this study was approved by the University of Auckland Human Subjects Ethics Committee.

For each subject, two initial measurements of refractive error were made using a precalibrated Humphrey Autorefractometer Model 530 (Humphrey Instruments, San Leandro, CA) in the auto-plus mode. The corneal radius of curvature in the vertical meridian was determined three times by means of the precalibrated Humphrey Autokeratometer Model 410. The ocular accommodation was paralyzed using two drops of 1% cyclopentolate hydrochloride, which also induced a mydriasis for the ophthalmome-try procedures. Three cycloplegic autorefraction measurements were made using the Humphrey Autorefractometer Model 530 in the auto-plus mode. The average spherocylindrical refractive error was then determined. The spherical equivalent refractive error was used for all calculations carried out in the following section.

The first, third, and fourth Purkinje images were recorded, and heights were measured using a video recording technique described elsewhere. The distance from the targets to the cornea was about 135 mm for measurements of the first and fourth Purkinje images and about 126 mm for the third. The angular separation of the two targets was about 5.9° and 6.3°, respectively. Also, the visual axis was approximately halfway between the targets and the camera, which were separated by about 20°. Although the light sources were not collimated, the calculations of equivalent mirror radii for the two surfaces of the crystalline lens took this into account.

The cornea was anesthetized with one drop of 1.0% proparacaine hydrochloride. Axial dimensions were measured with a Teknar (St. Louis, MO) Ophthasonic AB-scan III ultrasonometer.

We have used a biellipsoidal model of the crystalline lens, consisting of two semielipsoids with the circular equatorial section of the lens providing a common bounding surface. The major semiaxes of the two ellipsoids, given the symbol \( b_i \), are equal to each other and to the radius of the equatorial section. The minor semiaxes, given the symbols \( a_1 \) and \( a_2 \), are not equal in general. The sum of \( a_1 \) and \( a_2 \) is equal to the lens thickness, and the two vertex radii of curvature are given by \( b_1^2/a_1 \) and \( b_2^2/a_2 \). The three semiaxes of the biellipsoidal model are uniquely determined by specifying the anterior and posterior radii of curvature of the lens as well as its thickness. Therefore, the equatorial diameter of the lens, \( 2b \), is not an adjustable parameter and does not correspond to an anatomic dimension. We do not view this as a problem because the optical calculations to follow use the paraxial approximation and, therefore, involve lens geometry only in the immediate vicinity of the optical axis. It is further assumed that the iso-indicial surfaces of the lens are of the same form as the outer surface, i.e., ellipsoidal. It remains only to specify the mathematical form of the decline of index from the lens center to the surface. For this purpose, it is convenient to introduce a coordinate, \( r \), measured along a line from the lens center to the surface and normalized so that the value of \( r \) at the surface is unity. In our model, the dependence of the refractive index on this coordinate is given by:

\[
1.406 + (\beta - .02) r^2 - \beta r^4.
\]

The index at the center of the lens (\( r = 0 \)) is given by 1.406, and the index at the surface (\( r = 1 \)) is given by 1.406 - .02 = 1.386. These center and surface values are those of the Gullstrand no. 1 eye. Varying the parameter \( \beta \) changes the form of the index variation from the lens center to the surface without changing the end points. Some examples of this function are given in Figure 1, in which it is apparent that as
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....Varies... the index gradient becomes flatter in the central part of the lens and steeper in the outer part.

In principle, our data on each eye supply enough information to determine the index parameter \( \beta \). To do this, however, presents an algebraic problem. From the size of the fourth Purkinje image, one knows the radius, \( R_3 \), of the equivalent mirror associated with the posterior surface of the lens. However, the actual radius of curvature of the posterior lens surface, \( R_3 \), depends on the index gradient of the lens, i.e., it depends on the parameter \( \beta \) in our model. The problem then is to find values of \( \beta \) and \( R_3 \) that yield the known radius of the equivalent mirror. Similarly, the distance, \( z \), from the anterior cornea to the image of a distant object is known from ultrasound measurements and from the refractive error. Again, one must find values of \( \beta \) and \( R_3 \) that yield the correct image position. Thus, one has two conditions and two unknowns related by highly nonlinear equations. The approach used here is to assume that for the relatively small variations in parameters from eye to eye, the changes in these quantities are linearly related. Expanding a function \( f(x,y) \) of two variables in a Taylor series about the values \( x_0, y_0 \), keeping only linear terms, gives

\[
f(x,y) - f(x_0,y_0) = \frac{\partial f}{\partial x}(x-x_0) + \frac{\partial f}{\partial y}(y-y_0).
\]

The partial derivatives are to be evaluated at the point \( x_0, y_0 \). Let \( \beta_0 \), \( R_{30} \), \( R_{40} \), and \( z_0 \) be a typical set of values of parameters that are related through the exact equations for a particular eye. We then assume that for small changes in one or more of these quantities,

\[
a_{11}(\beta - \beta_0) + a_{12}(R_3 - R_{30}) = R_4 - R_{40}
\]

\[
a_{21}(\beta - \beta_0) + a_{22}(R_3 - R_{30}) = z - z_0.
\]

The coefficients, \( a_{ij} \), in these equations are therefore partial derivatives of \( R_4 \) or \( z \) with respect to \( \beta \) or \( R_3 \). They were determined by several exact calculations for a particular eye using the ray-tracing method of Sharma et al. The coefficients \( a_{11} \) and \( a_{21} \) were found by recording changes in \( R_3 \) and \( z \) due to changes in \( \beta \) while holding \( R_4 \) constant. Similarly, \( a_{12} \) and \( a_{22} \) were found by varying \( R_4 \). The resultant coefficients are assumed to have the same values for all eyes in the study. Thus, for example, we have assumed that the change in \( R_4 \) due to a small change in \( \beta \) is independent of the small variation in parameters from eye to eye. The problem reduces therefore to specifying convenient starting values for \( \beta_0 \) and \( R_{30} \), then finding the corresponding quantities \( R_{40} \) and \( z_0 \) for each eye by ray tracing. These will, of course, not be in agreement with the experimentally determined values, \( R_4 \) and \( z \). Substitution of these six quantities into the linear equations gives "correct" values for \( \beta \) and \( R_3 \). Our assumptions were justified by substituting calculated values for \( \beta \) and \( R_3 \) back into the exact relationships, verifying that the experimentally determined values for \( R_4 \) and \( z \) resulted. If necessary, the above equations can be iterated. We found satisfactory accuracy with a single application of these equations. The coefficient values used by us were \( a_{11} = 0.798 \), \( a_{21} = 40.925 \), \( a_{12} = 0.714 \), and \( a_{22} = 0.427 \).

**RESULTS**

The gradient index parameter \( \beta \) has been calculated as described above from measurements made on a group of 48 younger eyes and on a group of 48 older eyes. The resultant two distributions of this parameter are shown in Figure 2. Visually, the two distributions are well separated. This impression is strengthened by applying a t-test that rejects the hypothesis that the means are equal at the .001 level. Notice that the mean value of \( \beta \) for the older subjects is more positive than that for the younger subjects so that the corresponding index gradient for the older subjects is steeper in the outer lens than that for the younger subjects (Fig. 1). A steeper index gradient under the conditions of this model (fixed indices at the lens center and at the lens surface) implies a refractive power less than that for the same lens with a less steep gradient. The magnitude of this effect has been estimated by calculating lens power for typical lens dimensions and for the values of \( \beta \) corresponding to the mean values for the older subjects (\( \beta = +0.078 \pm 0.007 \)) and for the younger (\( \beta = -0.003 \pm 0.009 \)). We find a difference in lens power of between 1.5 to

![Figure 2. Distributions of values of the parameter \( \beta \) for 48 subjects in the younger group (filled bars) and for 48 subjects in the older group (unfilled bars). The mean value of \( \beta \) for the older group (mean = +.0078) is larger than that for the younger group (mean = -.0053), implying a steeper index gradient, on average, for the older group.](image-url)
Anterior lens radius (mm)
Vitreous chamber depth (mm)
Anterior chamber depth (mm)
Total axial length (mm)

groups. Our results are entirely consistent with and variation of the lens index gradient between two age groups. Statistical analysis of the data has been refractive index in the lens to differ between the two age groups. She proposed that changes in the lens gradient index. The notion that aging eye toward myopia could be resolved with subtle surface curvatures and index gradient of the lens changes in the lens gradient index. The hypothesis that axial length decreases with age, thus maintaining a nearly constant refractive error, is clearly of interest.

Our data confirm the existence of a lens paradox that is then resolved by allowing the distribution of refractive index in the lens to differ between the two age groups. Statistical analysis of the data has been performed elsewhere. The results appear in Table 1. Thus, it is shown that there are no significant differences in axial length (mean axial lengths 23.52 mm and 23.42 mm) or corneal curvature (mean corneal radii of curvature 7.78 mm and 7.77 mm) between the younger and older groups. Specifically, the hypothesis that axial length decreases with age, thus compensating for increased lens power, is not supported by these data. However, the older group does show a significantly larger mean lens power of approximately 2 D if one assumes the same refractive index distribution for the two groups. An age-dependent refractive index distribution is the only apparent plausible resolution.

How model dependent are our results? The existence of a gradient in the refractive index of the crystalline lens is firmly established. Although there may be agreement on broad features of this gradient, the details remain uncertain. We could easily have tried any number of gradient index models for use in this study. However, we think that whatever model we might have used would have led to much the same result, i.e., significantly different refractive index distributions in the two age groups.

Each of the data used in this study is, of course, subject to error. Zadnik et al., for example, have made a thorough study of repeatability errors for the biometric measurements used by us. We argue that because of the balance in selection of subjects in the younger and older groups, the data for each group are subject to the same errors. If so, our result that the distributions of the parameter β for younger and older subjects are separate is unaffected.

It is likely that a better understanding of the visual consequences of the gradient index will follow only from in vivo studies of the aberrations of the crystalline lens. This might be accomplished, for example, by measuring the aberrations of the eye, then optically removing the effects of the cornea. Recent developments in devices for measuring aberrations of the eye, as well as corneal topography, seem to make such an approach feasible.

**Key Words**
crystalline lens, gradient index, aging changes, refractive power

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2 D, depending on the lens dimensions, with the more positive value for β (steeper gradient) having the smaller power.

**DISCUSSION**

From our measurements and for a particular lens model, we have found a significant difference in the variation of the lens index gradient between two age groups. Our results are entirely consistent with and strongly in support of the hypothesis of Pierricenek and its elaboration by Smith et al. She proposed that the apparent contradiction between increasing lens surface curvatures and the failure of a tendency of the aging eye toward myopia could be resolved with subtle surface curvatures and index gradient of the lens changes in the lens gradient index. The notion that aging eye toward myopia could be resolved with subtle surface curvatures and index gradient of the lens changes in the lens gradient index. The hypothesis that axial length decreases with age, thus maintaining a nearly constant refractive error, is clearly of interest.

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