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Biometric, optical and physical changes in the isolated human crystalline lens with age in relation to presbyopia

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Abstract

The biometric, optical and physical properties of 19 pairs of isolated human eye-bank lenses ranging in age from 5 to 96 years were compared. Lens focal length and spherical aberration were measured using a scanning laser apparatus, lens thickness and the lens surface curvatures were measured by digitizing the lens profiles and equivalent refractive indices were calculated for each lens using this data. The second lens from each donor was used to measure resistance to physical deformation by providing a compressive force to the lens. The lens capsule was then removed from each lens and each measurement was repeated to ascertain what role the capsule plays in determining these optical and physical characteristics. Age dependent changes in lens focal length, lens surface curvatures and lens resistance to physical deformation are described. Isolated lens focal length was found to be significantly linearly correlated with both the anterior and posterior surface curvatures. No age dependent change in equivalent refractive index of the isolated lens was found. Although decapsulating human lenses causes similar changes in focal length to that which we have shown to occur when human lenses are mechanically stretched into an unaccommodated state, the effects are due to nonsystematic changes in lens curvatures. These studies reinforce the conclusion that lens hardening must be considered as an important factor in the development of presbyopia, that age changes in the human lens are not limited to the loss of accommodation that characterizes presbyopia but that the lens optical and physical properties change substantially with age in a complex manner. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Age changes in the biometric (e.g. weight, cross-sectional area), optical (e.g. focal length, spherical aberration) and physical properties (e.g. lens thickness, curvatures, hardness) of the human lens are frequently invoked to explain the progression of presbyopia. These include changes in mass, volume, shape, surface curvatures, refractive index distribution, elasticity and hardness of the lens. Given the prevalence of presbyopia, the impact on society and the abundant and disparate theories of its causes, surprisingly few studies have made optical or physical measurements of human lenses to understand the lenticular contribution to presbyopia. Fewer studies include both optical and physical measurements on the same group of human lenses. If the etiology and the causes of presbyopia are to be understood and attempts are to be made to slow its progression or reverse its effects, an essential basic requirement is a comprehensive understanding of the aging of the optical and physical properties of the human lens and an understanding of how these factors may interact during the aging process to contribute to presbyopia.

The lens optical and physical properties are closely related. The crystalline lens focal length and spherical aberration are profoundly influenced by the lens surface curvatures and gradient refractive index. Lens thickness and curvatures change during accommodation with resulting changes in lens power and spherical aberration (Glasser & Campbell, 1998). The substance of the young lens has been described as plastic (Fincham, 1937), purely elastic (Fisher, 1971) or viscoelastic (Beers & Van der Heijde, 1994, 1996) with the lens capsule

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serving to mould and alter the shape of the lens during accommodation and relaxation of accommodation. The properties of the lens substance and the role of the capsule are thus integral to the normal optical function of the crystalline lens. Only a few studies have attempted experiments to determine the nature of the interaction between the lens substance and capsule (Fincham, 1937; Fisher, 1969a,b, 1971, 1973); others have speculated on the interaction (Wyatt & Fisher, 1995). The mechanical properties of either the lens substance (human: Pau & Kranz, 1991; cat, rabbit and dog: Kikkawa & Sato, 1963; Ejiri, Thompson & O'Neill, 1969) or the human lens capsule (Krag, Olsen & Andreassen, 1997) have also been studied in isolation. No studies to date have undertaken systematic experiments to determine the optical and functional relationship between the capsule and the lens substance despite their obvious interdependence. Further, it is generally assumed that the capsule serves to mould the young lens into an accommodated form when the zonular forces are removed and that when the capsule is removed the lens takes on an unaccommodated form (Fincham, 1937). Remarkably, these theories are supported with evidence from only one monkey lens (Fincham, 1937) and one human lens (Fisher, 1969a). Not only are these two data points cited frequently, but complex hypotheses have been formulated based on this sparse data (Wyatt & Fisher, 1995). A comprehensive study exploring the relationships between the lens optical and physical properties and the role of the capsule is thus long overdue.

Age changes in the optical properties of the lens have been measured in a variety of cross sectional studies. Sorsby, Benjamin and Sheridan (1961) measured age changes in the eyes of subjects 3–15 years of age. Refractive error measurements, slit-lamp measurements of lens thickness and lens curvatures (to compute axial lengths) were used in conjunction with an age independent equivalent refractive index of the lens. A decrease in hyperopia towards emmetropia with a concurrent increase in axial length, anterior chamber depth and a decrease in lens power was reported for some 1500 subjects, but subsequent follow-up showed considerable individual variation in this generalized pattern (Sorsby et al., 1961). The changes in lens thickness, anterior chamber depth and axial length are essentially in agreement with subsequent ultrasound measurements (Larsen, 1971a,b,c; Zadnik, Mutti, Fusaro & Adams, 1995). Purkinje image photography of infants 3–18 months of age showed a decrease in the calculated equivalent refractive index and power of the lens over this age range (Wood, Mutti & Zadnik, 1996). Brown (1974) showed a decrease in both anterior and posterior lens radii of curvature with age in subjects aged 3–82 years using slit-lamp Scheimpflug photography. Koretz, Kaufman, Neider and Goeckner (1989) showed an increase in the thickness of the unaccommodated lens using ultrasound and Scheimpflug photography in subjects ages 18–70 years. The accuracy of the optical techniques of Purkinje image and Scheimpflug photography are limited by the fact that the calculations of anterior lens surface curvature must be made through the optics of the anterior segment of the eye and in addition the posterior lens surface curvature must be made through the unknown gradient refractive index of the lens itself. While corneal curvature and anterior chamber depth can be measured with some accuracy, age changes in corneal curvature (Saunders, 1982) and the asphericity of the peripheral cornea also represent sources of error for both anterior and posterior lens surface measurements such as those made by Brown (1974).

The anterior and to a lesser extent the posterior lens radii of curvatures are reported to decrease with age (Brown, 1974). Without other changes in the eye this would cause an increase in power of the lens with age resulting in myopia, yet presbyopia actually results in a loss of near vision rather than a loss of distance vision. This has led to the conception of the lens paradox (Koretz & Handelman, 1986, 1988) which has been resolved in theory by the suggestion that the refractive index gradient of the lens changes with age (Koretz & Handelman, 1988; Pierscionek, 1990, 1993a). This change is thought to compensate for increased lens surface curvatures to maintain lens power and emmetropia with age (Koretz & Handelman, 1988; Smith, Atchison & Pierscionek, 1992; Hemenger, Garner & Ooi, 1995; Ooi & Grosvenor, 1995). While studies have shown the theoretical feasibility of age changes in the gradient refractive index of the lens (Smith et al., 1992; Heminger et al., 1995), no empirical studies have shown an actual compensation between surface curvatures and the gradient refractive index of the human lens. This is in part due to the substantial theoretical and practical complexities involved in accurately determining the gradient refractive index distribution of the human crystalline lens. Direct measurements of the refractive index gradient in the human lens along the optical axis, close to the axis most relevant to vision, using an invasive optic fiber sensor have not shown significant age dependent changes (Pierscionek, 1997). Since lens surface curvatures were not measured, no relationships or compensation of curvatures and refractive index were identified (Pierscionek, 1997). Further, accommodative changes that occur when young human lenses are isolated make in vivo and in vitro comparisons difficult. A basic and concrete empirical knowledge of age changes in the lens is an essential first step towards modeling the human lens since the true value of theoretical work is realized only when the theoretical results and the empirical measurements can be shown to agree. This is equally important for schematic eye