A SIMPLE VIEW OF AGE-RELATED CHANGES IN THE SHAPE OF THE LENS OF THE HUMAN EYE

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SUMMARY

Data describing the radius of curvature of the anterior surface of the human lens have been re-examined for (i) far-accommodated lenses and (ii) near-accommodated or excised lenses. It is found that, with increasing age, the curvatures converge to an intermediate value. Taking this together with the body of work on the mechanics of accommodative lens changes, a perspective is suggested which affords a simple view of curvature changes with age. The only datum in the literature is found to fit reasonably well with this perspective.

The detailed causes of the loss of accommodative amplitude with age (presbyopia) are not universally agreed upon. Among the possible causes which have been dealt with seriously at one time or another are increased stiffness of the lens substance,[1-3] decreased stiffness of the lens capsule,[4] decreased effectiveness of the ciliary muscle,[5-7] increased stiffness of the choroid,[8,9] and the changing geometric relationship between lens, zonular apparatus, and other components of the accommodative system.[2,4,10-12] (Weale[13] has recently reviewed the topic.) Here a number observations of the shape of the lens, in near- and far-accommodated states, are re-examined and a simple hypothetical framework for presbyopia is suggested, which appears to unite many of these observations.

It is generally agreed that the anterior lens surface shows the greatest changes in power during accommodation.[14] Fig. 1 shows a number of measurements of the curvature of the anterior lens surface at various ages.[3-5,15-18] The filled symbols represent measurements of far-accommodated lenses *in situ*, while the open symbols represent measurements of maximally near-accommodated lenses *in situ* (diamonds) or of excised lenses (squares, circles, inverted triangles, triangle). (It is generally accepted that the excised lens has approximately the same shape as the maximally near-accommodated lens *in situ*, the latter being acted on by minimal zonular forces.[19]) The data for far-accommodated eyes were fitted with a linear regression (continuous line, $r = 0.69$; only slight increases in correlation were obtained by fitting polynomials of orders 2–4.) The data for near-accommodated eyes or excised lenses were fitted with a two-branch curve (dashed line) – linear for ages less than 65 years, and a polynomial for ages above 65 years. (The data from Howcroft and Parker[18] were weighted according to the number of pairs of eyes in each of their average values.) This entire set of data could have been fitted with a linear regression; however, there appeared to be a change in behaviour at about 65 years. The exact form of curve used to fit the data does not materially affect our central suggestion.

Fig. 1 leads to a possible simplified view of the changes with age in the shape of the lens. In its most simple form, this view requires three assumptions or hypotheses: first, it is assumed that the lens does not change substantially in size with age between the ages of, say, adolescence and 65 years. (This is an oversimplification to simplify initial presentation; the effects of relaxing the assumption are discussed later.) Secondly, and centrally, it is hypothesised that the anterior surface of the *isolated lens substance* (i.e. without the capsule) has a constant radius of curvature of approximately 10–11.5 mm over this age range. Thirdly, it is assumed – as Fisher's results[11,20] have suggested – that the effect of the capsule in the near-accommodated state is primarily to exert an equatorial squeeze on the lens substance, while the effect of the zonular forces on the capsule in the far-accommodated state is to remove this squeeze and, in addition, to exert a flattening force (via the capsule) at the front of the lens substance. These

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Eye (1995) 9, 772–775

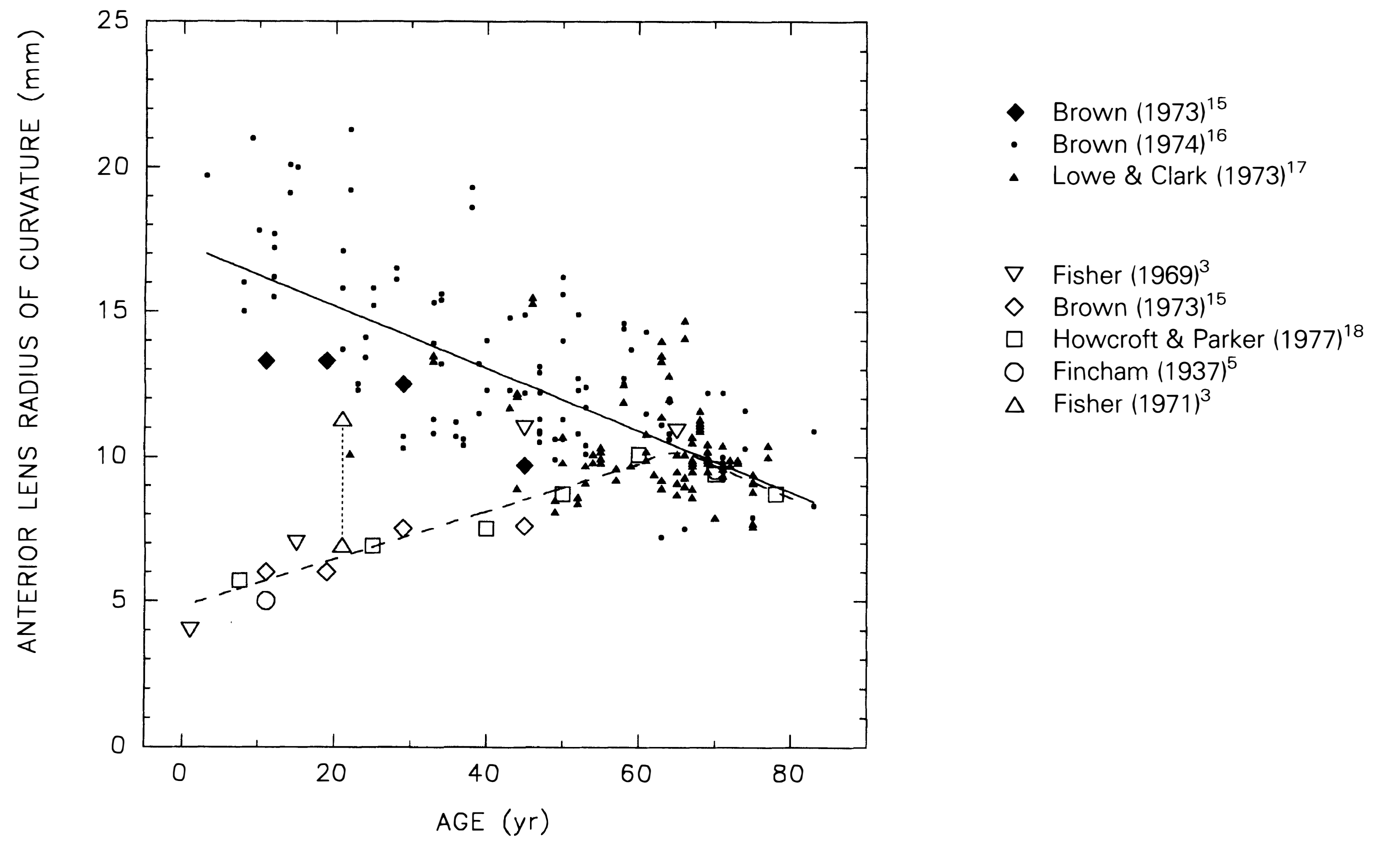

Fig. 1. *Radii of curvature of the anterior lens surface at various ages. Filled symbols show data for the far-accommodated lens of the living eye; open symbols show data for the maximally near-accommodated lens of the living eye (diamonds) or the excised lens (other symbols). The two triangles connected by a dashed line are measurements from Fisher[3] of the excised lens intact (lower triangle) and after the capsule was cut (upper triangle). See text for further details.*

forces are indicated diagrammatically in Fig. 2. (The curvature of the posterior lens surface changes considerably less than that of the anterior surface, very probably due to the substantially thinner posterior lens capsule being less capable of exerting this extra flattening force on the lens substance.[5]) At this point, it is only necessary to add in the effects of Fisher's findings that, with increasing age, lens substance stiffness increases,[3] and lens capsule stiffness decreases.[4] The consequence of these changes is clearly that both near- and far-accommodated lens shapes should approach the shape of the isolated substance: in the near-accommodated state, the weaker capsular forces (provided by the capsule itself in the near-absence of zonular forces) provide progressively less equatorial squeeze to modify the shape of the stiffer substance; in the far-accommodated state, the zonular forces transmitted by the capsule are progressively reduced in their ability to flatten the anterior surface of the stiffer substance.

Few data are available to test this hypothesis. Fincham[5] showed a decapsulated monkey lens which had a considerably flatter anterior surface than the excised intact lens. Fisher (fig. 10 of reference 3) recorded the shape of a 21-year-old excised lens, with and without the capsule. These diagrams were enlarged, digitised, and the central 4 mm of the anterior surface was described by a circle using a least-squares fitting technique. (This is an average fit over the 4 mm, and closely approximates the shape for the intact lens; for the decapsulated lens, the central 1 mm in Fisher[3] is flatter and the surrounding 1.5 mm wide annulus somewhat more curved.) The results appear in Fig. 1 as two triangles connected with a dashed line. The excised intact lens (lower triangle) falls along the average curve, while the curvature of the decapsulated lens is approximately the same as the level to which both curves converge as age approaches 65 years. Thus, these limited data support the notion that the convergence of average lens curvatures with age up to age 65 is equivalent to an asymptotic approach to the intrinsic curvature of the increasingly stiff lens substance. From this perspective, the shape of the ageing lens may be viewed as the emergence of the intrinsic shape of the lens substance when the 'veiling' influences of the zonular and capsular forces are weakened by age.

The data of Brown,[15] also analysed by Koretz *et al.*,[21] indicate that the accommodative change of the anterior lens surface is associated primarily with a change of form of the anterior portion of the lens nucleus. (These authors note that, during accommodation, the nuclear region 'bows' forward in the non-presbyopic eye, while the thickness of the cortical layers remains essentially unchanged.) It is plausible, therefore, that changes in the nucleus underlie the decreasing compliance of the lens substance. There are few data on this point (or, for that matter, on the larger issue of why the lens as a whole becomes stiffer with age). On the basis of a computational model for anisotropic elasticity of the lens substance as a whole, Fisher[3] suggested that substantial increases in nucleus stiffness occur relatively late (starting around age 35 years), while in the cortex they occur continuously throughout the first several decades. However, there has been no direct determination of elastic properties of different portions of the lens. Fisher and Pettet[22] found that the ease with which water was initially removed, by drying, from samples of the lens nucleus correlated significantly with the deformability of the intact lenses. (Total water content appears either not to change much with age,[22,23] or to decline slightly with age[24] (not significantly for cortex, and at about 0.072% of total mass per year for 'intermediate' layers and nucleus). Lahm *et al.*[24] observed a decline in freezable water in all parts of the lens in the order of 0.2% of total water content per year. While declining free water content may well be involved, the cause and location of the elasticity changes related to prebyopia remain to be determined.

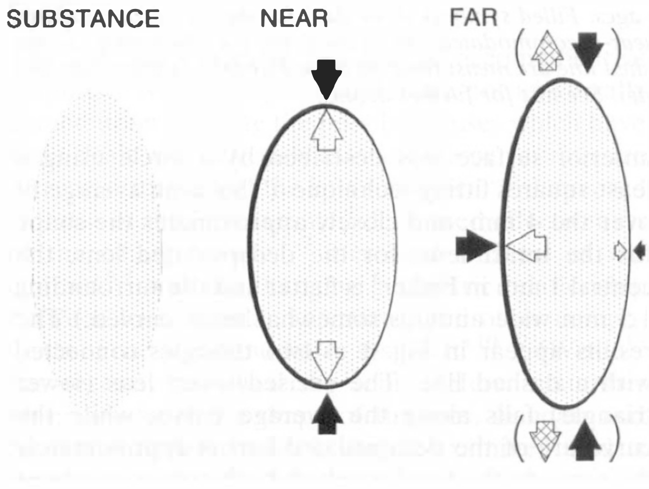

Fig. 2. *Diagram of the forces involved in accommodation in a non-presbyopic eye. The substance alone (left) has a flatter profile than the near-accommodated lens, but the anterior surface is more curved than the far-accommodated lens. The intact excised lens (centre, essentially the same as the maximally near-accommodated lens) has a shape different from the near-accommodated lens largely due to the equatorial squeeze exerted by the capsule. (This is indicated by an inward capsular force balanced by an outward elastic force exerted by the lens substance.) In the far-accommodated state, the equatorial squeeze is removed by zonular tension near the equator (shown as balanced outward zonular forces and inward capsular forces in parentheses, and the absence of an equatorial elastic lens substance force), and in addition an inward flattening force is exerted on the anterior surface by the capsule. (This is shown by balanced inward force and outward lens substance force; a similar pair of forces, but of considerably smaller magnitude, is shown for the posterior surface.)*

In developing the present general perspective, we neglected lens growth in the interval from adolescence to age 65 years. In this interval, the diameter of the lens increases in the range of 12%[25] to about 8% (data collected in fig. 4.14 of Weale[26]). In the same interval, the antero-posterior thickness increases in the range of 28% (data collected in fig. 4.13 of Weale[26]) to 44% (data collected in fig. 12 of Worgul[27]). The mass increases in the range of 25%[25] to 50% (data collected in fig. 4.12 of Weale[26]). Since the volume (and hence the mass, because water content remains fairly constant as noted above) presumably varies approximately as (diameter^2 × thickness), the smaller changes in dimensions seem more likely, because $1.08^2 \times 1.28 \approx 1.5$; i.e. the smaller values for the dimension changes roughly correspond to the larger values for the mass change.

It seems reasonable to assume that the shape of the isolated lens at age 65 years approximates the intrinsic shape of the lens substance at that age, the capsular forces then being weak relative to the substance elasticity. (This is supported by the convergence of the far and near curves in Fig. 1 at this age.) If one supposes that the isolated lens substances scales up uniformly by about 11.5% in linear dimension over this period, this would constitute a 50% increase in volume. In fact, the one datum point in Fig. 1 (upper triangle) lies somewhat above what would be predicted by this simplified introduction of the growth data into the proposal: instead of having a 10% smaller radius of curvature than the radius to which the far and near curves converge (as would be expected for 11.5% uniform scaling up in the interval), it has about a 10% larger radius. This could be the result of individual variation – clearly, more data points are needed – or it could be that the intrinsic shape of the lens substance gradually becomes more curved with age. There is modest support for the latter suggestion: First, visible markings in the deeper portions of the lens show increasing curvature with age.[21] Secondly, the data of Fig. 1 suggest that *above* age 65 years there is a decrease in the radius of curvature, at a time when the far and near curves are the same, and there is no accommodative amplitude. It is hard to avoid the conclusion that the intrinsic shape of the lens substance becomes more curved at this late stage, and therefore it is plausible that there is a more gradual increase in curvature of the intrinsic shape at younger ages – such a gradual curve might well pass through the single datum point.

It is worth noting that other proposed causes of presbyopia, such as geometric factors, can fit comfortably within the framework suggested here, since any factor which reduces the ability of the capsule to mould the lens substance will contribute to the 'emergence' of the intrinsic shape of the substance.

Finally, if, as proposed here, the intrinsic shape of the lens substance does not change much with age, then the refractive state which an individual is destined to reach in their presbyopic years (excepting the possibility of environmentally related elongation of the eyeball) could be predetermined – in fact, in a sense, could be *present* though not observed – at an early age.

Supported by the Schnurmacher Institute for Vision Research of SUNY. Proprietary interest: none.

Key words: Accommodation, Curvature, Elasticity, Lens, Presbyopia.

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