THE AGING EYE AND CONTACT LENSES – A REVIEW OF OCULAR CHARACTERISTICS

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(Received 18th March 1991, in revised form 20th May 1991)

Abstract — Most contact lens practitioners are dealing with an increasing number of otherwise healthy ‘older’ (presbyopic) patients. Examination of the literature indicates a persistent theme of age-related change, which generally becomes significant after the fourth decade. This review documents changes that are reported in the ocular adnexa, tear film, cornea, pupil, intraocular pressure, refractive state, spectral transmission, and chromatic aberration. The effects of these various changes on the fitting and wear of contact lenses by older patients are discussed.

KEY WORDS: Age, aging, review, tear film, cornea, pupil, ocular media, spectral transmission, chromatic aberration, intraocular pressure.

Introduction

The nature of contact lens fitting is likely to alter slowly as population demographics in all the western nations indicate a trend towards an aging population. This change to the classical population pyramid is enhanced by the post-war ‘baby boomers’, who are now entering the presbyopic age bracket. In addition, many of the patients fitted with contact lenses since their introduction are now entering this group and expecting a contact lens correction of their presbyopic visual problem.

Ocular changes that are acknowledged to occur with age and that may influence contact lens wear include decreased tonus of both upper1,2, and lower eyelids3, a reduced palpebral aperture4,5, decreased lacrimal secretion6,7, reduced tear stability8,9 changes to the cornea and ocular media, decreased pupil diameter4,10,11, and the effects of the increased intake of systemic drugs.12,13 Weale14,15 has given a very comprehensive review of ocular age-related changes. Aspects of such changes to ocular characteristics with regard to lens wear are discussed in this article. Visual performance changes with age include the decrease in visual acuity16 (which is greater under reduced levels of illumination17), the reduction in contrast sensitivity for high and intermediate spatial frequencies18–20, reduced stereoaucity21,22, and increased glare sensitivity23,24. All of these factors are of importance when fitting contact lenses to the aging eye. Physiological considerations may be different and visual performance generally reduced. Particular care must then be taken with contact lens modalities that compromise aspects of vision, for example, monovision and bifocal contact lenses.

The older contact lens patient can present special problems to the practitioner, in addition to presbyopia. Older patients may require fitting of aphakic or therapeutic contact lenses. This will often involve the use of extended-wear contact lenses, as older patients will often experience handling difficulties. Most advanced contact lens texts provide information about non-routine contact lens fitting requirements for older patients. Phillips25, for example, has produced a useful review.

Interest in bifocal contact lenses is increasing within the industry and the optical professions, and amongst the general public as they become aware of the option through the general and optical media. Contact lens companies are developing and publicising hydrophilic versions of the rigid bifocal contact lenses, as used by a limited number of experienced practitioners for many years, and new diffractive bifocal contact lenses are becoming available. Further development of bifocal contact lenses, the marketing capabilities of the large companies, and increased acceptance of contact lenses as a potential modality may lead to an increase in the number of presbyopes fitted with contact lenses. Despite this enormous potential market, surveys of contact lens fitting patterns26–28 indicate that only 1% of contact lens patients are fitted with bifocal lenses. A slightly larger group are fitted with the alternative presbyopic contact lens option (monovision), the most successful system29, but considered by many practitioners to be unsatisfactory due to its deleterious effects upon binocular vision.30–31

The proportion of contact lens patients who are presbyopic and the proportion of presbyopes who wear contact lenses are uncertain, but are generally assumed to be small. Despite this, as mentioned above, practitioners are likely to encounter an increasing number and proportion of presbyopic contact lens patients. With this in mind, some of the special ocular problems that may influence contact lens fitting and wear are reviewed herein.

Ocular Adnexa

There are marked alterations with age to the tissues of the ocular adnexa, due to a ‘progressive loss of tone and bulk’.32 Changes with age to the eyelids, including a loss of tonus, reduced movement, and the reduction...
in palpebral aperture (often referred to as senile ptosis or involutional blepharoptosis), are of interest to the contact lens practitioner dealing with a more elderly population group.

The vertical palpebral aperture was found by Loewenfeld to increase in size for the first three decades of life to an average of 10mm, and thereafter decrease slightly with age to an average of 9mm by the age of 80 years, as shown in Figure 1. The degree of ptosis, as assessed by the position of the upper lid in relation to the iris, increases after the third or fourth decade of life, and is greater in males. Sanke concluded that senile ptosis is 'a cumulative process occurring throughout life and only becoming obvious in later years.' The lower lid, as assessed by the same method by Shore, was also reported to rest against the globe in a position inferior to that of younger subjects. The increase in palpebral aperture during the first three decades of life may then be explained by normal growth, followed by progressive ptosis with increasing age after the third or fourth decade. The lower positioning in relation to the globe of the upper lid must occur at a slightly greater height on upward, primary, and downgaze, as opposed to other studies.

Senile changes to the palpebral aperture have been described by Hill. The shape of the aperture was demonstrated to alter, in particular a medial drift of the lateral canthus and a shortening of the horizontal length. Comparison showed neither enophthalmos, as described elsewhere, nor changes in the palpebral aperture height on upward, primary, and downgaze, as opposed to other studies.

Lid tension also decreases with age. A definite age-related increase in tissue laxity was demonstrated by Hill and Shore with the 'distraction' test, where the lower lid is drawn away from the globe. Vihlen and Wilson used a tensiometer to measure the elastic coefficient of the upper lid and demonstrated a decrease in lid tension after the sixth decade, as shown in Figure 2. Reduced lid tension may allow the lids to ride over a rigid contact lens more easily, reducing sensitivity, but may also lead to difficulty in removal of rigid contact lenses by some older patients. Phillips suggests the use of both hands, with pressure applied vertically to both lid margins, for the removal of rigid lenses by older patients. In addition, the loss of tonus can occasionally cause difficulty in everting the upper lid when checking for changes to the palpebral conjunctiva. The incidence of lid anomalies, such as ectropion, entropion, and trichiasis, increases with age. In such cases, a soft contact lens may be fitted as a therapeutic device to protect the cornea from abrasion and dessication.

Movement of the lower lid on alteration of gaze decreases with age. Hill noted that the retraction of the lower lid on vertical alteration of gaze was far greater in the younger group (<50 years old). Shore reported an apparently linear decrease in lower lid movement with age, from approximately 7mm at age 20 years to approximately 3mm at age 90 years. Significant to those attempting to fit alternating bifocal contact lenses, Borish and Perrigin measured pupil size, position, and movement of the lower lid on downgaze and concluded that, for the majority of their 107 subjects, the displacement of a bifocal contact lens would be insufficient for satisfactory near vision.

Changes in conjunctival oxygen tension and temperature with age have been noted by Isenberg and Green. This was explained by the authors as related to the known decrease in arterial oxygen concentration and a reduced ability to deliver oxygen to the peripheral tissues. The clinical significance of this finding to contact lens wear is uncertain, but may lead to a reduction in the amount of oxygen available to the cornea during
sleep, thereby increasing overnight swelling and possibly reducing tolerance to contact lens wear. Pyron et al. reported a selective adherence of certain bacteria to the human bulbar conjunctiva, which appeared to vary with age. This implies that there may be a differential susceptibility of individuals to infection with specific bacteria, which needs further investigation. Lawrenson, investigating the limbal touch threshold, has found an age-related decrease in sensitivity that is most pronounced after the fourth decade.

Pingueculae become more common with age and, if near the limbus, may lift the lids away from the surrounding conjunctiva and cornea, causing a local area of drying as the tear layer is not restored with blinking. Rigid lenses may cause irritation of pingueculae and increase the desiccation and associated vascularisation. Soft contact lenses may fail to centre properly.

The lids may swell during the menopause and the resultant hormonal changes may cause increased water retention. Xerosis of the conjunctiva may also occur during the menopause.

**Tear Film**

The literature demonstrates a controversy that exists regarding the relationships between tear flow, tear volume, and age. Early descriptions of a decrease in tear volume with age generally relied upon results obtained with the Schirmer test (e.g., Nort), which are acknowledged to induce reflex lacrimation (i.e., the tear flow due to discomfort associated with the test, and measured as the difference in tear flow with and without local anaesthetic). Lamberts et al. investigated reflex lacrimation and reported no age-related reduction in the Schirmer test results after the instillation of a topical anaesthetic. This was due to a negative correlation between age and reflex lacrimation. Corneal sensitivity decreases with age and would account for the decrease in reflex lacrimation and the earlier reports of age changes. Contradictory reports of a (subjective) fluorescein colorimetric matching procedure imply a possible age-related reduction in tear flow. A reduction in lacrimal secretion with age was demonstrated by Furukawa and Poolse, who measured tear-turnover rate (subjects aged 15–63 years) with a fluorophotometer. Earlier, Mishima et al. reported no tear flow–age relationship as assessed with colorimetric matching and fluorophotometry, with a smaller sample and no subjects over the age of 50 years. Hamano et al. measured tear volume with a phenol-red impregnated cotton thread which, due to its quick application (approximately 15 s), is claimed to estimate the inferior conjunctival tear volume (but probably includes some basal secretion). Hamano et al. reported that the percentage of eyes with less than 15 mm wet length increased significantly with increasing age. The percentage with a wet length of less than 10 mm was greatest in the 30–39 year age group, as shown in Figure 3. It is interesting to speculate that there may be two factors at work: the first, a real decrease in tear production with age, and the second, an increase in tear retention after the fourth decade due, perhaps, to changing lid shape and a reduced facility of punctum drainage. In addition, the constituents of the tears may alter with age.

The pre-corneal tear film, composed of lipids, proteins, mucus, salts, and water from many glands, is not solely dependent upon volume or flow rates. Changes with age in five tear protein concentrations have been demonstrated by McGill et al., but the significance of each of the numerous constituents has yet to be determined. McGill et al. suggest the diagnostic use of lysozyme and lactoferrin assays, as these proteins have been demonstrated to be at reduced levels in dry eyes. Some elderly patients will have reduced tear flow due to disease, such as rheumatoid arthritis [e.g., keratoconjunctivitis sicca (KCS) in Sjogren's syndrome]. KCS is an age-related aqueous deficiency syndrome, which affects more females than males, and commonly appears between the fifth and sixth decades. Rose bengal and lysozyme assay are diagnostic of KCS. Special care must be exercised if any patients with a reduced lysozyme tear content are to be fitted with contact lenses, as this may increase susceptibility to infection.

Koetting and Andrews reported an age-related reduction in tear pH (more acidic). This may affect the fitting characteristics of certain high water-content soft contact lenses.

All of these techniques are intrusive to varying degrees, so some non-intrusive techniques are now discussed. The inferior tear prism has been estimated to contain over 80% of the tear volume. Using a non-invasive technique, Port and Asaria measured the inferior tear prism with a modified optical pachometer and noted no age-related difference between two small population samples.

Clinical measures of tear stability are often used as diagnostic tests in contact lens practice. Andres et al. reported a significant reduction in fluorescein tear break-up time (BUT) with increasing age and found it
predictive of dry eye problems. BUT, the traditional assessment of tear stability, has been criticised as unreliable (different results on repeated tests47), unrelated to more sophisticated measures48, and a poor predictor of contact lens success.49 As both fluorescein and local anaesthetics are known to disrupt the pre-ocular tear film, a number of non-invasive techniques have been developed.50-52 Guillen and Guillon8 reported an age-related reduction in non-invasive tear break-up time (NIBUT), as assessed with a specially devised instrument. Similarly, Patel and Farrell9, assessing the quality of the mire image from a Bausch and Lomb keratometer, found a significant reduction in pre-corneal tear film stability between the ages 8–80 years. In conclusion, it would seem that the quality, but perhaps not the volume, of tears alters with age.

The number of apparently active meibomian glands (those from which secretion could be expressed) of the lower lid decreases with age, from about 14 at the age of 30 years to about 7 at the age of 80 years.53 Previously, Norn6 reported that about 45% of all meibomian orifices were active, as shown by lipid-specific vital staining, and that this was independent of age. This implies that the chemical composition of meibomian secretion varies with age, with a reduction in the ‘expressibility’. Also, while a positive correlation between the number of active meibomian glands and a thickened tear lipid layer was demonstrated by Norn53, the thickness of the lipid layer is independent of age.54 This maintained lipid layer despite an apparently reduced secretion may again be explained by a reduced elimination of tears with age.

There are many references in the literature to increased dry eye amongst older patients (e.g., Norn59), but no substantiating studies. McMonnies and Ho65 analysed the results of a dry eye questionnaire for a normal population (non-contact lens wearers) and found a lower incidence of reported symptoms with age. The lower incidence of ocular symptoms may be due to reduced corneal sensitivity41, an acceptance of symptoms as ‘normal’ with age, or fewer provocative situations encountered (e.g., swimming or smoky environments). The lower reported incidence of dry eye symptoms may also relate to an increased incidence of reports of ‘watery eyes’ in older patients, commonly due to diminished tear drainage resulting from poor apposition of the punctae, which is often related to reduced lid tension. Contact lens wear has been demonstrated by a variety of methods to interfere with the tear film.12,57-60 McMonnies and Ho61 reported a significantly higher frequency of dry eye symptoms in contact lens wearers, indicating that contact lens wear is provocative to tear function. Hamano et al.7 reported that eyes with shorter (phenol-red thread) wet lengths were more likely to experience superficial punctate keratitis and erosions with all types of contact lens. Clinical reports of increased incidence of dry eye symptoms in elderly contact lens wearers may then relate to a change in the quality of the tears with age, the tears being more easily disturbed by the introduction of a contact lens.

Various systemic and topical drugs alter the tears. Anticholinergics, antihistamines, diuretic hydrochlorothiazide, certain hormones (including those used in post-menopausal hormone replacement schemes), betablockers, psychotropics, tricyclic antidepressants, and salicylic acid appear to decrease tear production. Pilocarpine, bromhexine, and physalaemin appear to increase tear production. The contact lens practitioner must be aware of the increased use of these medications with age.

Cornea

The cornea changes colour, becoming more yellow with age as a result of changes in absorption42 and scatter43, due principally to changes in the stroma.64 The cornea also loses some of its lustre with age, probably as a result of changes in the cellular structures of the epithelium14 and an associated disruption of the tear film.

There is the build up of lipids in the corneal periphery, known as arcus senilis or gerontoxon, and a reduction in the corneal diameter due to circumbiletal corneal degeneration, from an average of 11.7mm to one of 11.4mm, which Weale44 considers not to be clinically significant.

At birth the human cornea is steeper in the periphery than the centre, with a progressive flattening of the periphery with age.65 The central cornea also flattens with age, but more in the vertical than the horizontal, the resultant change in central corneal toricity causing a general change from ‘with the rule’ to ‘against the rule’ astigmatism after about 40 years.2,66 The cornea also thins with age.67 Menopause and the resultant hormonal changes may cause increased water retention, leading to changes in corneal thickness and corneal curvature.15

Corneal touch sensitivity (corneal touch threshold-1) is greater in the centre than in the periphery68 and with age there is a progressive decrease in corneal touch sensitivity. Boberg-Ans69 demonstrated an age-related decline in corneal sensitivity from 10 to 90 years and a difference in peak corneal sensitivity of almost three times between the youngest and oldest subjects. Sedan et al.80 reported, for subjects over 65 years, a gradually diminishing sensitivity, particularly in the periphery. A considerable reduction was noted in certain corneal degenerative conditions, such as arcus senilis, relative to the degree of severity. Changes were noted with cataract, glaucoma, diabetes, and vascular hypertension. Millodot41 confirmed the results of Boberg-Ans69 and found little change in sensitivity up to about the fourth decade, after which there was an accelerating loss of sensitivity (Figure 4). Treatment with thyroxine has been reported to cause contact lens intolerance.70
Corneal fragility (corneal damage threshold⁻¹) appears to increase with age. Millodot and Owens\textsuperscript{71} found a progressive increase in fragility with age from 11 to 80 years, corresponding to the decrease in sensitivity, as shown in Figure 4. The means for each age group are shown. Corneal sensitivity decreases with age\textsuperscript{41}, while corneal fragility increases with age\textsuperscript{72} after about the fourth decade of life.

![Figure 4. Corneal sensitivity (corneal touch threshold⁻¹) and corneal fragility (corneal damage threshold⁻¹) as a function of age. The means for each age group are shown. Corneal sensitivity decreases with age, while corneal fragility increases with age after about the fourth decade of life.](image)

Corneal fragility (corneal damage threshold⁻¹) is partially compensated by an increased barrier function and decreased ionic permeability, and they note 'should last for a couple of centuries'. Contact lens induced oedema was used by O'Neal and Polso\textsuperscript{88} to demonstrate a correlation between endothelial cell area variation and recovery rate, as a measure of endothelial pump efficiency. Their data suggests that the endothelial pump function decreases by approximately 10% between the third and seventh decades. Sweeney and Holden\textsuperscript{77} demonstrated a relationship between induced corneal oedema and epithelial thickness and polymegathism. Wilson and Roper-Hall\textsuperscript{84} argue that, as in the clinically normal cornea it is so unusual to detect a pathologically low endothelial cell count, there is little to worry about. Long-term wear of hard contact lenses\textsuperscript{86} and extended-wear contact lenses\textsuperscript{86,87} causes endothelial changes over and above normal age-related changes in control subjects. Considering this, and the preliminary data of Wigham and Hodson\textsuperscript{82}, the endothelium is probably not the primary source of concern with corneal decompensation, until stressed by a contact lens. There is a large individual variation in corneal ablability to deal with anoxic stress, and patients should be assessed on an individual basis. Care must still be taken with regard to older long-term hard or extended-wear contact lens patients, and account taken of the increased incidence of endothelial pathology in older patients.

Cataract surgery may cause flattening of the cornea, a lower corneal apex, and increase in corneal toricity (steeper horizontal), thereby imposing difficulties in fitting rigid contact lenses.\textsuperscript{88} Epithelial thickness is slightly reduced\textsuperscript{25}; corneal innervation is reduced by half and hence sensitivity is reduced; the basal metabolic rate and oxygen demand are lower, resulting in greater tolerance to hypoxia\textsuperscript{90}; and endothelial cell density is reduced.

Diabetes, which becomes more common with advancing age, is known to retard corneal epithelial healing, increase the risk of corneal neovascularization\textsuperscript{91}, reduce corneal sensitivity, and increase corneal fragility.\textsuperscript{92} Diabetes has also been reported to lead to an increased susceptibility to infection\textsuperscript{93}, to increase the incidence of recurrent epithelial erosions\textsuperscript{94}, and to cause endothelial morphological changes.\textsuperscript{95} Finally, with increasing age there is an increased incidence of various corneal conditions.\textsuperscript{96}

Contact lens fitting for older patients is thus fraught with greater dangers than that for the typical younger patient. Practitioners must be aware of the decreased corneal sensitivity, increased corneal fragility, reduced rate of epithelial healing, reduced tear flow, increased incidence of corneal age-related disorders, and the greater possibility of corneal decompensation through contact lens induced stress.

**Pupil Size**

The size of the pupil is dependent upon the retinal luminance and state of adaptation, the state of the entire
central nervous system (e.g., fatigue), psychic influences, such as fear and pain (e.g., contact lens induced corneal irritation), and age. Due to the many sources of artifacts, measurement of the pupil size has proved difficult and can lead to many false conclusions.

**Dark Adaptation**

The age-related changes in pupil size have been thoroughly described by Birren et al., Seitz, Kadlecova et al., and Loewenfeld. The use of dark-adapted results is justified as demonstrating the 'absolute' pupil size and is more easily repeatable. The time of dark adaptation has a significant effect upon these results. Pupil size is known to increase rapidly in the first 10s of darkness, decrease, then to more gradually increase, and to reach maximum size after approximately 20min.

According to Loewenfeld, 'the pupils become larger within the first decade of life. During the second decade the curve rounds a gradual peak, and then a steady decline begins and continues over the remaining lifespan.' Figure 5 shows the change in pupil size with age as found in the four studies mentioned above. The two earlier studies used visible light flash photography, while the later two used infra-red flash photography.

![Figure 5](image)

**Light Reflex**

The light reflex is maintained with age. For a given pupil size, there is a constant proportional change with illuminance, independent of age, up to the age of 60 years. This is also true of the near reflex.

Kumnick concluded that, though there are changes in the response to light with age, 'the efficiency of the pupillary mechanism in relation to similar original diameter in the response to light stimuli remained constant with increasing age.' This was confirmed by Loewenfeld for short-duration flashes, but not for longer flashes (3s), which lead to the conclusion that there is an initial fast phase, which is maintained, and a slower component, which deteriorates with age.

**Light Adaptation**

Many studies report the light-adapted pupil size of their subjects, but with little or no reference to the lighting conditions, psychic state, or age of the subjects. To date there have been only limited investigations of the relationship between age and light-adapted pupil size under varied stable luminance conditions.

Figure 6 is a compilation from studies that reported light-adapted pupil size and subject age. The luminance in the quoted studies varies between 3–108cd/m². As can be seen in Figure 6, the results are quite variable, and appear not to be related to the luminance levels quoted. This is probably due to the particular experimental conditions, rather than to other factors such as race. In general, under light-adapted conditions, the reduced pupil size with age relationship remains. Though not intended as predictive, Figure 6 indicates that the average light-adapted pupil size is approximately 5mm at age 20 years, dropping to 3mm at age 80 years.

![Figure 6](image)
**Figure 7.** The refractive profile, shown as the distance spherical equivalent correction, changes with increasing age. The distribution percentage (in half dioptre steps) is shown for: (a) age 25-34 years; (b) age 35-44 years; (c) age 45-54 years; (d) age 55-64 years; and (e) age 65-74 years. With increasing age the proportion of the age group who require optical correction shifts from predominantly myopic to predominantly hypermetropic. The data is derived from US government information (quoted in Friant and Miller).
increasing age there is an increased intraocular illumination by the age of approximately one-third that at the age of 20 years. It is difficult to differentiate the effects of absorption and scatter in the various media. Both absorption and scatter appear to be wavelength-selective, resulting in greater attenuation of shorter wavelengths. This suggests that the scatter may be consistent with Rayleigh's law (inversely proportional to the fourth power of the incident wavelength), and hence short wavelengths (blue) undergo most scatter. The relative spectral transmission of an older observer as compared to a younger observer is shown in Figure 9.

The major age-related changes are attributed to the crystalline lens. Much of the alteration in ocular transmission with age is due to increases in the thickness in axial length of the crystalline lens with age and consequent decreases in its spectral transmission. Increases in lenticular axial length are enhanced by senile miosis, all the light having to pass through the thicker, central portion of the lens. A smaller pupil should reduce scatter from off-axis light. Other tissues and optical elements of the eye, including the cornea and vitreous, also show changes in spectral transmittance with age. These are discussed in more detail below.

**Cornea**

The older cornea becomes more yellow in appearance through changes in transmission and scatter. Boettner and Wolter demonstrated a slightly greater total transmission of the longer (red) wavelengths in extirpated corneas, and an increased attenuation of the shorter wavelengths due to scatter or absorption, with a slight age relationship. Lerman demonstrated a greater age-related increase in absorption between 8 and 80 years. Milldot and Newton, from measurements of Purkinje-Sanson images, found no alteration in the refractive index of the cornea with age.

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**Figure 8.** The refractive profile of dispensed Alges bifocal contact lenses. This most closely resembles the refractive profile for the 45-54 and 55-64 year-old age groups shown in Figures 7(c) and 7(d). Friant and Miller also note that half of the dispensed Alges bifocals were to patients with no previous contact lens experience.

**Figure 9.** The relative transmission of the entire ocular media as a function of wavelength. Transmission of the ocular media of a 63-year-old observer compared to a 21-year-old observer. The transmission of the younger observer is unity and that of the older observer relatively reduced (redrawn from Ruddock).

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lenses, as shown in Figure 8, was not predominantly myopic, as expected from typical contact lens wearing populations, but more closely matched the refractive distributions of persons aged 45–64 years, as shown in Figures 7(c) and 7(d). Given this different refractive profile, the contact lens thickness profile will also vary from the conventional myopic contact lens. In addition, alternating- vision bifocal contact lenses typically are prism ballasted, thereby increasing lens thickness. This may lead to a reduced oxygen supply to the cornea and, given the other age-related corneal changes mentioned above, contact lenses that allow high levels of oxygen transmission are recommended.

Aphakes and hypermetropic presbyopes will experience contact lens handling difficulties as they are unable to see the lens when uncorrected, and as they are less likely to have previous contact lens experience. A concave mirror for magnification and the use of appropriate spectacle correction may help to alleviate these problems. Those with marked handling difficulties may then be fitted with extended-wear contact lenses, with the attendant increased risks and difficulties that have been noted previously.

**Spectral transmission**

There is a wavelength-selective transmission of light through the ocular media of the human eye caused by reflection, absorption, and scattering. Retinal illumination by the age of 60 years is reduced to approximately one-third that at the age of 20 years, through a combination of reduced pupil size and increased attenuation by the ocular media.

Reflectance at the various surfaces, principally in the short wavelengths, is of minimal influence and probably does not alter significantly with age. Changes in reflectance from the pre-corneal tear film, due to changes in the corneal epithelial surface, may cause the reduction in lustre of the older cornea. With increasing age there is an increased intraocular scatter with attenuation of shorter wavelengths, though there are large individual variations. It is difficult to differentiate the effects of absorption and scatter in the various media. Both absorption and scatter appear to be wavelength-selective, resulting in greater attenuation of shorter wavelengths. This suggests that the scatter may be consistent with Rayleigh's law (inversely proportional to the fourth power of the incident wavelength), and hence short wavelengths (blue) undergo most scatter. The relative spectral transmission of an older observer as compared to a younger observer is shown in Figure 9.
Allen and Vos\textsuperscript{53} reported an increased back-scatter of light by the cornea with age. Vos and Boogard\textsuperscript{129} estimated that 25–30% of intraocular scatter is due to the cornea. Much of the attenuation is attributed to scatter that occurs principally in the stroma.\textsuperscript{64} Visual symptoms with corneal oedema have traditionally been explained as changes in the stromal matrix. Cox and Holden\textsuperscript{129} have demonstrated that epithelial oedema induced by hypotonic saline produces haloes and reduced contrast sensitivity, while anoxia-induced stromal oedema results in no measurable visual loss. This implies that reduction in visual function is not a good predictor of physiological corneal oedema.

**Aqueous**

The aqueous has a high transmittance through the visible spectrum. No age-related changes in spectral transmission\textsuperscript{62,130} or the refractive index\textsuperscript{131} of the aqueous have been noted.

**Crystalline Lens**

The crystalline lens is responsible for the majority of the intraocular attenuation of light transmission\textsuperscript{132} through absorption, probably related to pigmentation, and scatter. Said and Weale\textsuperscript{123} reported a progressive increase in the optical density of the lens with increasing age, particularly for short wavelengths, as shown in Figure 10. Boettner and Wolter\textsuperscript{62} demonstrated similar age-related changes in vitro. Millodot\textsuperscript{133} reported a reduction in ocular chromatic aberration of approximately one-third between phakic (normal) and aphaiki, age-matched eyes, inferring that the remaining chromatic aberration is due to the other ocular tissues. Millodot and Newton\textsuperscript{127} reported an age-related change in the refractive index of the crystalline lens. Back-scatter by the lens also increases with age,\textsuperscript{23,63} Siew \textit{et al.}\textsuperscript{134}, through analysis of light scatter of thin sections of crystalline lens, infer that the major age change is syneresis, a gradual reduction of water of hydration from the protein aggregates. This was confirmed by measures of lenticular water content by Lahm \textit{et al.}\textsuperscript{135} These ultrastructural changes result in an increase with age in the light scatter. The crystalline lens is the principal u.v. filter in the human eye, and thus the aphaiki eye is prone to damage from this short wavelength radiation. Aphaiki patients should be routinely fitted with contact lenses that incorporate a u.v. filter.

**Vitreous**

There is some back-scatter within the vitreous\textsuperscript{25,118} and an age-related reduction in transmission of about 10%.\textsuperscript{62} The refractive index does not alter with age.\textsuperscript{137}

**The Retina and Colour Discrimination**

Forward scatter by the retina also reduces the light available to the receptors by an estimated 30%.\textsuperscript{136} Macular pigmentation is subject to large individual variations\textsuperscript{122,123} and will selectively attenuate the light transmitted to the photoreceptors, influencing colour perception. Human retinae examined by high performance liquid chromatography demonstrated no dependence upon age for the quantities of the two major macular pigments (zeaxanthin and lutein), for donors aged 3–95 years.\textsuperscript{137} With colorimetric examination, Kelly\textsuperscript{138} and Ruddock\textsuperscript{121,122} have demonstrated no age-related effect of macular pigmentation upon colour discrimination.

In a variety of colorimetric experiments, Ruddock\textsuperscript{122} demonstrated a correlation between age and spectral transmission for wavelengths 420–600 nm and ages 16–61 years, and a greater decrease in transmission for shorter wavelengths. Despite large individual variations, Werner\textsuperscript{123} has demonstrated an increased attenuation of short, but not medium or long, wavelengths with increasing age, from 4.5 months to 66 years (400–650 nm), as measured with visually evoked responses.

**Diffractive Bifocal Contact Lenses and Spectral Transmission**

The age-related wavelength-selective reduction in transmission may have some unexpected results. Diffractive bifocal contact lenses are wavelength dependent, with the distance image being more ‘blue’ and the near image more ‘red’\textsuperscript{130,149}, as shown in Figure 11. As the older eye is less able to utilise short (blue) wavelengths, there is a possibility that some wearers may find the distance image inadequate. This may be further enhanced by the spectral content of the illuminating source. A diffractive lens designed to give a 50:50 ratio between distance and near images, given the human spectral sensitivity ($V$, as shown in Figure 12) in daylight (e.g., D65 in Figure 12), will give a different ratio under a different illuminant. For example, when used with tungsten filament lamps (e.g., Standard Illuminant A), which produce most of their energy in the longer (red) wavelengths, as shown in Figure 12, the energy in the two images would alter from 50:50 to 47:53. This may thus further reduce

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig10.png}
\caption{The variation in optical density of the human lens with age at various wavelengths. The change is greatest after about 25 years of age and greater with shorter wavelengths (redrawn from Said and Weale\textsuperscript{129}).}
\end{figure}
distance vision with diffractive bifocal contact lenses under certain conditions. In contrast, the current designs of Diffrax rigid bifocal contact lenses are more often noted by wearers to be distance vision biased. Echelon soft diffractive bifocal lenses are almost equally balanced between distance and near vision. This balance can be modified with lens design.

Chromatic Aberration

The longitudinal chromatic aberration (LCA) of the human eye has been measured in the range 0.78–2.25D, with an average of approximately 1.55D, for wavelengths 450–650nm. These studies have generally tended to neglect any age effects. There is conflicting evidence about age-related changes in LCA.

Millodot and Mordi and Adrian reported an age-related reduction in LCA. Millodot, for 58 subjects aged 10–80 years, found a decrease in LCA (458–656nm) with age after the fourth decade. LCA was determined by simple over-refraction while viewing coloured targets. With a more sophisticated technique, Mordi and Adrian, for eight cyclopleged subjects, found a significantly reduced LCA (437–671nm) for subjects in the fourth and fifth decades as compared to subjects in the third decade for short wavelengths (577.7nm), but not at the long wavelength (red) end of the spectrum. These findings have been disputed by Ware, Pease and Cooper, and Howarth et al. Ware reported no age variation in LCA (420–720nm) when comparing results for six older subjects (average age 60 years) with those of six young subjects (average age 23 years). Pease and Cooper reported no age-related change in LCA (425–700nm) of 26 subjects aged 19–70 years. Howarth et al. reported no difference in LCA (420–645nm) between four cyclopleged younger subjects (27–33 years) and six older subjects (48–72 years) as measured with two different techniques. There is no obvious reason for the different results. Some doubts have been expressed as to the technique utilised by Millodot. The active accommodation of younger subjects would be expected to decrease LCA, but the larger pupil diameters would reduce the depth of focus, tending to increase LCA. The conflicting results of Mordi and Adrian and Howarth et al. are not subject to these doubts. The study by Millodot remains the only study with large subject numbers.

In a longitudinal study, Ware found no significant alteration in the LCA of two subjects over a period of 25 years. Conversely, Mordi and Adrian, using a cycloplegic, reported a decrease in LCA for one subject after 20 years, again only at the blue end of the spectrum.

Millodot reported, for 10 aphakic subjects, that the age-related decrease in LCA was retained, but at a reduced level, inferring that approximately one-third of LCA in the eye is due to the crystalline lens, and that other ocular elements, which account for much of the aberration, also alter with age. With increased age the refractive index of the crystalline lens increases in the red and decreases in the blue, and there is no alteration in the refractive index of the cornea. Age-related changes in the refractive index of the vitreous are thus required to explain a reduction in LCA, which is noted in both phakic and aphakic eyes. Benefiel et al. found no difference in refractive index of the vitreous of 24 eyes aged from 26 weeks gestation to 83 years.

The near focal length of current diffractive bifocal contact lenses is inversely proportional to wavelength, the reverse of the case with refractive chromatic aberration, such as with spectacle lenses and in the human eye. Theoretical predictions suggest that the LCA of the first order (near) focus of a diffractive bifocal contact lens would reduce the inherent LCA of the human eye. The normal human ocular LCA (between 450–650nm) for near objects would then be reduced from approximately 1.5 to 0.8D.
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Postscript. Estimates of the variance of data (e.g., standard deviation) have not been included in the figures in an attempt to improve clarity and to retain a consistent style. Interested readers are advised to consult the original source as indicated.

REFERENCES
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