Do small-aperture presbyopic corrections influence the visual field?

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Abstract

Purpose: To explore the effect of small-aperture optics, designed to aid presbyopes by increasing ocular depth-of-focus, on measurements of the visual field.
Methods: Simple theoretical and ray-tracing models were used to predict the impact of different designs of small-aperture contact lenses or corneal inlays on the proportion of light passing through natural pupils of various diameters as a function of the direction in the visual field. The left eyes of five healthy volunteers were tested using three afocal, hand-painted opaque soft contact lenses (www.davidthomas.com). Two were opaque over a 10 mm diameter but had central clear circular apertures of 1.5 and 3.0 mm in diameter. The third had an annular opaque zone with inner and outer diameters of 1.5 and 4.0 mm, approximately simulating the geometry of the KAMRA inlay (www.acufocus.com). A fourth, clear lens was used for comparison purposes. Visual fields along the horizontal meridian were evaluated up to 50° eccentricity with static automated perimetry (Medmont M700, stimulus Goldmann-size III; www.medmont.com).
Results: According to ray-tracing, the two lenses with the circular apertures were expected to reduce the relative transmittance of the pupil to zero at specific field angles (around 60° for the conditions of the experimental measurements). In contrast, the annular stop had no effect on the absolute field but relative transmittance was reduced over the central area of the field, the exact effects depending upon the natural pupil diameter. Experimental results broadly agreed with these theoretical expectations. With the 1.5 and 3.0 mm pupils, only minor losses in sensitivity (around 2 dB) in comparison with the clear-lens case occurred across the central 10° radius of field. Beyond this angle, sensitivity losses increased, to reach about 7 dB at the edge of the measured field (50°). The field results with the annular stop showed at most only a slight loss in sensitivity (≤3 dB) across the measured field.
Conclusion: The present theoretical and experimental results support earlier clinical findings that KAMRA-type annular stops, unlike circular artificial pupils, have only minor effects on measurements of the visual field.

Introduction

It has long been recognised that the depth-of-focus (DOF) of the eye increases as the pupil diameter decreases and that, in principle, this might be helpful to presbyopes by giving them adequate vision over a greater range of object distances. One simple way of achieving a small pupil is by using high light levels to constrict the pupil, or a topical medication with a miotic effect,[1] but the same result can also be achieved with an artificial pupil. It was therefore originally suggested that painted contact lenses, which were opaque except for a small central aperture, might provide enhanced near vision for presbyopes while still allowing good distance vision since they were worn monocularly in the non-dominant eye.[2] The disadvantage of such lenses is that less light contributes to the retinal image, so that the wearer may find vision more difficult under mesopic or scotopic conditions. There may also be a reduction in visual field,[2] leading to problems with mobility. As a result of these major limitations, reduced-aperture contact lenses have found little application,[3–5] except as artificial pupils for albinos.[6]

More recently, however, substantial use has been made of the KAMRA corneal inlay (www.acufocus.com),[7–12] which is based on broadly the same optical principle as an earlier design of a contact lens[13] for increasing DOF. This monocularly-implanted inlay partly overcomes the disadvantages associated with a simple circular aperture. It consists of an annular opaque stop. There is a small central circular aperture of diameter 1.6 mm but, rather than the surrounding area being opaque out to large corneal diameters, the outer diameter of the inlay is only 3.8 mm. Thus light can pass without obstruction through the more peripheral portions of the cornea. The inner diameter represents a compromise between improved depth-of-focus, light loss and optical quality, since diffraction with smaller diameters degrades retinal image quality and acuity.[14] Although the effects on retinal illumination with an annular design are less pronounced than those for simple, small-aperture lenses[15] the interocular differences in retinal illuminance may be still high enough to cause a Pulfrich experience[11] which does not appear to be reduced by adaptation.[16,17] These effects may lead to distortions in the perception of relative movement and, in some cases, to possible hazard in practical situations such as driving.

Although recent reviews[3,5] and earlier clinical findings[18] have suggested little effect of KAMRA-type stops on the clinically-measured visual field, related theoretical calculations for the KAMRA inlay by Langenbucher *et al.*[19] postulated a vignetting effect for combinations of pupil sizes and field angles, with the attenuation of image brightness reaching levels up to 60%. Three studies show that the vignetting effect of the KAMRA inlay can cause shadows and other artefacts in the retinal images obtained with some types of imaging system.[20–22] Moreover, significant field loss in the midperiphery has also been found in studies with patients wearing coloured contact lenses[23] or annular contact lenses with a clear pupil and a coloured portion covering the iris.[24] In the case of small-pupil contact lenses, Carkeet[25] has shown that the limits to the unobstructed field and to the field boundary of the absolute field depend upon the diameters of both the contact lens pupil and the natural pupil, although he did not explore the variation in retinal illuminance across the field in detail.

It is clear that there are apparent inconsistencies between claims that KAMRA type inlays have no effect upon the visual field and other evidence which suggests that some field effects may occur. In an attempt to reconcile these views, in this article we first discuss the theoretical background of the possible impact of any small-aperture device on the visual field. Then, we present some ray-tracing and experimental data on the practical effects involved when using contact lenses or corneal inlays having circular, central apertures or annular stops.

Methods

A simple model of the links between artificial pupil geometry and the visual field

The reasons why an artificial pupil placed at the cornea affects the visual field can be understood in reference to *Figure* 1. For simplicity it is assumed that the artificial pupil is located at the cornea of a schematic eye in which the cornea is represented by a single refracting surface (the KAMRA inlay is located about halfway through the corneal thickness of around 0.55 mm, but this has only a minor effect on the argument). From any field direction θ, the incident chief ray is refracted to pass through the centre of the iris, which forms the aperture stop of the eye and lies at an axial distance b from the cornea. The corresponding incidence height is h and C is the centre of curvature of the cornea, which is assumed to be spherical with radius of curvature R. If n is the index of the eye media and i and i' are the

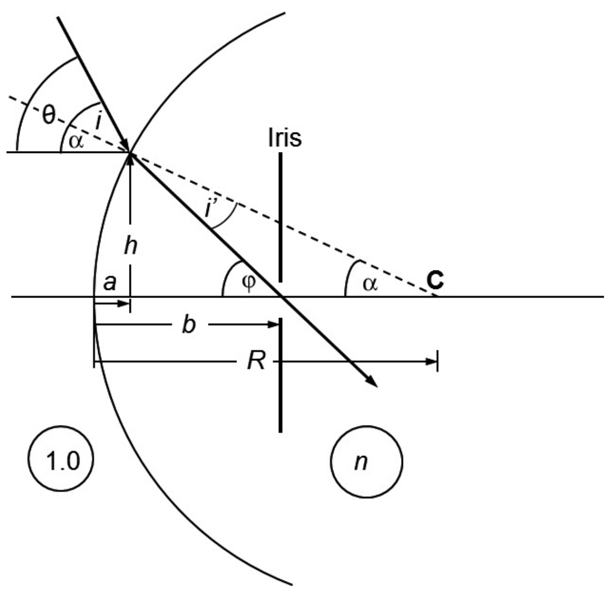

Figure 1. Geometry linking chief ray field angle θ and incident height h.

angles of incidence and refraction, respectively, of the chief ray, we have

$$\sin i = n \sin i'$$

where

$$i' = \varphi - \alpha \text{ and } \theta = \alpha + i$$

Combining these equations gives

$$\sin(\theta - \alpha) = n \sin(\varphi - \alpha) \quad (1)$$

It can be seen from *Figure* 1 that

$$\varphi = \tan^{-1}[h/(b-a)] \text{ and } \alpha = \tan^{-1}[h/(R-a)],$$

where the sag a is given by

$$a = R - (R^2 - h^2)^{1/2}$$

Given the constants for the eye we can evaluate a as a function of the incidence height h, determine the corresponding values of α and φ, and then use these in *Equation* 1 to obtain the values θ for each value of h. *Figure* 2 shows the result. It has been assumed that R = 7.8 mm, b = 3.6 mm and n = 1.336 from the Emsley–Gullstrand schematic eye.[26]

Although the results are only approximate for real eyes, it can be seen that if we use a centred, small, circular artificial pupil placed at or near the anterior surface of the cornea, so that only light having small incident heights at the cornea can enter the eye, only rays corresponding to relatively small field angles will be admitted to pass through the centre of the iris stop aperture, e.g. an artificial pupil 2 mm in diameter will admit such rays only over a field of semi-diameter about 20°.

As noted earlier, the KAMRA inlay is an opaque annulus with inner and outer diameters 1.6 and 3.8 mm, respectively, which suggests that rays which would normally be refracted to pass through the centre of the iris stop aperture would be blocked over an annular field zone of inner and outer diameters, of about 15° and 35°, respectively (*Figure* 2). However, this does not mean that no light will enter, since the iris stop aperture is not a point. The extent to which the artificial pupil, located at the cornea a few millimetres in front of the iris, blocks light from different field directions depends both on the geometry of the annular stop itself and on the iris aperture diameter. A qualitative idea of this can be gained from *Figure* 3, which shows what is effectively the 'shadow' of the annular KAMRA stop moving across natural pupils of diameters 3 and 5 mm as the field angle is increased. In simple terms, there is a parallax movement as a result of the axial distance between the artificial and natural pupils. It is clear that some light always gets through both pupils but that in general the fraction of the pupil area obscured by the inlay is likely to be greater for the smaller pupil.

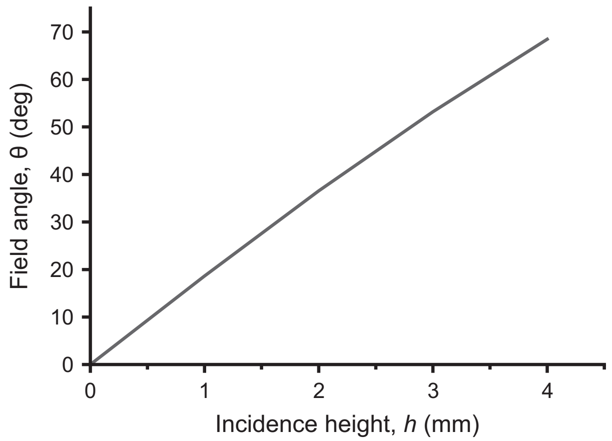

Figure 2. Relationship between chief ray field angle θ and incident height h for small stop diameters.

Ray-tracing results

Ray-tracing provides a more accurate representation of the impact of a small-aperture contact lens or inlay on the proportion of light passing through the natural pupil from

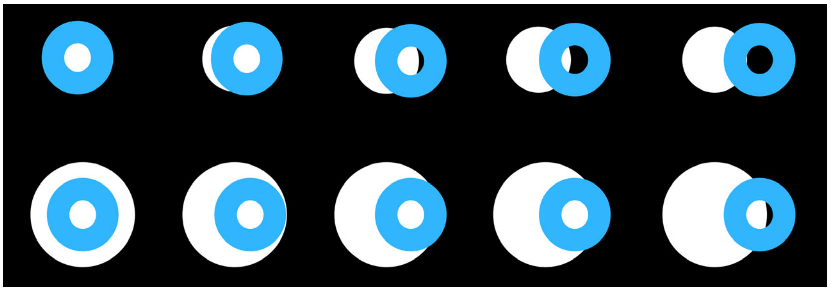

Figure 3. Schematic diagrams of a KAMRA (1.6–3.8 mm annulus) on top of a 3 mm (top) and a 5 mm (bottom) natural pupil, as viewed from increasing field angles.

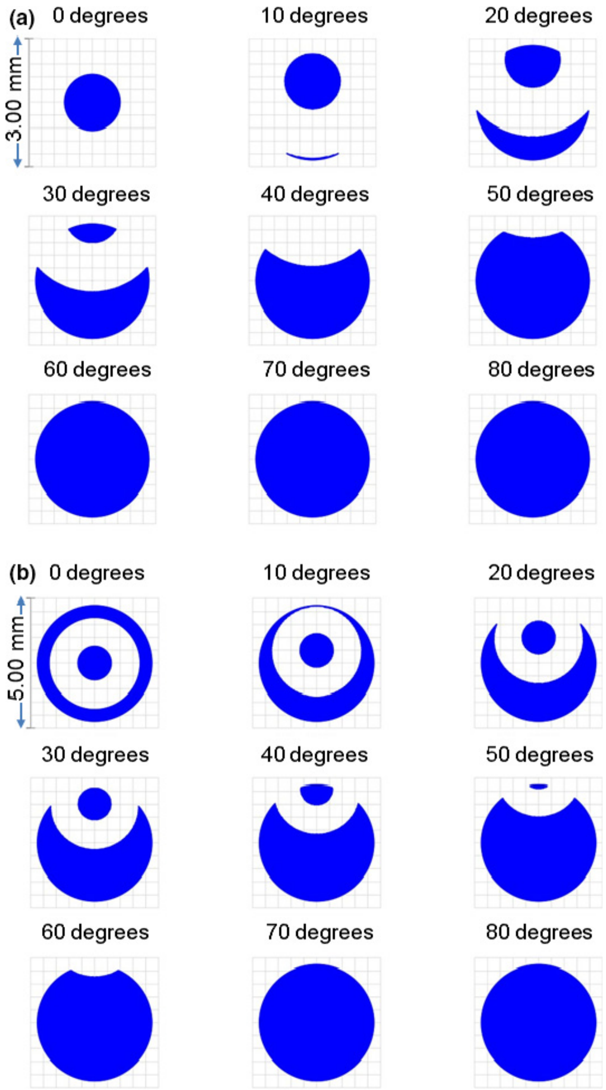

Figure 4. (a) Ray concentration (blue) in the plane of the iris pupil for light beams from angular field positions in the vertical meridian as indicated (i.e. 0–80° at 10° intervals). The natural axial entrance pupil diameter is 3 mm and a contact lens with an opaque annular stop with inner and outer diameters of 1.5 and 4.0 mm is worn. (b) The same but for a natural entrance pupil 5 mm in diameter. Note the different scales in (a) and (b).

various directions in the visual field. *Figure* 4 shows the results when rays are traced using Zemax Optics Studio version 15 (www.zemax.com) from a distant object point in the field directions with respect to the optical axis as indicated into an emmetropic Navarro model eye.[27] Ray tracing was performed for a contact lens with an annular opaque stop, a refractive index of 1.375 and a central thickness of 0.22 mm. This was assumed to take up a shape with the back surface to match the cornea and to have a front surface of radius to make the contact lens have zero power. The inner and outer diameters of the opaque annulus were 1.5 and 4.0 mm. Apart from minor differences associated with the dimensions of the opaque annulus, the optical effects of the contact lens would be expected to be similar to those of the KAMRA inlay, since the stromal depth of the flap/pocket in which the inlay is placed is only 0.20 mm.[7]

Simulations were carried out for natural iris pupil diameters corresponding to on-axis entrance pupil diameters of 2–6 mm, with *Figure* 4 showing the results for diameters of 3 and 5 mm. The diagrams represent the intersections of a spatially-uniform array of rays with the plane of the iris, the rays being incident obliquely on the iris (*Figure* 1). When viewed from outside the eye the pattern of rays in the plane of the iris will appear magnified by about 13%, due to the effects of the cornea, and off-axis the dimensions of the natural pupil and of the ray intersection pattern will appear compressed along the field meridian, i.e. the natural pupil will appear elliptical. Dimensions in this direction must be multiplied by a factor of about $\cos(\varphi/1.12)$.[28] Optical effects are similar in all field semi-meridians and no allowance has been made for any field restrictions caused by the facial geometry.

With a 3 mm natural axial entrance pupil (*Figure* 4*a*), on-axis the opaque annulus acts as a simple circular aperture but as the field angle increases an additional crescent of light starts to enter the iris aperture, increasing the light flux reaching the retina. The unobstructed fraction of the area of the iris aperture is minimal on axis (about 30%) but rises to 100% for field angles greater than about 55°. For a 5 mm natural entrance pupil (*Figure* 4*b*), on-axis both an outer annulus and a circular central area of light enter the iris aperture, so that more (48%) of the iris aperture is effective than was the case for the smaller natural aperture. However, obscuration persists out to larger field angles (about 70°) than was the case with the smaller natural pupil. Evidently, if the retinal images are not precisely focused, the retinal blur patches would be expected to take forms corresponding to the effective pupil geometries of *Figure* 4, rather than being simple blur circles, although in practice this simple concept is modified by the effects of aberration and diffraction.

Figure 4 shows that while a simple circular stop, corresponding to the inner dimension of the annulus, would completely obstruct the outer peripheral field, the contact lens with the opaque annular stop allows unobstructed entry of light from larger field angles. Any loss in the light flux reaching the retina is therefore confined to small and intermediate field angles. This effect is shown in more detail in *Figure* 5. This gives the relative transmittance, i.e. the ratio of the unobstructed iris stop area with the inlay to the full stop area, as a function of the field angle for various natural entrance pupil diameters (2, 3, 4, 5, 6 mm). Three cases are illustrated, the first (green curves) for an opaque

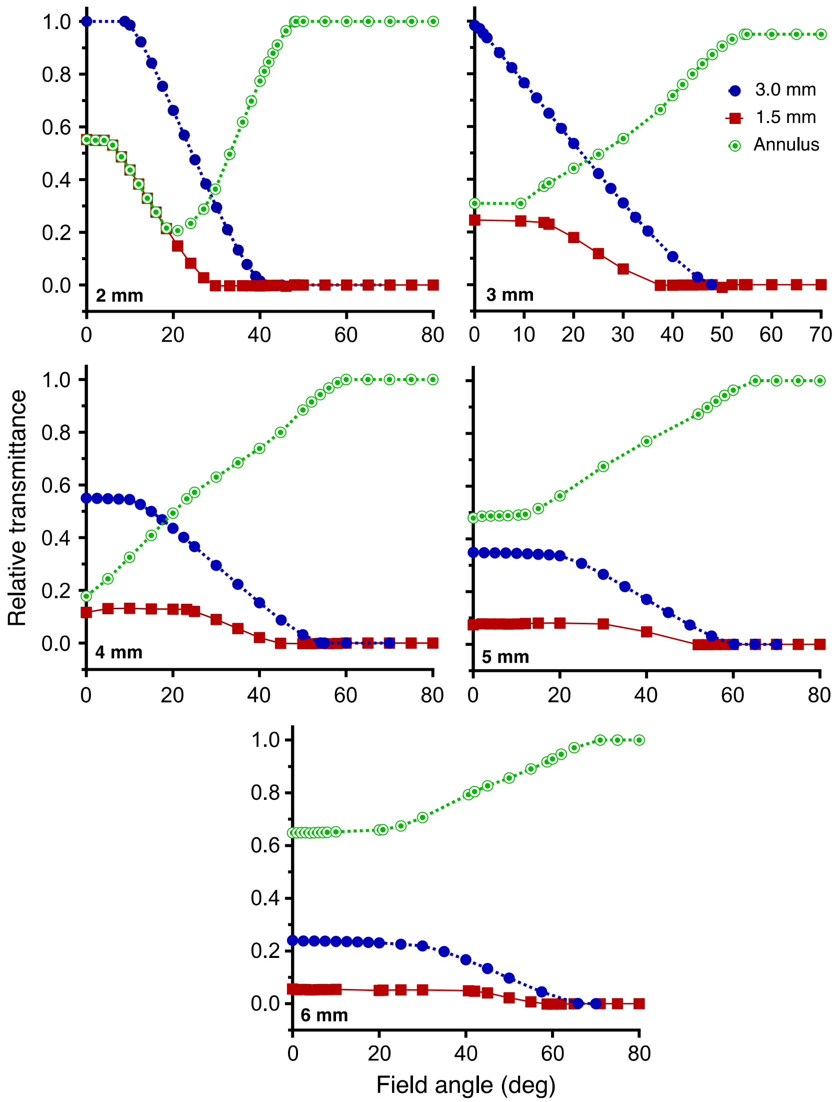

Figure 5. Relative transmittance as a function of field angle for natural entrance pupil diameters ranging from 2 to 6 mm. The blue and red curves show the relative transmittance for contact lenses with circular apertures of 3.0 and 1.5 mm diameter, respectively, and the green curves show the transmittance for the annular contact lens, with inner and outer diameters of 1.5 and 4.0 mm. Note that with the simple circular apertures, the relative transmittance falls to zero in the peripheral field, whereas that for the annular stop rises towards unity.

contact lens with a circular clear aperture of 1.5 mm in diameter (and a pupil area of 1.8 mm^2), the second (red curves) for an opaque contact lens with a circular aperture of 3.0 mm in diameter (and a pupil area of 7.1 mm^2), and the third (blue curves) for a clear contact lens with an opaque annulus having inner and outer diameters of 1.5 and 4.0 mm (and an opaque area of 10.8 mm^2), respectively.

Considering first the case of the simple circular 1.5 and 3.0 mm diameter apertures, it can be seen that on axis the relative transmittance declines as the natural entrance pupil diameter increases. Off-axis, it falls to zero at a field angle which increases with the diameter of the natural pupil. For a 4 mm natural pupil this angle is about 50° (green curve) and 55° (red curve) for the 1.5 and 3.0 mm apertures, respectively, so that there is a substantial restriction of the effective field. With the annular contact lens stop, however, there is no field restriction, since light entering the natural pupil from around the outer boundary of the stop contributes a progressively greater fraction of the light forming the retinal image. Note that, for on-axis vision, it is only when the natural entrance pupil is less than the outer 4.0 mm outer diameter of the opaque stop that all the relative transmittance is contributed by the central 1.5 mm diameter aperture. For larger natural pupils, any out-of-focus blur circles formed by the central aperture will be surrounded by 'blur annuli' due to the annular region between the inlay and the margin of the natural pupil (*Figure* 4*b*). It can be seen that, when the natural pupil is 2 mm, the annular stop leads to a marked annular field of reduced relative transmittance, with a mean radius about 20°. However, when the natural pupil exceeds about 3 mm, the relative transmittance is lowest at the centre of the field and then increases with field angle to reach unity at an angle that increases with the diameter of the natural pupil. These results are broadly in agreement with those of Langenbucher et al[19] for the KAMRA inlay, which are expressed in terms of relative illumination on the retina. Similarly the field limits with the circular contact lens apertures are similar to those found by Carkeet.[25]

Experimental results

If indeed contact lenses of design similar to those used in the theoretical analysis affect the pupil transmittance and hence the level and distribution of retinal illuminance, it might be expected that this would affect visual field measurements. Static perimetry was therefore used to explore this possibility.

Five volunteers (four females, one male) with an age range of 26–44 years participated in the study. Three of the volunteers were emmetropes while the other two were low myopes and no refractive correction was needed for the measurements since their visual acuity at 40 cm distance was better than 0.00 logMAR in each eye. The participants had no history of refractive or other ocular surgery. The study adhered to the tenets of the Declaration of Helsinki and all subjects gave their informed consent.

Recordings were performed using three afocal, hand-painted opaque soft contact lenses (74% water content), supplied by David Thomas Contact Lenses (www.davidthomas.com). Two were opaque over a 10 mm diameter but had central clear circular apertures of 1.5 and 3.0 mm in diameter. The third lens had an annular opaque zone with inner and outer diameters of 1.5 and 4.0 mm, respectively. A fourth, unpainted clear (plano) lens with the same basic characteristics was used for comparison purposes.

The lenses were inserted in the left eye of each volunteer, the right eye being occluded. Visual fields were evaluated with static automated perimetry (Medmont M700, stimulus Goldmann-size III-0.43°, www.medmont.com) in the horizontal meridian up to 50° eccentricity (1°, 3°, 6°, 10°, 15°, 22°, 30°, 40°, 50°), using the clear contact lens (baseline) and the above-mentioned small-aperture lenses. The background field had a luminance, L, of 10 apostilbs (3.2 cd m^{-2}). Sensitivity in dB was given as

$$\text{dB} = 10\log(1000/\Delta L)$$

where (ΔL) is the stimulus luminance with a maximum value of 1000 apostilbs. One dB steps were used during the establishment of thresholds.

Natural entrance pupil size as measured without the lenses *in situ*, using an IR pupil tracking providing a ×2.8 magnified image of the eye, averaged 4.0 mm (range 3.2–5.4 mm). Note that pupil size is expected to be slightly higher when any small-aperture lens is worn, due to the partial obscuration of the natural pupil, this effect being more pronounced the smaller the aperture.

Figure 6 shows average sensitivity values along the horizontal meridian of the field for the five volunteers and the four contact lenses. A drop in sensitivity as visual field angle increases is evident in all the small-aperture cases, with the effect being most pronounced, as expected, for the lens with the 1.5 mm aperture. Paired *t*-test analysis showed statistically significant differences in sensitivity ($p < 0.05$) between the clear lens and the 1.5 mm lens at 3°, 10°, 30°, 40°, 50° temporally and at 6°, 15°, 22°, 30°, 40° and 50° nasally. For the 3.0 mm lens, statistical significant differences in sensitivity were found at 30°, 40°, 50° temporally and 15°, 22°, 40° and 50° nasally, when compared to the clear lens. The annulus lens caused a significant decrease in sensitivity, compared to the clear lens, only at 30° temporally ($p = 0.048$), while at 22° the decrease was marginally non-significant ($p = 0.07$). An ANCOVA on the absolute thresholds, with visual field angle as a covariate and the type of contact lens as a factor, confirmed that

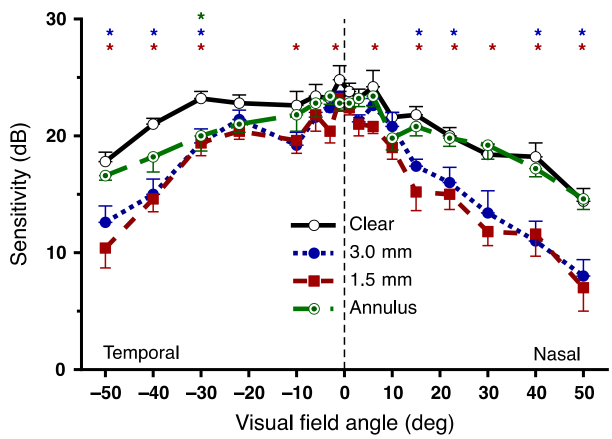

Figure 6. Mean sensitivity (S.E. bars) for the four conditions along the horizontal meridian of the field. The black curve is the baseline condition with the clear contact lens, while the blue and red curves show the sensitivities for contact lenses with circular apertures of 3.0 and 1.5 mm, respectively. The green curve shows sensitivity for the contact lens with the annular stop having inner and outer diameters of 1.5 and 4.0 mm. *Statistically significantly different from the clear lens condition (blue – 3.0 mm, red – 1.5 mm, green – annulus).

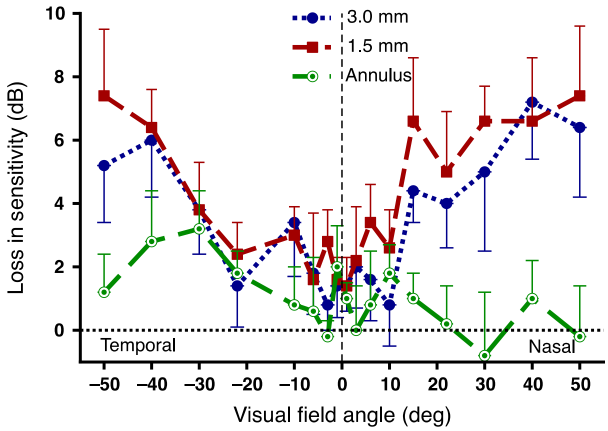

Figure 7. Mean sensitivity loss (S.E. bars) compared to the baseline condition, in which the participants were wearing a clear contact lens. The blue and red curves show the losses in sensitivities for contact lenses with apertures of 3.0 and 1.5 mm, respectively. The green curve shows sensitivity loss for the annular contact lens with inner and outer diameters of 1.5 and 4.0 mm.

whereas the 1.5 and 3.0 mm aperture results differed significantly ($p < 0.001$ in both cases) from those for the clear lens, those for the annulus did not ($p = 0.72$).

Figure 7 shows the differences between the sensitivities for each of the three small-aperture lenses and the baseline clear-lens condition, along the horizontal visual field. For each small-aperture lens there is a small loss in sensitivity over the central field. The sensitivity losses with the circular small-aperture lenses increase with field angle, but losses with the annular aperture lens do not show a trend with field angle.

Discussion

When comparing the theoretical and experimental results, it must be borne in mind that natural pupil diameters varied between subjects and that the various artificial pupils may not always have been exactly centred to the axis of the eye and the natural pupil. Some lens movement was also possible. A further problem is that, during the field measurements, the natural pupil diameters were probably a little larger when the small-aperture lenses were worn, due to the obscuration of the natural pupil, than when the clear 'baseline' lens was worn, Thus, the relative transmittances with the small-aperture lenses in comparison with the baseline case would be expected to be a little higher than those suggested in *Figure* 5.

Considering now the possible effect of each lens on the field, it is clear from *Figure* 5 that the two lenses with the simple circular apertures would be expected to reduce the relative transmittance to zero at specific field angles, i.e. they set absolute limits to the radius of the effective field. Within this limited field, retinal illuminance is always lower than in the baseline condition and falls markedly with increasing field angle. In contrast, the annular stop has no effect on the absolute field but transmittance is reduced over the central area of the field, the exact effects depending upon the natural pupil diameter.

Any reduction in retinal illuminance caused by reduced relative transmittance affects both the background (L) and the stimulus (ΔL). Since the visibility of the stimulus depends upon the Weber–Fechner fraction (stimulus luminance/background luminance, or $\Delta L/L$), and this is approximately constant while the background continues to lie within the photopic range, the lenses should have minor effects provided the relative transmittance remains reasonably high.[29] However, as can be seen in *Figure* 5, relative transmittance falls to progressively lower levels towards the edge of the available field for the lenses with circular apertures, to ultimately reach zero. It would therefore be expected that the Weber–Fechner fraction would rise as the field margins were approached, producing a loss in sensitivity.

Considering now the experimental results it can be seen from *Figures* 6 and 7 that these broadly agree with these theoretical expectations, although only a relatively small cohort was tested. With the simple 1.5 and 3.0 mm pupils, only minor losses in sensitivity (≤3 dB) occur across the central 10° radius of the field. Beyond this, sensitivity losses steadily increase, presumably because the retinal illumination levels are falling progressively further into the mesopic range. Referring to *Figure* 5, the expected absolute limits to the field, where the relative transmittance falls to zero, are dependent on the natural pupil diameter during the field measurements. Since the natural pupil under the clear-lens baseline conditions was about 4 mm, we expect that the pupil dilated slightly, to around 5 mm, behind the simple circular aperture lenses. *Figure* 5 then suggests that under these conditions the field boundary should lie at field angles of about 60°, which is compatible with the trend of the observed loss in sensitivity at field angles beyond 30° (*Figure* 7). For comparison, Gabriel *et al.*,[30] using kinetic perimetry and a 31.8 cd m^{-2} Goldmann I-0.11° stimulus, found that the area of the visual field was limited to about 2.8 steradians in subjects wearing contact lenses with a 3 mm clear aperture, corresponding to a field radius of about 54°.

The field results with the annular stop show only slight loss in sensitivity (≤3 dB) over the measured field (*Figure* 7). This is as expected, since with relatively large natural pupil diameters the relative equivalent transmittance values are quite high at most field angles (*Figure* 5) and thus the Weber–Fechner fraction should be almost constant. For comparison, in broadly similar static perimetric studies (bowl luminance 3.2 cd m^{-2}, with a Goldman

II-0.21° stimulus) in which visual fields were compared when either a mydriatic or a miotic drug was instilled in the subjects' eyes, Wood *et al.*[29] found that the difference in pupil size (around 7 mm compared to 3 mm, giving a factor of 5 between the areas) was associated with a difference in sensitivity of around 3 dB at field angles 10–50°.

The present theoretical and experimental results successfully reconcile earlier clinical findings that KAMRA inlays have no significant effect on measurements of the visual field with the observation that they introduce annular shadows and other artefacts in some types of fundus imaging. They confirm that, although annular KAMRA-type stops introduce variations in illuminance across the fundus, they have little effect on the visual field. This accords with the earlier clinical findings[18] and differs from the field restrictions introduced by devices with simple circular apertures.[25] Although presbyopes are likely to have smaller pupils, which will produce greater local variations in retinal illuminance (*Figure* 5), any practical effect will be limited since the inlay is normally implanted in only one eye and may not affect the binocular visual field. Under binocular conditions, it appears likely that the associated interocular differences in retinal illuminance are too small to cause significant losses in stereopsis,[31] although Pulfrich-type effects may occur.[16,17] The vignetting effects of the KAMRA inlay can, however, cause detectable 'shadows' or other artefacts during some types of fundus photography, with the exact effects depending upon the ray paths of the illuminating and observation beams of the particular instrument.[20,21,29]

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Disclosure

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