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OBJECTIVE AND SUBJECTIVE EVALUATION OF DYSPHOTOPSIA IN NORMAL AND POST-OPERATIVE EYES

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Doctor of Philosophy

ASTON UNIVERSITY

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Maana Kaur Aujla asserts her moral right to be identified as the author of this thesis

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Abstract

The principle theme of this thesis is the measurement of dysphotopsia, a common complaint in both the ageing population and after cataract or refractive surgery. Despite the availability of multiple objective and subjective methods to measure dysphotopsia, no single method is in common use, nor are photic effects commonly measured prior to cataract or refractive surgery. In this thesis, objective measures are taken using the Aston halometer and C-Quant, whilst subjective complaints are graded using simulated images.

Whilst many previously published studies have reported monocular halometry results, an early study in the thesis found monocular halo areas to be approximately 30% larger ($P < 0.001$) than the binocular area, indicating the effect of binocular summation on objective measures of halo area. The thesis investigates the link between objective measures and subjective complaints of dysphotopsia. Subjective complaints were not linked to binocular halo area ($P = 0.478$), monocular halo area ($P = 0.896$) or C-Quant straylight values ($P = 0.128$). Halometry and C-Quant also showed no relationship ($P = 0.229$). The results highlight the difficulties in being able to predict the potential subjective complaints a patient may experience from objective measures alone. However, a weak correlation was found between binocular halo area and subjective night halo complaints ($r_s = 0.330$, $r_s^2 = 0.109$, $P < 0.001$), which may be due to the fact that halo area assessed would relate directly to the night halo image on the photographic images of photic phenomena (PIPP) plates.

Binocular and monocular halo areas both increased with age ($r_s = 0.449$, $r_s^2 = 0.202$, $P < 0.001$ and $r_s = 0.403$, $r_s^2 = 0.162$, $P < 0.001$, respectively) in healthy eyes ($n = 141$, age range 18 – 82 years). Retinal straylight values also increased significantly with age ($r_s = 0.457$, $r_s^2 = 0.209$, $P < 0.001$), as did subjective grading ($r_s = 0.314$, $r_s^2 = 0.099$, $P < 0.001$). The results indicate a significant age-related increase in dysphotopsia, even in healthy eyes, which is attributed to media changes over time.

Due to the effects of a bright light source on the pupil size, and the issue of senile miosis, this programme of research considered, for the first time, whether pupil size had an effect on the size of the halo area measured with halometry. No significant difference in halo area with various simulated pupil sizes (4.5, 6.0 and 7.5 mm) was detected ($\chi^2 (3) = 7.56$, $P = 0.056$). The Aston halometer is therefore a robust way to evaluate dysphotopsia without measuring or controlling pupil size.

A longitudinal study tracked photic effects in individuals for a year after laser-assisted in situ keratomileusis, and another measured dysphotopsia pre- and up to a year post-cataract surgery. Subjective complaints resolved by 3 months post-refractive surgery, objective halo area took 6 months to resolve post-cataract surgery and up to 12 months post-corneal refractive surgery. A glare effect ratio was calculated for binocular halometry (median = 1.28; IQR 0.75 – 2.15) and retinal straylight (median = 5.63; IQR 2.72 – 7.97). The glare effect ratio is independent of age, and it is suggested that the glare effect ratio could be used to identify individuals most at risk of significant subjective complaints of dysphotopsia following procedures such as corneal refractive surgery.

Key words: Dysphotopsia, glare, halos, photic phenomena, refractive surgery.
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<td>DGI</td>
<td>Disability Glare Index</td>
</tr>
<tr>
<td>EDTRS</td>
<td>Early Treatment Diabetic Retinopathy Study</td>
</tr>
<tr>
<td>ESD</td>
<td>Estimated Standard Deviation</td>
</tr>
<tr>
<td>FDT</td>
<td>Functional Disability Test</td>
</tr>
<tr>
<td>IOLs</td>
<td>Intraocular Lenses</td>
</tr>
<tr>
<td>IQR</td>
<td>Interquartile Range</td>
</tr>
<tr>
<td>LASEK</td>
<td>Laser-assisted sub epithelial keratectomy</td>
</tr>
<tr>
<td>LASIK</td>
<td>Laser-assisted in situ keratomileusis</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>LOCS</td>
<td>Lens Opacities Classification System</td>
</tr>
<tr>
<td>LogMAR</td>
<td>Logarithm of the Minimum Angle of Resolution</td>
</tr>
<tr>
<td>MTF</td>
<td>Modular Transfer Function</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>Neodymium-doped yttrium aluminium garnet</td>
</tr>
<tr>
<td>NHS</td>
<td>National Health Service</td>
</tr>
<tr>
<td>PCO</td>
<td>Posterior Capsule Opacification</td>
</tr>
<tr>
<td>PERK</td>
<td>Prospective Evaluation of Radial Keratotomy</td>
</tr>
<tr>
<td>PIPP</td>
<td>Photographic Images of Photic Phenomena</td>
</tr>
<tr>
<td>PMMA</td>
<td>Polymethyl Methacrylate</td>
</tr>
<tr>
<td>PRK</td>
<td>Photorefractive Keratotomy</td>
</tr>
<tr>
<td>PVD</td>
<td>Perceived Visual Disability</td>
</tr>
<tr>
<td>RK</td>
<td>Radial Keratotomy</td>
</tr>
<tr>
<td>Sqd</td>
<td>Square degrees</td>
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<tr>
<td>UCVA</td>
<td>Uncorrected Visual Acuity</td>
</tr>
<tr>
<td>UHB</td>
<td>University Hospitals Birmingham</td>
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<tr>
<td>VA</td>
<td>Visual Acuity</td>
</tr>
</tbody>
</table>
1.1. General introduction

Dysphotopsia including glare and halos is common after cataract surgery with implantation of intraocular lenses (IOLs), or after laser refractive surgery (Tester et al., 2000, Gutierrez et al., 2003, Jabbur et al., 2004, Souza et al., 2006, Cervino et al., 2011, de Vries and Nuijts, 2013). It is usually more profound in patients fitted with multifocal IOLs (Akutsu et al., 1993). Despite good distance and near visual acuity, quality of life may be affected if activities such as night driving are compromised (Tester et al., 2000, Souza et al., 2006). Previously published work report dysphotopsia such as glare and halos as being the most common cause of dissatisfaction (Tester et al., 2000, Souza et al., 2006, de Vries and Nuijts, 2013). As many as 50 % of those implanted with IOLs complain of glare symptoms (Woodward et al., 2009, de Vries et al., 2011, Chang et al., 2012). Multifocal IOLs are more likely to cause photic phenomena than monofocal IOLs (Leyland and Pringle, 2006). Some patients only experience mild subjective complaints; however, there are a few who find it that detrimental to their quality of life that they request the precarious procedure of IOL explantation (Davison, 2000, Mamalis, 2000, Tester et al., 2000, Pepose, 2008, Mainster and Turner, 2012). No evidence based approach is in use pre-operatively to attempt to identify individuals who might be most severely affected subjectively; with surgeons basing the decision of whether to operate on the patients’ personality rather than using a clinical method (Pepose, 2008, Braga-Mele et al., 2014).

Almost a century of research into dysphotopsia has resulted in vast literary coverage of the subject. As such, rather than offering an exhaustive review of previous literature, this report considers key matters most relevant to the author’s research. Different definitions of dysphotopsia are detailed, along with the theories and causes. Methods used to measure amounts of dysphotopsia are discussed, with particular attention paid to halometry and the retinal straylight.

1.2. What is dysphotopsia?

Dysphotopsia describes any undesirable light-related visual phenomenon and may be experienced by both phakic and pseudophakic patients (Tester et al., 2000). Dysphotopsia is classified into two main types; positive and negative. Negative dysphotopsia denotes the perception of a dark crescent in the temporal visual field (Schwiegerling, 2006, Osher, 2008). Positive dysphotopsia encompasses effects such as flashes of light, arcs,
increased light sensitivity, glare, halos (Tester et al., 2000), and is perhaps the most common type experienced by patients (Souza et al., 2006, de Vries and Nuijts, 2013).

There are many different ways in which to describe the term glare. Glare is the result of light entering the eye that does not aid vision, usually too intense or a variable environmental luminance across the visual field (Wordenweber, 2010). Inevitably, most adults will have experienced glare at some point. For example, when driving towards the sun while it is low in the sky, driving at night with on-coming cars with undipped headlights, or walking down dark streets at night with poorly shielded street lamps. These sources of glare involve small bright lights in a relatively darker field, making it difficult to see objects near to the source of glare (Smith, 2002). This is known as disability glare, also known as physiological glare (Vos, 2003b, Schreuder, 2008). Glare is not only caused by small bright light sources, but can also occur when the extended field of view is brighter than we can normally adapt to (Smith, 2002). Sunlight reflecting off snow at high altitudes often has this effect. Extended light sources with luminance of greater than about 10,000 cd/m² usually lead to some feeling of discomfort (Smith, 2002). Fresh snow in bright sunlight can have a luminance of up to 30,000 cd/m², which is usually beyond the comfort zone (Smith, 2002). Glare of this type is called discomfort glare, also known as psychological glare (Vos, 2003b, Schreuder, 2008).

Thus there are two main types of glare; discomfort glare and disability glare. In simple terms, discomfort glare is glare that causes discomfort, without leading to a decrease in vision. In contrast, disability glare may not cause any discomfort, but leads to some loss of vision (Smith, 2002).

The term disability glare is used when the visibility of an object is reduced due to a bright light source in the visual field (Koch, 1989, Aslam et al., 2007b, Allen et al., 2009). The resultant increase in intraocular light scatter or straylight from the bright light source causes a veiling glare and a loss of contrast across the retinal image (Vos, 1984, van den Berg, 1995, Aslam et al., 2007b, Allen et al., 2009). A loss in contrast typically reduces the observer’s ability to distinguish detail within a visual scene. Contrast is decreased by a factor equal to background luminance divided by the sum of veiling and background luminances (Smith, 2002, Narisada and Schreuder, 2004). Veiling luminance from straylight depends on (1) the illuminances that glare sources produce at the observer’s eye and the angular distance between those sources and the observer’s visual axis (Holladay, 1926, Vos, 1984, Smith, 2002) and (2) the observer’s age and pigmentation (Wolf, 1960, Vos, 1984, Elliott and Bullimore, 1993).

Disability glare is usually encountered in scotopic light conditions as pupil dilation allows more intraocular scatter to enter from the glare source (Allen et al., 2009). Dim light makes
contrast loss more significant as rod photoreceptors need larger contrast differences for
target detection than cones (roughly 20 % vs 1 %, respectively; Smith, 2002,
glare gives an understanding of the patient’s actual experience of the visual impairment
(Vos, 2003b, Aslam et al., 2007b, Schreuder, 2008), inducing an almost complete blindness
close to the light source whilst only hampering visual performance when further away

Discomfort glare is caused by illumination that is too intense for an individual; classed as a
normal response to abnormal illumination. Discomfort glare causes an annoyance resulting
in squinting, distraction, blinking, tearing and light aversion (Bullough, 2009,
Fekete et al., 2010). The threshold for discomfort glare varies considerably between
individuals as it depends on a person’s adaptation luminance and the characteristics of
surrounding natural and artificial light sources (luminaires). Glare is intensified by increasing
the number and luminance of light sources, or by decreasing the angular separation
between glare sources and the visual axis (Narisada and Schreuder, 2004,
discomfort, with recent data showing that the sensitivity spectra for discomfort glare peak
between 510 and 550 nm (green) for light exposures within 5 degrees of the visual axis
(Bullough, 2009, Fekete et al., 2010). In general, the relative contributions of rod, cone, and
retinal ganglion photoreceptors to visual discomfort probably vary considerably for different
people and glare situations (Mainster and Turner, 2012).

For people with normal binocular vision, shutting one eye decreases binocularly summed
retinal illuminance, therefore reducing discomfort glare, photophobia and dazzle
(Bourassa and Witschafeter, 1966, Witschafeter and Bourassa, 1966, Plainis et al., 2006).
Conversely, if someone with normal binocular vision views a scene with a neutral-density
filter over one eye, shutting that eye increases image brightness even though total retinal
illuminance has decreased (a phenomenon known as Fechner’s paradox; Mainster and
Turner, 2012). Thus, emphasizing that discomfort glare does not depend on brightness
(Bourassa and Witschafeter, 1966, Witschafeter and Bourassa, 1966, Plainis et al., 2006),
and that there is a difference between brightness perception and the luminance of light
sources (Hopkinson, 1957, Lennie et al., 1993, Rea et al., 2011). Discomfort glare varies
little with age (Narisada and Schreuder, 2004), unlike disability glare (Wolf, 1960, Elliott and

The term dysphotopsia encompasses more phenomena than glare alone. There are
currently ten different types that are recognised: dark arc, bright arc, bright room, night
halos, night starburst, day halos, day starburst, central flash, streaks of light and ripple effect (Aslam et al., 2004a). A commonly reported complaint is halos; the subjective perception of a bright ring around a light source (Aslam et al., 2007b, Buznego and Trattler, 2009). The effect is regularly perceived when looking at a bright light source in the dark, such as when looking at street lamps on a foggy night. This type of dysphotopsia is formed by light rays that are scattered outside the focussed image creating a dim disc of light around the light source (Allen et al., 2009). Although visual acuity is normal, the effect of the bright headlight causes such a severe detriment to the vision of some that it causes individuals to stop driving, which in turn reduces quality of life (Ranney et al., 2000, Theeuwes et al., 2002).

In the field of ophthalmic science the key scattering component to analyse is the forward scattering, which occurs when light is incident to the retina causing a veiling luminance superimposed on the retinal image reducing retinal contrast (Dewaard et al., 1992, Aslam et al., 2007b, van den Berg et al., 2013). Backward scatter is the dispersion of light reflected out of the eye and is typically used in slit lamp examination to assess the quality of ocular tissues (McCally et al., 2007, Patel et al., 2007). Back scattered light is not a cause of any photic effects as it only reduces the amount of light reaching the retina (Atchinson and Smith, 2000).

1.3. Light scattering theory

The initial light scattering theory was that of Rayleigh light scattering in which forward scatter was said to be equal to backward scatter, however, it was only applicable to small spherical particles with a diameter of less than one tenth of the wavelength of the incident light (Hahn, 2006, Piñero et al., 2010, van de Hulst, 2012). Blue light is scattered more than red as according to Rayleigh scattering, it is more effective at short wavelengths (Aslam et al., 2007b).

The theory of Mie light scattering however, accounts for general scattering independent of particle size. Intensity and direction of scattered light are a function of the scattering properties of the media and the wavelength of the incident light (van de Hulst, 2012). According to the Mie theory, the intensity and direction of scattered light by an isotropic, homogeneous and spherical particle can be calculated using the following mathematical relationship, assuming a flat monochromatic incident wavefront and homogeneous surrounding medium (van de Hulst, 2012):
\[ I_s(x, m, \theta) = s^2(x, m, \theta) \frac{I_0 \lambda^2}{4\pi^2 d^2} \]

Equation 1.1

Where \( I_s \) is the intensity of scattered light, \( s \), the scattering coefficient of the particle for which Mie derived exact formulas, \( I_0 \), the intensity of incident light, \( \lambda \), the wavelength of light, and \( d \), the position where the scattering is measured. Therefore, increased light scatter occurs for longer wavelengths, higher intensities and with light sources that are closer to the eye.

\( I_s \) and \( s \) parameters are a function of three parameters, the angle of incident light (\( \theta \)), \( x \) and \( m \). \( x \) and \( m \) are calculated with the following expressions (Piñero et al., 2010):

\[ x = \frac{\pi D}{\lambda}; m = \frac{n_1}{n_2} \]

Equation 1.2

Where \( D \) is the diameter of the spherical particle, \( n_1 \), the index of refraction of the particle, and \( n_2 \), the index of refraction of the surrounding media. Equation 1.1 is therefore dependent on the size of the particle and the wavelength of the light, where a larger particle would cause more scattering as would short wavelength light. A greater difference between the refractive index of the particle and the surrounding media would also cause increased scattering.

In the eye, most light scatter is not wavelength dependent, and thus Mie’s theory stands (Wooten and Geri, 1987, Holden et al., 1993). Mie scattering of light is of important use as it predicts that assessment of back scatter during slit lamp examination, does not necessarily equate to the amount of forward scatter on the patient’s retina (Bettelheim and Ali, 1985, Weale, 1986, Dewaard et al., 1992, Holden et al., 1993, Donnelly et al., 2004, Aslam et al., 2007b).

In an ideal eye with optically-clear media and perfect optical surfaces, no back and forward scatter would occur. However, the human eye is imperfect and each of the various structures within the eye contributes to the amount of light scatter through diffraction and aberration (see Fig 1.1 and Table 1.1). In normal individuals, previous authors have estimated that the cornea accounts for about 30 %, the lens 40 % and retina approximately 20 % of scattered light (Yuan et al., 1993). Similarly, Vos (2003a) approximated that 20 %
of the glare veil is caused by the retina, when it comes to scattering from the fovea towards the periphery; the cornea and lens together make up about 60 % of the veiling luminance.

**Figure 1.1:** Sources of ocular scatter, values from Yuan et al. (1993)

van den Berg et al., 1991). The amount of light that can pass through is dependent on the level of pigmentation, whereby blue/green eyes with lower amounts of pigmentation would transmit and scatter more light than dark brown eyes (van den Berg et al., 1991). When light reaches the retina, some of it is absorbed, whilst some is reflected back contributing to the intraocular scattering (van den Berg et al., 1991); this type of scattering is also dependent on the subjects’ level of pigmentation. The vitreous humour is usually a transparent gel due to the regular structure of its fibrils. The transparency of this element may be severely affected by the presence of blood or cells in pathological conditions such as vitreous haemorrhage or posterior uveitis (Piñero et al., 2010).
<table>
<thead>
<tr>
<th>Source</th>
<th>Key Points</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cornea</strong></td>
<td>- Increased scattering when transparency is reduced.</td>
</tr>
<tr>
<td></td>
<td>- Corneal Surgery – Photorefractive Keratectomy/Radial Keratotomy/LASEK/LASIK.</td>
</tr>
<tr>
<td></td>
<td>- Corneal Haze – Oedema/Dystrophies/Wounds.</td>
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<tr>
<td></td>
<td>- Contact lens induced corneal oedema.</td>
</tr>
<tr>
<td><strong>Crystalline Lens</strong></td>
<td>- Increased scattering when transparency is reduced.</td>
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<tr>
<td></td>
<td>- Cataract.</td>
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<td></td>
<td>- Posterior Capsular Opacification.</td>
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<tr>
<td><strong>Iris</strong></td>
<td>- Allows some light to pass through from outside the eye when not completely opaque.</td>
</tr>
<tr>
<td></td>
<td>- Fuchs’ heterochromic cyclitis (iris translucency).</td>
</tr>
<tr>
<td></td>
<td>- Reduced pigmentation in albinism allows more light to pass through.</td>
</tr>
<tr>
<td></td>
<td>- Blue/green eyes have less pigmentation, so would transmit and scatter more light than highly pigmented brown eyes.</td>
</tr>
<tr>
<td><strong>Sclera</strong></td>
<td>- Allows light to partly pass through from outside the eye when not completely opaque.</td>
</tr>
<tr>
<td></td>
<td>- Reduced pigmentation allows more light to pass through, again blue/green eye have less pigmentation, so would transmit and scatter more light than highly pigmented brown eyes.</td>
</tr>
<tr>
<td><strong>Retina</strong></td>
<td>- Some incident light is absorbed, whilst some is reflected back, contributing to intraocular scatter.</td>
</tr>
<tr>
<td></td>
<td>- Reduced pigmentation will result in less absorption, and more light will be reflected back.</td>
</tr>
<tr>
<td><strong>Vitreous Humour</strong></td>
<td>- The presence of blood or cells creates irregularities in the transparent media off which more scatter occurs.</td>
</tr>
<tr>
<td></td>
<td>- Posterior Uveitis.</td>
</tr>
<tr>
<td></td>
<td>- Vitreous Haemorrhage.</td>
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<tr>
<td></td>
<td>- Floaters.</td>
</tr>
<tr>
<td><strong>Intraocular Lenses</strong></td>
<td>- Increased ocular scattering with multifocal IOLs as they produce two or more focal points simultaneously.</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td>- Increase with age due to lenticular changes, such as increased density and increased homogeneity, causing more scatter.</td>
</tr>
<tr>
<td><strong>Pathology</strong></td>
<td>- Choroideremia.</td>
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<td></td>
<td>- Retinitis Pigmentosa.</td>
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<td></td>
<td>- Hereditary Corneal Dystrophies.</td>
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<td></td>
<td>- Keratoconus.</td>
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<tr>
<td><strong>Angle of incidence of glare source</strong></td>
<td>- Smaller angle between glare source and visual axis results in increase scattering.</td>
</tr>
<tr>
<td><strong>Uncorrected Astigmatism</strong></td>
<td>- Especially for higher cylinders (&gt;1.00 DC).</td>
</tr>
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</table>

Table 1.1: Summary of keys causes of straylight.
Stiles (1929) and Holladay (1926) used the idea of veiling light falling on the retina from a bright light source reducing the contrast of the retinal image in the formulation of the disability glare equation (Cobb, 1911). The Stiles-Crawford effect states that light entering the eye via the centre of the pupil is about five times more effective than light entering the periphery of the pupil (Snyder and Pask, 1973, Marcos and Burns, 2000). In the eye the strength of this veiling light (equivalent veiling luminance) can be calculated and used as a measure of glare. The value found is dependent on the angular distance (θ) of the glare light from the object being viewed (Vos, 2003a) and the strength of light falling in the plane of the eye (veiling luminance):

\[ L_v(\theta) = \left[ 10E/\theta^2 \right] \text{ for } 1^\circ < \theta < 30^\circ \]

**Equation 1.3**

Where \( L_v \) = luminance of the veiling background (cd/m²), \( E \) = illumination (lux) incident on the cornea and \( \theta \) = the angle between the line of sight and glare source (°). Thus, a greater veiling glare luminance shall be experienced as the incident angle of the glare source approaches the visual axis (θ). Extensive studies reviewed by Vos (2003a) have validated this formula for angles between 1 - 30°.

The Commission Internationale de l’Eclairage (CIE) modified this expression to take into account the age of the subject, the level of pigmentation and angles outside 1 - 30° range (Aslam et al., 2007b). When adapted for age, the new version of the equation shows that disability glare tends to increase rapidly beyond the age of 60 years. A simplified version is (Vos and van den Berg, 1999):

\[ \left( \frac{L_{veil}}{E_{glare}} \right) = 10 \left( 1 + \left[ \frac{Age}{70} \right]^4 \right) \frac{1}{\theta^2} \]

**Equation 1.4**

Where \( L_{veil} \) = luminance of the veiling background (cd/m²), \( E_{glare} \) = illumination (lux) incident on the cornea, and \( \theta \) = the angle between the line of sight and glare source (°).

The initial Rayleigh light scattering theory was dependent on short wavelength light, and only held true for small particles. Mie scattering, however, could be used for particle of any size, and was independent of the wavelength of the incident light. The veiling luminance equation was limited to glare sources less than 30° from the line of sight. The CIE modified the veiling luminance equation to take into account further factors that cause glare including
age and level of pigmentation, as well as standing true for angles outside the 30° range. The latter is the most commonly used theory when looking at glare now.

1.4. Why measure dysphotopsia?

An increase in intraocular straylight may be one of the most important causes of photic complaints because it results in a visual handicap of much more than the general nature of glare alone (Piñero et al., 2010, van den Berg et al., 2013). Patient complaints include problems of ‘hazy vision’, difficulties in recognising faces when looking against the light, and halos around bright lights in low light conditions. Even in photopic conditions, loss of contrast and colour can occur (Piñero et al., 2010). These effects are further enhanced when a driver tries to identify low contrast objects, such as unilluminated obstacles or pedestrians along the roadside at night time (Theeuwes et al., 2002); highlighting why measurements of glare sensitivity are considered important for the assessment of drivers (Mantyjarvi and Tuppurainen, 1999).

Dysphotopsia is a well-known complaint after refractive surgery or cataract surgery (Tester et al., 2000, Souza et al., 2006, Woodward et al., 2009, Chang et al., 2012, de Vries and Nuijts, 2013). Such surgeries are becoming increasingly common since the introduction of multifocal IOLs, which allow patients spectacle independence as good distance and near visual acuity are achieved (Schwiegerling, 2006, Calladine et al., 2012). Multifocal IOLs create two or more focal points focused at different planes. For distance viewing, the distance focal point produces a spot image with the near focal point creating an out of focus blur circle on the retina. The surrounding blur results in the retinal image having less contrast against its background and therefore, also results in the halo phenomenon (Buznego and Trattler, 2009). Previously published work report dysphotopsia such as glare and halos as being the most common cause of dissatisfaction (Tester et al., 2000, Souza et al., 2006, de Vries and Nuijts, 2013). Various studies have reported on the amount of patients implanted with IOLs that complain of dysphotopic symptoms (see Table 1.2). Souza et al. (2006) reported values of 13 % and 20 % of glare and halos respectively in 30 eyes fitted with monofocals; these values increase to 40 % and 50 % of 50 eyes, respectively with multifocals. Woodward et al. (2009) discovered 42 % of 43 eyes fitted with multifocal IOLs complained of photic phenomena, although 8 of these 18 eyes effects were attributed to posterior capsular opacification. In a study by de Vries et al. (2011), a value of 38.2 % of 76 eyes receiving multifocal IOL implantations had dysphotopsia. Chang et al. (2012) investigated 45 eyes for complaints of halo, night glare, and starburst; with 48 %, 15 % and 22 %, respectively, experiencing moderate to severe symptoms. A 2006 Cochrane review of multifocal IOLs found that photic phenomena
are 3.5 times more likely with multifocal IOLs than with monofocal IOLs (Leyland and Pringle, 2006). The subjective complaints of glare and halos can vary greatly from mild, to quite severely debilitating, to the extent that a patient requests IOL explantation; which in itself carries inherent risks (Tester et al., 2000, Pepose, 2008). A retrospective review of 44 patients dissatisfied with visual outcomes after multifocal IOL implantation aimed to devise a symptom-specific treatment algorithm to maximise post-operative outcomes with minimally invasive treatment strategies (Woodward et al., 2009), highlighting the need to avoid explantation and if possible distinguish those potentially problematic patients pre-operatively.

<table>
<thead>
<tr>
<th>Author and key features of the study</th>
<th>Proportion of patients experiencing dysphotopsia</th>
</tr>
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<tbody>
<tr>
<td><strong>Souza et al. (2006)</strong></td>
<td>• 13 % and 20 % reported of glare and halos respectively with monofocal IOLs</td>
</tr>
<tr>
<td>n = 30 eyes of 15 patients in monofocal group, 50 eyes of 25 patients in multifocal group</td>
<td>• 40 % and 50 % respectively with multifocal IOLs</td>
</tr>
<tr>
<td><strong>Woodward et al. (2009)</strong></td>
<td>• 42 % of the multifocal IOLs patients complained of photic phenomena</td>
</tr>
<tr>
<td>n = 43 eyes of 32 patients</td>
<td></td>
</tr>
<tr>
<td><strong>de Vries et al. (2011)</strong></td>
<td>• 38.2 % of multifocal implantations had dysphotopsia</td>
</tr>
<tr>
<td>n = 76 eyes of 49 patients</td>
<td></td>
</tr>
<tr>
<td><strong>Chang et al. (2012)</strong></td>
<td>• Complaints of halo, night glare, and starburst were 48 %, 15 % and 22 %, respectively with multifocal IOLs</td>
</tr>
<tr>
<td>n = 45 eyes from 29 patients</td>
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</table>

**Table 1.2:** Summary of reports on the proportion of patients implanted with IOLs that complain of dysphotopsia.

Cataract surgery techniques have improved with the use of phacoemulsification and small incision surgery that now with careful biometry, refractive outcomes can be predicted. This has led to clear lens extraction or refractive lens exchange as a method of refractive surgery, especially in older patients or higher refractive errors. The need to measure glare is becoming ever more important as patients are being fitted successfully with multifocal IOLs, not only in cataract surgery but also with refractive lens exchange as an alternative to laser eye surgery in presbyopia (Barisic et al., 2008, Chang et al., 2012). Refractive lens exchange is becoming increasing popular as it is an easy procedure that addresses both
refractive error and presbyopia (Goes, 2008). Multifocal IOLs now increases the likelihood of spectacle independence (Pager, 2004, Hawker et al., 2005, Munoz et al., 2011, Ferrer-Blasco et al., 2012). Previous presbyopic correction options with laser included PresbyLasik and monovision; however these were not commonly recommended procedures due to the variable outcomes. With refractive lens exchange, the goal after IOLs implantation has altered, it is no longer accepted to simply remove the cataractous lens, replacing it with an IOL of a close pre-operative refractive error (Lichtinger and Rootman, 2012); it also comes with increased patient expectation of the achievement of the best possible refractive outcome with restoration of vision for near and distance without spectacles (Aslam et al., 2004a, Pager, 2004, Hawker et al., 2005, Munoz et al., 2011, Braga-Mele et al., 2014). It has become increasingly common that a lot refractive lens exchange patients have no refractive error for distance pre-operatively, and have the surgery simply to be rid of their reading spectacles (Schena, 2005). In these cases, it is more evident that patients with moderate visual acuity pre-operatively are less happy with making the trade-off of good visual acuity at the cost of troublesome glare and loss of contrast sensitivity (Aslam et al., 2007b). Chang et al. (2012) found that the most satisfied patients were those who underwent bilateral refractive lens exchange and were habitual spectacle wearers pre-operatively. Considering that dysphotopsia is a chief complaint after otherwise successful cataract surgery (Tester et al., 2000, Welch et al., 2010, Kinard et al., 2013); there are few studies that have investigated the change in objective and subjective measures of dysphotopsia in response to cataract surgery. Whilst some studies have reported post-operative effects, they are rarely on a longitudinal basis (Aslam et al., 2007) with no pre-operative measures for comparison.

One of the biggest challenges is that there is currently no evidence based approach used pre-operatively to attempt to identify individuals who might be most severely affected subjectively; with some surgeons suggesting that prospective patients who have a Type A personality or simply ask too many questions should be refused multifocal IOLs (Pepose, 2008, Braga-Mele et al., 2014). Patients who do happen to suffer from dysphotopsia post-refractive surgery are often told that it will reduce over time, with very little evidence in place to support whether it does in fact reduce (Arnold, 1994, Davison, 2000). Whilst anecdotal evidence suggests that subjective photic effects reduce with time following laser refractive surgery, there is a lack of empirical data to support this viewpoint past 6 months. It is also unclear how much of the apparent improvement is due to a subjective acceptance of the disturbances (by neural adaptation) or an actual physical reduction in halo area (Fan-Paul et al., 2002) and straylight. A subjective study which examined pseudophakic patients at 12 to 18 months after surgery found that 17 of 55
patients still complained of symptoms of halos and glare at night and day, although arc effects and central flash seemed to be less common (Aslam et al., 2007a).

Various methods developed to quantify the amount of light scatter experienced by an individual, such as representative pictures (Hunkeler et al., 2002, Aslam et al., 2004a), subjective questionnaires (Shoji and Shimizu, 1996, Jacobi et al., 2003, Kohnen et al., 2006, Harman et al., 2008), glare testers (measuring the size of halo; Miller et al., 1972, Bores, 1983, Holladay et al., 1987, Bailey and Bullimore, 1991, Gutierrez et al., 2003, Allen et al., 2008, Babizhayev et al., 2009) and psychophysical techniques (van den Berg, 1986, Cervino et al., 2008). Several instruments provide coefficients that indirectly measure ocular scattering, but most do not have clinical validation. Currently there is still no widely accepted test for glare (Rubin, 1990, van den Berg, 1991, Elliott and Bullimore, 1993), as there is no standard definition for the parameters that should be used to characterise ocular scattering (Aslam et al., 2007b). There is no consensus regarding the size, intensity and location of the glare source (van den Berg et al., 2003). An even bigger problem is the lack of consensus about the relation between glare sensitivity and difficulties as experienced during daily activities (van den Berg et al., 2003). The likely reason for this is due the fact that it manifests in many forms, which are difficult to measure and differ between patients (Aslam et al., 2007b). Whilst there are various objective and subjective measures of dysphotopsia, most studies report the use of one or the other; the link between the two is unknown in a pre-operative cohort.

1.5. Effect of intraocular lens design on dysphotopsia

Although multifocal IOLs have become popular, the commonest cause of dissatisfaction is due to dysphotopsia (Tester et al., 2000, Souza et al., 2006, de Vries and Nuijts, 2013). The multifocal IOLs design creates two or more focal points focused at different planes (see Fig 1.2). For distance viewing, the distance focal point produces a focused image with the near focal point creating an out of focus blur circle on the retina. The surrounding blur results in the retinal image having less contrast against its background and therefore, also results in the halo phenomenon (Gil-Cazorla et al., 2016).

Many different designs of multifocal IOLs have been developed over the years to improve both distance and near vision but also to combat unwanted side effects such as glare and halos. The design of the lens affects the light distribution, the number of focal points, the distance of their separation, and ultimately the quality of the images.
There are various designs of multifocal IOLs, a full review of all designs is beyond the scope of this literature review, thus a brief overview is given. Multifocal IOLs can be divided into refractive and diffractive designs. Refractive designs can be subdivided into concentric and sectorial, while diffractive designs can be categorised as fully diffractive or partially diffractive.

**Figure 1.2:** The multifocal IOLs design creates two or more focal points focused at different planes.

### 1.5.1. Refractive multifocal intraocular lenses

#### 1.5.1.1. Concentric refractive multifocal intraocular lenses

In refractive multifocal IOLs, refractive power changes from centre to the periphery of the lens and produces many foci (see Fig 1.3; Barisic *et al.*, 2008). Concentric refractive multifocal IOLs have several concentric zones that differ in curvature, creating two or more refractive powers. The *Array* (Abbott Medical Optics, Inc., Santa Ana, CA, USA), *ReZoom* (Abbott Medical Optics, Inc., Santa Ana, CA, USA), and *MFlex* (Rayner Intraocular Lenses Ltd, Hove, UK) are all five-zone concentric refractive multifocal IOLs; alternating near and distance zones surround the central distance zone. The *Array* and *ReZoom* are similar in design as both have a near addition equivalent to + 3.50 D at the IOL plane (approximately + 2.60 D at the spectacle plane). The posterior surface of the *Array* optic is spherical, however, the *ReZoom* incorporates an aberration reducing aspheric posterior surface optic. The *ReZoom* has three zones, including the central that is for distance vision, the other two are for near; it distributes 10 – 11 % of light to intermediate focus by contributions from the defocus characteristics of both primary lens powers (Davison and Simpson, 2006, Barisic *et al.*, 2008). The *MFlex* multifocal is available with either a
+ 3.00 D or a + 4.00 D addition and with four or five refractive zones depending on the base power of the IOL; the MF-4 is a four-zone concentric refractive multifocal IOL with a centre near zone surrounded by alternating distance and near zones. Due to the refractive zones in all refractive multifocal IOLs being relatively large, the design is pupil size dependent. Centre distance designs ensure preservation of distance vision even with the smallest of pupil (Kawamorita et al., 2009); however, those with small pupils are likely to struggle with reading.

Rau et al. (2003) noted a relatively high level of spectacle independence with the MF-4, but a prevalence of dysphotopsia of 45 %. Perez et al. (2003) reported that visual acuities with the MF-4 were inferior when compared with a diffractive multifocal IOL with an equivalent addition. Optical bench studies were unable to determine the disparity between the IOLs as they both produce equivalent image formations (Gobbi et al., 2007). Whilst very few studies have been done on the MF-4 IOL, the Array and ReZoom five-zone, refractive multifocal IOLs have been extensively evaluated in both in vivo and in vitro studies. Such studies have reported reduced contrast sensitivity in lower lighting conditions and lower spatial frequencies with the five-zone refractive multifocal IOLs (Montes-Mico et al., 2004, Cillino et al., 2008), whilst the prevalence of dysphotopsia is higher than with a monofocal IOL (Haring et al., 2001, Pieh et al., 2001, Cillino et al., 2008). In regards to near vision (Cillino et al., 2008), spectacle dependence (Fujimoto et al., 2010) and reading ability (Harman et al., 2008) the five-zone refractive multifocal IOLs are superior in comparison with a monofocal IOL.

**Figure 1.3:** Optics of a three, four, and five zone refractive multifocal IOLs, i.e. Array or ReZoom. In the three zone lens, the centre distance zone supports distance vision in bright light conditions such as daylight driving with constricted pupils. The surrounding near zone provides good near vision in moderate to low light conditions. The outer distance zone provides additional distance vision support in dim light conditions, such as night driving when pupils are dilated. In the four and five zone lenses, the extra zones provide good vision in differing light conditions. Shaded regions = near power, non-shaded regions = distance power.
1.5.1.2. Sectorial refractive multifocal intraocular lenses

In contrast to concentric refractive multifocal IOLs, these lenses are rotationally asymmetrical. Sectorial refractive multifocal IOLs have the reading addition in a specific region of the lens; similar to the appearance of a bifocal spectacle lens. The mechanism of action, like all other multifocal IOLs, is simultaneous rather than translating vision.

The *Lentis MPlus* (Oculentis/Topcon Europe, Capelle a/d Ijssel, The Netherlands) has the appearance of a C-type bifocal spectacle lens; the near segment covers 100° of the inferior IOL and has a small in-cove for distance vision (see Fig 1.4). The near portion of the IOL has an addition of 3.00 D over the distance refractive correction of the IOL. The manufacturers of this lens recommend placing the IOL with the near segment inferiorly.

![Figure 1.4: Optic of the Lentis MPlus, a sectorial multifocal IOL; the inferiorly placed near segment (shaded) covers 100° of the lower IOL and the small in-cove allows good undisrupted distance vision.](image)

Sectorial multifocal IOLs are dependent on IOL centration. The amount of light dedicated to distance or near is dependent on the proportion of the near segment occupying the pupil. A sectorial multifocal IOL requires the central radius points of the distance and near portions of the IOL to run along the same optical path, therefore negating image jump (Maxwell and Nordan, 1991). The sectorial multifocal IOL has the advantage that it is not pupil dependent. It also has reduced photic phenomena as glare and halos are confined to the area corresponding to the near segment, although not completely eliminated (Munoz *et al.*, 2011).

1.5.2. Diffractive multifocal intraocular lenses

Diffractive multifocal IOLs are based on the Huygens-Fresnel principle, in which concentric rings on the optic surface typically generate two foci (distance and near; Slagsvold, 2000,
A diffractive pattern is created by light diffracted by a boundary; this creates an interference pattern and results in multiple orders of light. The separation between these orders of light determines the IOL addition (Davison and Simpson, 2006). The distance between the ring edges determines the order separation and thus the effective addition (Davison and Simpson, 2006). However, not all of the light is distributed to the desired light orders and some is spread diffusely to the higher orders (Sheppard et al., 2013). In the case of a + 4.00 D diffractive multifocal IOL, designed to separate the light equally between two orders, 18% of the light is lost to higher orders (Davison and Simpson, 2006, Huetz et al., 2006). Chromatic aberration occurs as a consequence of both refraction and diffraction; however, the spread of light into different colours occurs in the opposite direction to the spread through refraction (Maxwell and Nordan, 1991).

1.5.2.1. Fully diffractive multifocal intraocular lenses

Fully diffractive multifocal IOLs have concentric rings that cover the entire optic of the IOL (see Fig 1.5). These lenses are therefore pupil-independent and the split of light is maintained regardless of pupil size (Valle et al., 2005). The Tecnis ZM900 (Abbott Medical Optics, Inc., Santa Ana, CA, USA) has a silicone fully diffractive multifocal optic with the diffractive pattern on the posterior surface. It has an aspheric anterior surface that acts to suppresses spherical aberrations. The effective addition of the IOL is + 4.00 D at the IOL plane; this IOL also has an equal split of light towards the distance and near focal points. There is also an acrylic version of the IOL, the Tecnis ZA900.

![Optic of Tecnis ZM900](image)

**Figure 1.5:** Optic of Tecnis ZM900, a fully diffractive multifocal IOL with alternating distance and near zones allows an equal split for distance and near vision despite the pupil size.
Equal split fully concentric multifocal IOLs offer a high level of near acuity and spectacle independence in comparison with a monofocal IOL and refractive concentric multifocal IOLs (Cillino et al., 2008, Packer et al., 2010). The literature is equivocal in regards to the quality of intermediate vision with the equally split fully concentric multifocal IOLs: defocus curve profiles (Schmidinger et al., 2006), and optical bench tests (Terwee et al., 2008) have demonstrated a reduction in intermediate vision whilst a study measuring visual acuity at an intermediate distance has not corroborated these findings (Packer et al., 2010). Distance visual acuity is superior with the distance dominant lens; the reverse is true for near visual acuity. Binocularly the vision is summated providing relatively good distance and near vision (Jacobi et al., 1999). Optical bench studies (Gobbi et al., 2007) and clinical studies (Alio et al., 2004) have highlighted the presence of dysphotopsia. Moreover on assessment of distance contrast acuity via optical bench testing, contrast acuity has been found to be improved with the distance dominant multifocal IOL when compared to an equal split fully diffractive multifocal IOL (Gobbi et al., 2007).

1.5.2.2. Partially diffractive multifocal intraocular lenses

Unlike fully diffractive multifocal IOLs, partially diffractive multifocal IOLs only have the diffractive pattern over a specific area of the optic (see Fig 1.6). AcrySof ReSTOR apodized diffractive IOL (Alcon Laboratories Inc., Fort Worth, TX, USA) has a single piece biconvex optic. The optic is composed of the same proprietary acrylic material that has been used in ReSTOR lenses since 1995. This material has been shown to provide excellent clinical benefits through its high refractive index (1.55), flexibility, ultraviolet wavelength-absorbing properties and biocompatibility. The lens can be folded before insertion, allowing placement through an approximately 3.5 mm incision. The ReSTOR MA60D3 has a 6.0 mm diameter biconvex optic and an overall length of 13.0 mm. Twelve diffractive zones in the central 3.6 mm region divide light between two foci. The diffractive steps gradually reduce in height and spacing from the lens centre to the edge of the diffractive region (apodization); distributing the light for a full range of vision. Step heights decrease smoothly from 1.3 μm in the central zone to 0.2 μm at the diffractive periphery. The outer refractive region has no diffractive zones and is strictly refractive dedicated to distance vision. Therefore the lens is pupil-dependent: the larger the pupil the greater the distribution of light to the distance. The lens incorporates a +4.00 D add at lens plane equal to a +3.2 D at spectacle plane (Kohnen et al., 2006, Souza et al., 2006) and is also available in a +3.00 D near addition.
Figure 1.6: Optic of ReSTOR, a partially diffractive multifocal IOL. Only the centre region has the diffractive zones, whereby the outer refractive region is for distance vision only, giving those with larger pupils a greater distribution of light to distance.

The ReSTOR has been extensively examined in optical and clinical studies. Near visual acuity and spectacle independence is better in comparison with a monofocal IOL, distance visual acuity is comparable, however, contrast sensitivity with the + 4.00 ReSTOR is reduced (Vingolo et al., 2007, Cionni et al., 2009, Hayashi et al., 2009b). Interestingly Hayashi et al. (2009a) concluded that the + 3.00 version of the multifocal IOL produced similar contrast sensitivity levels in comparison with a monofocal IOL. However, de Vries et al. (2010) found no difference in contrast sensitivity between the + 4.00 and + 3.00 versions of the ReSTOR. A significant limitation of the + 4.00 ReSTOR multifocal IOL is its ineffectiveness at providing intermediate vision (Blaylock et al., 2006, Pepose et al., 2007). This is less of a problem with the + 3.00 D ReSTOR multifocal IOL which provides a longer working distance for the patient hence improving intermediate vision (Maxwell et al., 2009).

1.5.3. Trifocal multifocal intraocular lenses

A trifocal multifocal IOL is a lens that supports good intermediate vision. A combination of 2 diffractive profiles can provide 3 foci for distance, near and intermediate distance (Gatinel et al., 2011). FineVision IOL (PhysIOL, Belgium) is a single-piece aspheric fully diffractive trifocal IOL, allowing for an improved intermediate vision. It is composed of 25% hydrophilic acrylic material and the overall diameter is 10.75 mm and the optic 6.15 mm. It features two diffractive profiles consisting of alternating diffractive steps of different heights on the anterior surface, resulting in three foci: one for distance, one for intermediate (+ 1.75 D add), and one for near (+ 3.00 D add). It also has an apodized optic with
decreasing step height from the centre to the periphery, resulting in variable distribution of light energy to far, intermediate, and near vision with changing pupil diameters. The proportion of incident light directed to far vision is greater than for near or intermediate vision at all pupil diameters and rises with pupil size to increase distance-vision dominance. For a 20 D IOL and a 3.0 mm pupil diameter, the light-energy distribution to distance, near, and intermediate vision is 42 %, 29 %, and 15 %, respectively (Gatinel et al., 2011). Approximately 14 % of light energy is lost at higher orders of diffraction with this IOL compared with 18 % with IOLs of a typical bifocal refractive design (Davison and Simpson, 2006).

Sheppard et al. (2013) reported a good standard of distance visual acuity and intermediate and near visual function with the Finevision trifocal IOL, in a prospective interventional study on 15 patients after bilateral IOL implantation. The increasing far-vision dominance of the IOL as pupil size increases may be effective in reducing the photic phenomena frequently associated with multifocal IOLs (Sheppard et al., 2013), especially in night time conditions where photic phenomena are most prominent.

A theoretical study on model eyes showed that diffractive multifocal IOLs are superior to refractive multifocal IOLs for near vision, whereas for distance vision they are comparable (Pieh et al., 2002). Clinical studies also confirm the superiority of the diffractive over the refractive principle for near vision (Knorz, 1993, Weghaupt et al., 1996, Walkow et al., 1997, Steinert et al., 1999) and have shown that refractive multifocal IOLs are significantly more pupil dependent (Koch et al., 1991, Knorz, 1993, Hayashi et al., 2001). A pupil diameter of less than 4.5 mm cannot provide useful near visual acuity (Hayashi et al., 2001); therefore mean pupillary size in a normal cataract population needs to be considered. A study by Weghaupt et al. (1998) showed that results for distance and near visual acuities are very satisfactory with a diffractive multifocal IOL, whereas for intermediate distances visual acuity may be limited to activities that do not require optimal vision.

In various studies evaluating diffractive (Rossetti et al., 1994) and/or refractive (Dick et al., 1999, Javitt and Steinert, 2000, Pieh et al., 2001) multifocal IOLs, visual phenomena, mainly glare and halos, have been proven to be increased relative to monofocal IOLs; however, rates of self-reported patient satisfaction remain high with simultaneous vision IOLs. Steinert et al. (1999) observed statistically significant differences in rating of visual symptoms reported by subjects implanted with the Array zonal-progressive multifocal IOL in comparison to the monofocal control. Difficulties with halos, glare/flare, and blurred far vision were reported most frequently, and at higher proportions in the zonal multifocal IOL subjects than in the monofocal subjects.
Javitt et al. (2000) also reported a significantly higher degree of problems with glare, halos, or rings around lights for the multifocal Array IOL subjects versus monofocal IOL subjects. The study involved bilateral implantation; with 127 participants receiving multifocal IOLs and 118 participants receiving monofocal IOLs. In comparison, lower proportions of these symptoms were reported as severe by the ReSTOR IOL subjects in a study by Kohnen et al. (2006), evidenced by 8.5 % for glare/flare and 4.2 % for halos. Kohnen et al. (2006) successfully observed 117 participants for 330 to 420 days after bilateral multifocal IOL implantation. Conversely, glare and halos have been reported not to differ statistically significantly between a monofocal IOL and a zonal-progressive multifocal IOL (Dick et al., 1999), after monocular implantation of a monofocal IOL in 28 subjects and multifocal IOL in 28 subjects. In a study by Pieh et al. (2001), halos were detected in all 24 patients with a refractive multifocal IOL under clinical setting conditions, and 23 patients reported seeing halos at night, whereas only one patient was disturbed by this phenomenon. Patients receiving refractive multifocal IOLs (Array) were more likely to report halos, although their overall visual function and satisfaction were rated higher than those in the monofocal control group (Javitt and Steinert, 2000).

Visual phenomena have been reported to be more severe with diffractive IOLs than with monofocal IOLs, but not leading to less patient satisfaction (Rossetti et al., 1994, Leyland and Zinicola, 2003, Montes-Mico et al., 2004). Kohnen et al. (2006) reported that the AcrySof ReSTOR IOL provided clear vision, with a low incidence of severe visual disturbances. The favourable performance of the AcrySof ReSTOR might be attributed to the sophisticated technology it employs, apodization, which renders to the diffractive portion of the optic gradual decreases in step height and spacing, allowing for a smooth transition of the distribution of light energy between distance and near focal points. The blend of near and distance vision reduces the potential for glare, halos, and other visual disturbances. Mean low-contrast distance visual acuity with AcrySof IOL improved during binocular testing; compared with monocular testing providing evidence that binocular implantation is beneficial for the patient.

1.5.4. Intraocular lens material and edge design

In pseudophakic dysphotopsia, the design and material of the IOL are typically responsible for redirecting the unwanted light to the retina. IOLs have made significant advances in achieving superior vision following the removal of cataract. One of the drawbacks of IOLs has been posterior capsular opacification. Acrylic square-edge IOLs were introduced to reduce the incidence of posterior capsular opacification and seemed to provide a significant step forward towards eliminating it. Both material and mechanical design offered
advantages. However, the lenses resulted in an increase in dysphotopsia (Schwiegerling, 2006). Holladay et al. (1999b) compared the edge glare caused by sharp and rounded edge designs using non-sequential ray tracing techniques. Both square and round-edged IOLs produce straylight, but only the square-edged design concentrated the light into a well formed arc on the retina. Round-edge designs tended to disperse the straylight over a much larger portion of the retina.

Ellis (2001) presented several case studies of patients with dysphotopsia following the implantation of acrylic IOLs. Of the 543 eyes examined, 1.5 % provided unsolicited complaints of positive dysphotopsia. The number of problems was fairly small, but these patients were unhappy with their visual results. Several IOL exchanges were performed in this group. Polymethyl methacrylate (PMMA) IOLs were used as replacements and glare problems did not recur with this lens material. The visual side effects are attributed to the edge designs of the implanted lenses and the high refractive index of acrylic (Ellis, 2001).

Farbowits et al. (2000) performed a retrospective study of acrylic IOL explantations performed at two clinical sites. The incidence of exchange is not given, but nine eyes of eight patients were described over a 2 year period. Glare and starbursts were the dominant complaints. The dysphotopsia subsided following the removal of the acrylic IOLs and replacement with silicone or PMMA IOLs. This group offers two possible explanations for the straylight effects; the first is the traditional square-edge effects suggested in other reports previously and the second is a double reflection that occurs at the faces of the IOL. The higher surface reflectance of acrylic when compared to silicone and PMMA is suggested as the difference (Schwiegerling, 2006).

Davison (2002) presented results of 2630 consecutive cases of acrylic lens implantation over a 1.5 year period. In this study, the acrylic lenses had been modified by the manufacturer to address some of the concerns that had arisen previously. The modifications were designed to retain the material and sharp edge design to keep the incidence of posterior capsular opacification low. Specifically, the edges of these lenses were textured to reduce their reflectance. Furthermore, the unequal proportions of the surface curvatures were adjusted to address the reflection issue. Davison (2002) found that 0.2 % (4) of patients had positive dysphotopsia and 0.5 % (14) had negative dysphotopsia. This rate of incidence was considerable lower than that reported by Ellis (2001).

Meacock et al. (2002) performed a prospective study of 60 patients split between acrylic lenses with textured and non-textured edges. By prospectively analysing the two groups, the advantages of textured edges were assessed. One month post-operatively, 67 % of the
non-textured IOL patients and 13 % of the textured IOL patients had glare symptoms. The textured edges provided a statistically significant reduction in glare symptoms.

Diffractive multifocal IOLs enable excellent near and far vision and have no restriction on pupil size as well as reducing night visual issues, but exhibit poor intermediate vision. Refractive lenses give excellent far vision, good near and intermediate images but their disadvantages are problems with halo and glare. Acrylic square edge designs reduce posterior capsular opacification but result in increased dysphotopsia. IOLs of PMMA and silicone with rounded edges, along with square-edge acrylic IOLs with non-reflective surfaces, appear less likely to cause clinically significant pseudophakic dysphotopsia (Davison, 2000).

1.5.5. Intracorneal inlays

Intracorneal inlays are an additional method for presbyopic patients; placed in the non-dominant eye, implanted under a LASIK style flap or more commonly into a corneal pocket created by a femtosecond laser (Greenwood et al., 2016). A variety of light focusing principals are employed. Inlays such as Raindrop utilise corneal curvature alteration whereas, KAMRA uses small aperture pinhole principals to increase depth of focus and reduce blur (Naroo and Bilkhu, 2016).

1.6. Laser refractive surgery and dysphotopsia

The excimer laser became commercialised for refractive surgery after Trokel et al. (1983) found it to be a precise corneal cutting device, where tissue is ablated rather than burnt. The 193 nm ultraviolet wavelength Argon-Fluoride (ArF) laser is the most commonly used in ophthalmology (Basting et al., 2002). Photorefractive keratectomy (PRK) was the first successful (and now least used) excimer laser refractive surgery technique (Munnerlyn et al., 1988), after excimer laser keratotomy failed due to different corneal healing processes (Marshall et al., 1986). In PRK, the corneal epithelium is completely removed and discarded manually, mechanically or more commonly with dilute alcohol, before the corneal stroma is reshaped to the predetermined profile. After surgery, a protective bandage lens is used whilst the epithelium regrows naturally (Yu & Jackson, 1999).

Compared with PRK, in laser-assisted sub-epithelial keratectomy (LASEK), the epithelium is retained; it is simply moved out of the way usually after alcohol softening.

One of the most common procedure performed to ideally abolish refractive error by administrating laser to corneal tissue is laser in situ keratomileusis (LASIK) surgery
Generally a 160 micrometre (µm) corneal flap is created with a microkeratome or more recently with a solid state femtosecond laser. The flap is pulled back so the corneal stroma can be sculpted with the excimer laser. The corneal flap is then repositioned and the epithelium continues to regenerate as normal (Yu & Jackson, 1999). LASIK technique provides improved clinical outcome success (Hersh et al., 1998) and healing pattern compared to its predecessor; PRK (Chang et al., 1998). Following successful PRK and LASIK, some patients will complain of the occurrence of glare and halos; the prevalence of which lies within 3 – 40 % (Obrart et al., 1994).

The study by Lackner et al. (2003) examined the glare and halo size experienced under mesopic lighting by computer simulation prior to LASIK and 1, 3 and 6 months after surgery. At each of the post-operative stages, the glare and halo sizes observed by patients were significantly greater than the measures taken pre-operatively. There was a peak at one month, which was followed by a decrease in glare. It is thought that the peak occurrence of glare increase at one month post-LASIK may be due to the subsequent use of an excimer laser, where interruption to the arrangement of corneal collagen fibrils and increase interfibrillar spacing when compared to an unoperated eye, is so extensive that obliteration of scattered light no longer occurs by the process of destructive interference (Kaji et al., 1998). The ocular surface healing leads to corneal haze and corneal oedema, which peaks at 4 weeks (Kaji et al., 1998) and lessens with time (Chang et al., 1998), thus reducing glare and halo size as observed at 3 and 6 months post-operation (Lackner et al., 2003). Therefore, it has been suggested that LASIK increases manifestation of dysphotopsia, correlating with the elevation of light scatter from corneal healing. A more recent study by Pop and Payette (2004) agrees with the finding.

1.7. Measurement of dysphotopsia

The measurement of visual acuity alone cannot be used as an indicator of disability glare as it has been shown that disability glare and visual acuity are poorly correlated with cataract and aphakic patients (Le Claire et al., 1982, Abrahamsson and Sjostrand, 1986, van den Berg, 1986). Many attempts have been made to establish an instrument that could be used clinically to assess the amount of glare. Unfortunately many of these have had limited success as they do not directly assess the straylight or glare, and no single device is in wide spread clinical use as there currently is no gold standard available for the clinical evaluation of dysphotopsia.

Both psychophysical and optical methodologies have been developed to measure intraocular forward scattering. In psychophysical procedures, the assessment is dependent on the participant’s performance, and therefore, relates to their actual visual function.
(Piñero et al., 2010). In contrast, the optical methods are less dependent on patient response and have the limitation of providing estimations of scattering for a small angle domain, where the level of scattering is minimal; this provides a less functional measure (Piñero et al., 2010).

1.7.1. Early methods

One of the earliest methods to measure halos involved drawing the outline of the halo created from a candle on a cardboard strip with a pencil; this method was clumsy and unsatisfactory (Elliot, 1924). Another used a device that had two points of light at a fixed distance showing through a metal disc; a large one for the creation of the halo, and a small one whereby any particular ring can be located. The technique had a great disadvantage as the smaller light aperture itself gives rise to halos and can confuse the patient (Elliot, 1924).

1.7.2. Elliot halometer

Elliot (1924) developed a halometer comprising of a circular wooden box containing a 4-volt tungsten lamp creating the principal light seen through a 7 mm aperture. Attached to the box is a ruler with a sliding box; the observer is required to slide this up and down until it corresponds with the outer rim of the halo to provide an outline of the photopic scotoma surrounding the light source. The ruler has an inch scale in numerals, corresponding to the radius of the glare circle; the value is converted to the angle subtended at the eye using the Tan equation together with the distance of the eye from the source of light. Elliot (1924) calculated the angle subtended for each radius on the rule for a viewing distance of 100 inches, and noted these on the ruler for ease of use without need for calculation if used at 100 inches.

1.7.3. Miller-Nadler glare tester

The Miller-Nadler glare tester was introduced by Miller et al. (1972) and later modified by Le Claire et al. (1982). The instrument presents a series of constant sized, randomly orientated Landolt rings of progressively reduced contrast (92 to 2 %) surrounded by a broad glare source of constant luminance with a viewing distance of 40 cm. The disability glare score is recorded as the last correctly identified slide. The Miller-Nadler glare tester was used to assess 32 eyes with IOLs (Nadler et al., 1984) and it was discovered that glare score correlated with the percentage of capsular opacification as estimated by an independent observer. Outdoor visual acuity (with subjects facing the sun) was poorly predicted by consulting room measures of acuity ($r = 0.57$) but better predicted by their glare
scores \((r = 0.80; \text{Hirsch et al., 1984})\). Disadvantages of the Miller-Nadler glare tester include difficulty in controlling the density of the target slides and the directional properties of the screen make the test sensitive to the positioning of the patient. For example, a patient moving 10 cm off line experiences a 50% reduction in the effective intensity of the glare source \((\text{van der Heijde et al., 1985})\). It has been reported that results obtained with this device showed no significant differences between radial keratotomy patients and normal even though radial keratotomy patients reported symptoms of difficulty with night driving \((\text{Waring et al., 1985})\). Elliott and Bullimore \((1993)\) stated poor repeatability of the test when three subject groups \((\text{young normals, } n = 24; \text{older normals, } n = 22 \text{ and early cataract, } n = 33)\) were evaluated on two visits. Another study using a different technique to evaluate glare sensitivity showed radial keratotomy patients did have increased susceptibility to glare \((\text{Applegate and Wolf, 1987})\), after which Bailey and Bullimore \((1991)\) speculated that it raised questions about the sensitivity of the Miller-Nadler test.

### 1.7.4. The Vistech MCT8000

The targets and glare sources of the Vistech MCT8000 are contained within a portable unit \((\text{Bores, 1983, Olsen and Andersen, 1991, Elliott and Bullimore, 1993, Fan-Paul et al., 2002})\). A console provides control of target presentation, luminance, and glare source position. The unit allows contrast sensitivity measurements at 1.5, 3, 6, 12 and 18 cycles/degree under night-time \((3 \text{ cd/m}^2)\) and day time \((125 \text{ cd/m}^2)\) luminance conditions with or without a central or peripheral glare source. Each target consists of seven circular discs, each containing a sine-wave grating of a fixed spatial frequency. The gratings are either vertical or tilted 15° to the right or left, and the contrast of the grating progressively decreases from disc one to seven. Starting at disc on, the subject is asked to indicate the orientation of each grating or to respond ‘blank’ when nothing is seen. The last disc whose orientation is correctly identified determines the contrast sensitivity score. Measurement of contrast sensitivity at 6 cycles/degrees with and without glare is described as a functional disability test \((\text{FDT})\) and is recommended as an initial screening technique \((\text{Vistech Consultants Inc.})\). The chart and glare source luminance levels can be checked using the internal calibration feature before any measurements are taken. It is recommended that night-time measurements should be made first \((\text{Vistech Consultants Inc.})\). The ability to vary luminance has been helpful to test for glare disability post-refractive keratotomy \((\text{Bores, 1983})\). Neumann \(\text{et al.} \, (1988)\) found it to be lacking in validity and to have difficult testing times. Similar tests include the Vistech chart 6500 \((\text{Reeves et al., 1991})\) and the CSV 1000 \((\text{Ghaith et al., 1998})\).
1.7.5. Simple pen torch glare assessment

In this most simple and accessible test, the patient reads a vision chart to distinguish their visual acuity without any glare source, and then repeats the test in the presence of a glare source, for example, a pen torch. Such methods have been found to provide a rapid test of glare (Williamson et al., 1992). The test may be subject to inaccuracies caused by pupil miosis (Tan et al., 1998, Boxer-Wachler et al., 1999) and the difficulties in standardising the glare source distance.

1.7.6. Brightness Acuity Tester

The Brightness Acuity Tester (BAT) was introduced by Holladay et al. (1987) and consists of an internally illuminated white hemispherical bowl, 60 mm in diameter with a 12 mm central aperture (see Fig 1.7). It is a relatively cheap and simple to use handheld device, that the patient holds to their eye to view a visual acuity chart through the aperture. The luminance of the internal surface of the hemisphere may be varied. Elliott et al. (1993) used the medium intensity setting (measured to be 345 cd/m² using a spot photometer) when testing reliability. The high intensity setting has been reported to give inappropriately high prediction of disability glare (Neumann et al., 1988, Prager et al., 1989) and can reduce contrast beyond a chart’s limits with some early cataract patients (Elliott and Hurst, 1990, Regan, 1991). Holladay et al. (1987) and Mantyjarvi et al. (1999) used the BAT with an ETDRS high contrast acuity chart but variable or low contrast charts, such as the Pelli-Robson contrast sensitivity or Regan visual acuity charts, can be used.

The Pelli-Robson chart is an 86 x 63 cm chart that contains 16 triplets of 4.9 x 4.9 cm letters (Pelli et al., 1988). At a test distance of 1 m, these letters correspond to spatial frequencies of about 1 - 2 cycles/degree. Within each triplet, the letters have the same contrast, and the contrast in each successive triplet decreases by a factor of 0.15 log units. A by-letter scoring system that gives credit (0.05 log units) for each letter read correctly was used. This has been shown to provide more reliable test scores that the originally recommended scoring rule (Elliott et al., 1991). The chart is illuminated to 100 cd/m². Contrast sensitivity can then be measured with and without the BAT.

The Regan Charts are logMAR (Logarithm of the Minimum Angle of Resolution) acuity charts of varying contrast. Elliott and Bullimore (1993) used the BAT with the 25 % and 11 % contrast charts, as well as the traditional high-contrast 96 % chart. The 25 % and 11 % have been discovered to be the most useful for disability glare evaluation in older patients and those with cataract (Regan, 1991). By the letter scoring method of 0.0125 log units per letter was adopted. The chart was illuminated to 100 cd/m², and the recommended
viewing distance of 3 m was used. Visual acuity was measured with and without the BAT for each of the three charts.

Figure 1.7: Brightness Acuity Tester consists of an internally illuminated bowl white hemispherical bowl. The patient holds the device to their eye and views a visual acuity chart through the aperture. Image from Marco Ophthalmic Inc. website.

Neumann et al. (1988) reported that the BAT was an excellent predictor of outdoor visual acuity and in this respect it was superior to the Miller-Nadler glare tester; it was also the quickest, least expensive and most simple of tests used. Holladay et al. (1987) compared normal and cataract patients’ visual acuity inside with the BAT and these results were compared to visual acuities measured outside in bright sunlight. The BAT correlated extremely well ($r = + 0.84, P < 0.0001$) with acuities measured outside. There was no decrease in visual acuity in the 14 normal patients, but there was a one to ten line decrease in vision among the cataract patients. Mantyjarvi et al. (1999) wanted to investigate the use of contrast sensitivity and visual acuity in glare as a predictor of those drivers with cataracts who are likely to struggle in traffic. Using the BAT with an Early treatment diabetic retinopathy study (ETDRS) chart, none of the control eyes lost any of the lines the visual acuity chart, whereas in the cataract eyes, the loss of lines with highest glare varied from 0 to 6 lines (mean 1.4 ± 1.5). Elliott et al. (1990) also demonstrated its sensitivity in registering glare disability in patients with cataract who were subject to a battery of tests and to a visual ability questionnaire. Magno et al. (1997) looked at improvements in glare after laser capsulotomy using a BAT. Wilkins et al. (1996) similarly showed that the
strongest improvements in vision after Neodymium-doped yttrium aluminium garnet (Nd:YAG) laser were in contrast sensitivity with glare.

The results obtained with the BAT will depend on the design, luminance, and contrast of the test chart and some standardisation will be necessary to allow meaningful comparison of results (Bailey and Bullimore, 1991). As the patient holds the instrument, frequently over spectacles, the angular size of the aperture and its position relative to the test target is variable and this could have some influence on results (Bailey and Bullimore, 1991). Elliott et al. (1993) proved it to be a very repeatable test. However, more recent experimenters report the BAT device to have poor sensitivity and validity because of the pupil miosis that it induces (Tan et al., 1998, Boxer-Wachler et al., 1999). Another study by Rubin et al. (2001), the relationship between psychophysical measures and self-reported difficulty with everyday tasks was assessed in individuals of age 65 and over. The association of visual disability with glare sensitivity with BAT was the most tenuous of all the visual function links (Rubin et al., 2001). Such conflicting arguments with the BAT has led to some doubts being raised over the lack of evidence for its validity, despite its ease of use and low expense (Aslam et al., 2007b).

### 1.7.7. The Berkeley glare test

The Berkeley glare test consists of a reduced low contrast Bailey-Lovie letter chart (Weber’s contrast = 18 %) mounted on a triangular opaque panel in the centre of a 30 x 27 cm opal Plexiglas panel (see Fig 1.8; Bailey and Bullimore, 1991). The chart is front illuminated (80 cd/m²), and the glare source is provided by transillumination of the Plexiglas panel at the medium setting (750 cd/m²). Low contrast visual acuity (VA) is measured at 1 m with and without the glare source, with credit (0.02 logMAR units) given for each letter read correctly.
Figure 1.8: Berkeley glare test with mounted Bailey-Lovie test chart. The VA is measured with the low contrast chart under different glare conditions. Images reproduced with permission from BMJ Publishing Group (Niesen et al., 1997).

1.7.8. Perimetry glare test

Namiki and Tagami (1993) attached a glare source within an Octopus 500E (Haag-Streit, Koeniz, Switzerland) automated perimeter to determine the extent of visual field loss surrounding a central glare source. Twelve normal control phakic eyes together with a number of other pseudophakic groups each consisting of 6 eyes were enrolled in this study. These groups were a 6 mm no hole lens group, a 6 mm 4 hole lens group, a 5.5 times 6.5 mm 2 hole lens group, a 5.0 times 6.0 mm no hole lens group and a diffractive multifocal group. There were minimum glare disabilities in the visual field in the control group. The 6 mm no hole lens group and the diffractive multifocal group showed no statistical
significance compared to the control group. Groups with the two types of ovoid lens and the 6 mm 4 hole lens group showed a statistically higher degree and a greater extent of glare disabilities in the static visual field than the control group. Careful selection of appropriate patients to receive implants of small efficient optic IOLs, such as IOLs with positioning holes and ovoid lenses, according to the pre-operative pupil size under scotopic or mesopic condition and efficient lens optic size are important in order to reduce hole and edge glare. The diffractive multifocal IOLs group showed a slightly higher degree and a greater extent of glare than the control group and the 6 mm no hole monofocal lens group but the difference was very small and statistically insignificant. Therefore the effects of diffractive microstructure on glare disabilities were considered to be slight and clinically acceptable.

1.7.9. van den Berg Straylight meter

Initial attempts to measure ocular straylight using the equivalent veiling luminance theory required measurements of two types of thresholds; in the presence of a distant glare source, and in the presence of a homogeneous background luminance. The equivalent luminance could be derived from these measurements, defined as the luminance yielding identical thresholds as the glare source (equivalent veil method; Vos, 1984). van den Berg (1991) compared results from various groups, all using this method, and concluded that these results varied considerably. The method was not widely used as it was not easily accessible for clinical application (Franssen et al., 2006).

In 1986, a new psychophysical method was designed to overcome the problems experienced with glare testers, called the Direct Compensation technique (van den Berg, 1986). A bright ring shaped flickering light source around a dark test field is presented. Due to intraocular scatter, part of the light from the bright ring shaped source will be projected on the retina at the location of the test field, inducing a weak flicker in the test field. To determine the exact amount of straylight, a variable amount of counter phase compensation light is presented in the test field. By adjusting the amount of compensation light, the flicker perception in the test field can be extinguished. In this way, the straylight modulation caused by light scattered from the glare source is ‘directly compensated for’.

In 1990, van den Berg and Ijspeert introduced a small portable device to implement the Direct Compensation method, called the Straylight meter (Ijspeert and van den Berg, 1992, van den Berg and Ijspeert, 1992). Subsequently, many studies on ocular straylight have been published using the Direct Compensation method, such as on normal population ageing effects where straylight was shown to increase with age (Ijspeert et al., 1990, Hohberger et al., 2007). A study exploring the relationship between straylight and the translucency of the ocular wall noted that straylight values increase a more translucent
ocular wall (van den Berg et al., 1990, Lahey et al., 1993). Increased ocular pigmentation resulted in a decrease in ocular straylight (van den Berg et al., 1991). Dewaard et al. (1992) investigated the effects on straylight on populations with different kinds of cataract. It was used as a gold standard to assess the validity of glare tests (Elliott and Bullimore, 1993).

The method has some major drawbacks for routine clinical or large-scale use (Franssen et al., 2006): (1) Judgement of the weak flicker in the test field often appeared to be difficult for untrained subjects; this seemed to be caused by the presence of the strong flicker of the straylight source. (2) Usually, visual tests are based on what subjects actually see. On the contrary, in the direct comparison method, the subjects have to indicate whether the flicker perception has disappeared. The continuous flickering of the straylight source in the periphery made this contra intuitive task even more difficult. (3) The accuracy of the measurement seemed to depend on the adjustment strategy, which could differ considerably between subjects, and on proper explanation of the test. (4) There was no control over an individual’s measurement reliability. (5) Subjects had the ability to influence the test outcome. As a result of these drawbacks, the straylight meter largely remained limited to laboratory use.

1.7.10. Glare and Halo test

The Glare and Halo test is a standardised commercially available computerised test used to measure the size of photopic phenomena. A central white target 15 mm in size is displayed on the screen and the subject is required to place a mark at the boundary of the photopic phenomenon for 12 equidistant orientations separated by 30 degrees surrounding the glare source. The central glare area in degrees is then calculated in accordance with the working distance of the subject. The Glare and Halo test has been used in three studies examining the difference in halo area between a monofocal IOL and the Array refractive multifocal IOL; Pieh et al. (2001) discovered a significant difference in dysphotopsia between the two types of pseudophakic correction, however, two further studies did not find a significant difference (Eisenmann et al., 1996, Dick et al., 1999). The Glare and Halo test has also been used to assess photopic phenomenon in post-LASIK subjects (Lackner et al., 2003). Repeatability studies have not been conducted using this instrument.

1.7.11. C-Quant

One of the most used clinical psychophysical procedures for measuring intraocular forward scattering was defined in 2003 and implemented in the commercially available C-Quant (Oculus Optikgerate GmbH, Wetzlar-Dutenhofen, Germany); this uses the compensation comparison method. Compensation comparison was developed to overcome the limitations
of the direct compensation method (van den Berg and Ijspeert, 1992). The main advantage of the compensation method is that the two central stimuli are compared simultaneously, in contrast to the direct compensation method where the subject has to compare different stimuli sequentially. The new approach enabled control over the reliability of the assessment (van den Berg et al., 2013). It was no longer possible to influence the measurement outcome, and quality control factors could be defined (van den Berg et al., 2013).

The task involves the patient viewing a central circular stimulus that is split into two hemispheres, and is surrounded by a larger annulus of bright light, with a radius of 5 to 10 degrees resulting in an effective average of angular value of 7 degrees (see Fig 1.9; van den Berg, 1995). The straylight is caused by presenting a flickering light in the peripheral ring of the stimuli, which is scattered by the ocular structures.

**Figure 1.9:** Diagram of stimulus seen when using C-Quant.

The compensation light is presented in one of the two randomly chosen central halves (referred to as field B); the resultant flicker is a combination of straylight and compensation light modulated at the same frequency in counter phase with the straylight source (Franssen et al., 2006). No compensation light is presented in the other half (referred to as field A) so the perceived modulation comes from straylight alone (Franssen et al., 2006). During the test, differing amounts of the compensation light are presented in field B, making its half appear to flicker more or less than the unmodulated half, depending on the brightness of the modulation (Franssen et al., 2006). A 2-alternative forced choice psychophysical method (2AFC) is used, where the subject has to decide which of the two hemispheres flickers stronger. The subject's responses are recorded by means of two push buttons, representing the left and right test fields. With this method, the subject indicates a choice even when there is no perceived difference between the two halves, and as the
number of trials increases each half will be chosen about 50 % of the time (Piñero et al., 2010).

1.7.12. Halometers

Various types of halometers have been developed over the years in attempt to outline the size of halos. A gross estimation halometer technique involved a central light source with an overlaying neutral density filter being place 3 m from the subject. The subjective measure required instructing the examiner to move their hands until they intersected with the outer rim of the photic phenomena. The distance between the examiner’s hands was taken as the representation of the size of the photopic scotoma. The technique failed to identify any difference between a multifocal IOL and monofocal IOL; no validation studies have been conducted using this technique (Hunkeler et al., 2002).

The halometer described by Gutierrez et al. (2003) was designed to measure post-LASIK dysphotopsia in subjects. The halometer comprises of a board with a central hole through which a light emitting diode (LED) is placed to provide the glare source. To create the targets, a series of holes radiating away from the central light also have LEDs shining through them. These LEDs flash in sequence, similar to a visual field screening test allowing the area of glare scotoma to be mapped. No repeatability studies have been conducted using this instrument.

Allen et al. (2008) measured the halo using a red fixation cross within a white ring (luminance of 86.6 cd/m²), which generated the halo source on a black background. The subject, at a distance of 100 cm, positions a marker at the outer limit of the halo using a computer mouse, thus recording the side of the halo around the ring at 30 degree intervals. It has been used to assess dysphotopsia following multifocal implantation. The design used for examining multifocal IOLs was not assessed for repeatability and was found to show similar results with both multifocal and monofocal IOLs (Allen et al., 2009).

Babizhayev et al. (2009) later described a halometer with a central light source with a variable intensity control. A luminous optotype of a set size and brightness is moved horizontally towards and away from the glare source until it is just distinguishable. The working distance is set as 30 cm and the distance between the optotype and the glare source are recorded. The halometer was validated on phakic subjects with and without cataracts (Babizhayev et al., 2009).
1.7.12.1 Vision Monitor

Halo radius has been measured using the Vision Monitor and low luminance optotypes presented at 2.5 m (Puell et al., 2014). An off axis light source was used, with the participant’s head positioned with centre of monitor, whilst the LED glare source is at the edge of the screen. Optotypes arranged in three radial lines of letters appear from the periphery, moving towards the glare source. Each line contains 10 letters forming 10 rings at intervals of 33 arc min. Each letter subtends 15 arc min and corresponds to 0.5 logMAR. The Vision Monitor only quantifies the halo extent in 3 meridians, and from these halo radius values, the overall halo map is approximated (Puell et al., 2013). However, it has been reported that halos are not perfectly circular (Castro et al., 2011, Meikies et al., 2013); accentuating the importance of measuring the halo in multiple meridians.

1.7.12.2 Aston Halometer

Buckhurst (2011) developed a new halometer; consisted of a display screen presenting a series of dots, of varying contrasts, radiating away from a central LED, which was controlled by a single battery. The design was inspired by that of Gutierrez et al. (2003). Subjects were requested to count the number of dots seen in each direction. Subsequently, the dot targets were changed to letters as keeping track of the number of dots observed with the central glare was a difficult task for the participant. It became apparent that in its current form, results would be unreliable and not sensitive enough to detect differences in glare profiles (Buckhurst, 2011). Instead of using a static display, a bespoke computer programme was developed for the Aston halometer that allowed a changing letter to move away and towards the glare source in 8 meridians separated by 45 degrees. The letter targets were designed to have multiple contrast levels. A letter size equivalent to 0.3 logMAR was selected. The letters ‘D’, ‘E’, ‘F’, ‘H’, ‘N’, ‘U’ and ‘Z’ were chosen due to their similar legibility (Bailey and Lovie, 1976).

The program is designed so that the letter size and its position on the screen were controllable. The letter size is displayed in degrees subtended at the eye in the corner of the screen. The programme is based around a turtle graphics design; the left/right arrow moved the letter towards or away from the centre of the screen 0.05° at a time. The letter can be randomised at the press of a button.

To ensure the repeatability and validity of the test, it was important to ensure that the glare source retained a constant brightness. A warm white luxeon emitter white star LED was mounted at the end of a telescopic arm so it could be attached to the edge of a flat screen and the light positioned in the centre (see Fig 1.10). The LED has a correlated colour...
temperature of 3200 K, whilst maintaining 70 % lumen over 50,000 hours of operation. The telescopic arm was shrink-wrapped in a black matt plastic to ensure non-reflectance. The halometer was connected to a 18 pin board designed to provide protection against a drop in output by running the current through 10 K, 47 K, 100 R and 22 L resistors; this was then connected to a mains output with a consistent voltage, the current was limited to 5 V and 100 mA (full load 1 W).

**Figure 1.10:** Set up of the halometer device involves attaching a telescopic arm to the edge of the flat screen with a LED mounted at the end so that the light can be positioned in the centre.

Buckhurst *et al.* (2015) reported the halometer to demonstrate good inter- and intra-repeatability for the measurement of dysphotopsia with and without Bangerter foil. The intraclass correlation co-efficient (ICC) based on a two-way mixed ANOVA model with a 95 % confidence interval. Intra-observer variability can be seen in Table 1.3 and inter-observer variability is displayed in Table 1.4.

<table>
<thead>
<tr>
<th>Contrast of the Optotype target</th>
<th>1000 $C_w$</th>
<th>500 $C_w$</th>
<th>100 $C_w$</th>
<th>25 $C_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control Lens</strong></td>
<td>0.876</td>
<td>0.843</td>
<td>0.775</td>
<td>0.806</td>
</tr>
<tr>
<td><strong>0.8 Bangerter foil</strong></td>
<td>0.979</td>
<td>0.929</td>
<td>0.874</td>
<td></td>
</tr>
<tr>
<td><strong>0.6 Bangerter foil</strong></td>
<td>0.929</td>
<td>0.840</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 1.3:** Intra-observer variability of halometer with each *Bangerter foil* and at each contrast level (n=20).
<table>
<thead>
<tr>
<th></th>
<th>Control Lens</th>
<th>0.8 Bangerter foil</th>
<th>0.6 Bangerter foil</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contrast of the Optotype target</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 C&lt;sub&gt;W&lt;/sub&gt;</td>
<td>0.776</td>
<td>0.696</td>
<td>0.576</td>
</tr>
<tr>
<td>500 C&lt;sub&gt;W&lt;/sub&gt;</td>
<td>0.729</td>
<td>0.675</td>
<td>0.529</td>
</tr>
<tr>
<td>100 C&lt;sub&gt;W&lt;/sub&gt;</td>
<td>0.632</td>
<td>0.532</td>
<td></td>
</tr>
<tr>
<td>25 C&lt;sub&gt;W&lt;/sub&gt;</td>
<td>0.675</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.4: Inter-observer variability of the halometer with each Bangerter foil and at each contrast level (n=20).

The halometer is also available as a tablet app version for easier clinical application. The software works in the same way, but on an iPad. It has a custom built attachment and arm to create the central light source (see Fig 6.1). Intra-observer repeatability was good for the iPad halometer (ICC = 0.89; Buckhurst et al., 2017).

1.7.13. Questionnaires

Quality of life surveys are gaining acceptance as effective evidence-based methods of measuring patient visual well-being (Aslam et al., 2004b). The underlying reason for using quality of life questionnaires in clinical practice is to ensure that treatment plans are centred on the patient rather than the disease. Questionnaires used to assess vision with presbyopic correcting IOLs are mainly bespoke and few have been validated using either classic test theory (CTT) or with Rasch analysis. Questionnaires should be validated on the target group for the questionnaire, however, rarely have the questionnaires been validated with multifocal IOLs.

1.7.13.1. Kohnen questionnaire

To assess the incidence and impact of visual phenomena such as glare and halos, subjects were asked to rate the impact of any observed phenomena. The subjects were specifically queried about glare (trouble seeing street signs due to bright light or oncoming headlights), halos (rings around lights), distorted near vision (straight lines looking crooked close up), distorted far vision (straight lines looking crooked at distance), blurred near or far vision, problems with night vision, double vision with both eyes or with other (non-operated eye) closed, and problems with colour perception. Patients rated the effect of each phenomenon on a scale from 0 to 7, with 0 meaning not observed; 1 is easily tolerated; and 7 is incapacitating. A rating of 1 to 2 was interpreted as mild, a rating of 3 to 5 was defined as moderate, and a rating of 6 to 7 was defined as severe. Kohnen et al. (2006) enrolled 127
patients and for glare at 120 to 180 days after the second implant, of the 118 patients who answered the question 8.5 % (n = 10) rated their observation as severe in effect, 24.6 % (n = 29) rated it as moderate, and 66.9 % (n = 79) rated it as none or mild. Halos were reported as severe by 4.2 % of patients, moderate by 16.1 %, and absent or mild by 79.7 % of patients.

Apart from halos (which slightly increased), the mean rating of the visual disturbances decreased after second eye implantation compared with assessment after first eye implantation. The results of the subjective questionnaire on perceived optic phenomena and quality of life in this study of the AcrySof ReSTOR IOL MA60D4 demonstrated lower rates of visual symptoms in comparison to published values from multifocal studies, and high rates of patient satisfaction consistent with other studies (Steinert et al., 1999, Javitt and Steinert, 2000). The questionnaire has not be validated.

1.7.13.2. Cataract TyPE Specification questionnaire

The Cataract TyPE Specification questionnaire is a 13-item questionnaire developed to determine the patient’s outcome after cataract surgery in five dimensions: distance vision, near vision, day-time driving, night-time driving and glare (Javitt et al., 2003). It has been validated for this purpose in monofocal and multifocal pseudophakic subjects demonstrating high Cronbach’s alpha and good correlation with visual acuity. Gothwal et al. (2009) validated the questionnaire in subjects with cataracts using Rasch analysis, they reduced the questionnaire to a 12 item questionnaire, which demonstrated good measures of visual function within this group. The questions cover assessment of vision and glare. The questionnaire was internally valid (Cronbach alpha = 0.94), both on self-administration in the patient care setting and upon mailed survey administration and across patient race and gender (Javitt et al., 2003).

1.7.13.3. Quality of Vision questionnaire

The Quality of Vision questionnaire was designed to measure the overall subjective perception of vision. It is a 30 item questionnaire, 9 questions specific to dysphotopsia, 12 enquire about blurred, distorted and hazy vision and 9 are specific to focussing and depth perception. Rasch analysis was used to validate the questionnaire in a study involving 900 subjects (including correction with monofocal, multifocal and accommodative IOLs; Mcalinden et al., 2010).
1.7.13.4. Self-Perceived Quality of Vision questionnaire

The Self-Perceived Quality of Vision questionnaire was designed to assess vision post IOL implantation. It contains 17 questions detailing perception of satisfaction, photopic phenomena and ability to perform visually dependent tasks. The questionnaire was validated for monofocal pseudophakic subjects using CTT and by examination of Cronbach’s alpha and repeatability (Aslam et al., 2004b). Subsequently, the questionnaire was used to assess subjects implanted with multifocal and single optic accommodative IOLs (Harman et al., 2008).

1.7.13.5. Welch’s questionnaire

A study carried out by Welch et al. (2010) investigated the causes in dissatisfaction after uncomplicated cataract surgery. Sixty-one patients had uncomplicated cataract surgery, and there was forty control patients.

The patient was asked questions dealing with dysphotopsia:

1. Do you experience glare when looking into light (ranked no, hardly ever, more often than not, or always)?
2. Do you experience sensitivity to light (ranked no, hardly ever, more often than not, or always)?
3. Do you see flashes of light (yes or no)?
4. Do you see haloes around lights (yes or no)?

A dysphotopsia score was calculated by adding the scores for all 4 questions where no equals 0, hardly ever equals 1, more often than not equals 2, and always equals 3. For the two yes and no questions, no equals 0 and yes equals 2.

Overall satisfaction with vision after surgery was scored as very satisfied equals 0, satisfied equals 1, no change since before surgery equals 2, dissatisfied equals 3, and very dissatisfied equals 4 (Welch et al., 2010). The only significant correlation with dissatisfaction was dysphotopsia ($r = 0.602, P < 0.0001$). Highlighting that whilst satisfaction with cataract removal and IOL placement is high, dysphotopsia is the most important contributor to dissatisfaction and is relatively common (Welch et al., 2010). No validation has been carried out for this questionnaire.
1.7.13.6. The Perceived Visual Disability questionnaire

The Perceived Visual Disability (PVD) questionnaire was designed to determine the effect of cataract on lifestyle. The questionnaire consists of 20 items, the results of which were correlated against measures of glare, visual acuity, and contrast sensitivity (Elliott et al., 1990). The questionnaire has not been validated on pseudophakic subjects.

1.7.13.7. Photographic questionnaires

Hunkeler et al. (2002) developed a series of images simulating night time visual phenomena that are often experienced, alongside 12 illustrations of visual phenomena under high contrast conditions varying in terms of detail, brightness and thickness (see Fig 4.1 and Fig 4.2). Of 22 patients that had bilateral implantation of Array multifocal, on the images most patients chose the clear starburst (image 4 on Fig 4.1) and blurred starburst (image 5) as representative of their visual sensations. None chose double ring halos (image 3) or cataract-like glare (image 6). Most patients picked the starburst illustrations in the third column (31, 32, and 33 on Fig 4.2) and fourth column (41, 42, and 43) as representative of their visual phenomena. No patients picked the bright-light illustrations in the first column (11, 12, and 13). Some of the participants stated that the images were a good match.

Aslam et al. (2004a) developed a similar style of questionnaire with images depicting different types of dysphotopsia and varying severities of each (see Fig 3.3). Aslam and Dhillon (2004) stated that questionnaire assessments provide scores that are perhaps closest to patient’s perceived morbidity but have poor specificity and are subject to interpretation errors, ambiguity, use of jargon and biases in responding. The images were developed to avoid these problems. The photographic images of photic phenomena (PIPP) provided a range of glare conditions including dark arc, bright arc, serrated arc, night halos, night starburst, day halos, day starburst, central flash (glare from the sun causing excessively bright light), streams of light and ripple effect; which participants would be able to relate to. The images showed good repeatability when tested on 22 patients and good reliability when two examiners tested 12 patients on 2 separate intervals.

1.7.13.8. Other questionnaires

Sedgewick survey instrument that only asks a single question about glare; Are you bothered by glare, halos, or rings around lights? Response options are never, occasionally, about half the time, often or always (Sedgewick et al., 2002). The Javitt questionnaire is a detailed quality of life questionnaire, with respect to dysphotopic symptoms (Javitt et al., 1997). It
involves questions related to spectacle wearing habits, self-reported rating of vision (zero to 10) and eight further sets of questions related to symptoms of glare and halo occurring during activities of daily life, scored on a scale of zero to four. The questionnaire was validated using 100 subjects implanted bilaterally with a silicone optic foldable zonal progressive IOL. The questionnaire was valid with a Cronbach’s alpha of 0.94.

The Winther-Nielsen questionnaire involves questions relating to necessity for wearing sunglasses, a comparison of pre- and post-operative vision, and some very specific questions pertaining to the type of dysphotopic symptoms that were originally volunteered with the early multifocal lens types (Allen et al., 2009). The answers were weighted and given a score on a scale of zero to 10 for their relative importance.

The Tester questionnaire was designed to determine whether a patient was experiencing any form of dysphotopsia (Tester et al., 2000). Patients who do experience dysphotopsia are then asked more about the nature of the symptoms. The questionnaire is structured around six stems, with the first three questions on dysphotopic symptoms being graded on a scale of zero to three. Overall satisfaction with vision is scored on a scale of zero to five.

1.8. Aims of thesis

To summarise, glare tests that were introduced often consisted of either visual acuity charts including ETDRS (Holladay et al., 1987, Prager et al., 1989, Mantyjarvi and Tuppurainen, 1999), Ferris-Bailey (Elliott et al., 1990), Bailey-Lovie (Bailey and Bullimore, 1991, Elliott and Bullimore, 1993), or Regan (Elliott and Bullimore, 1993) or contrast sensitivity charts including sinusoidal gratings (Ginsburg et al., 1987, Neumann et al., 1988, Prager et al., 1989, Dewaard et al., 1992, Elliott and Bullimore, 1993), Landolt rings (Hartmann and Wehmeyer, 1980, Le Claire et al., 1982, Prager et al., 1989, van Rijn et al., 2005), Pelli-Robson (Elliott et al., 1990, Elliott and Bullimore, 1993), with and without a glare source presented at some angular distance in the visual field (van den Berg et al., 2013). Some studies utilised a laboratory setup, with and without glare source present, with visual field stimuli (Verriest and Uvijls, 1989), a flashing test field (Yuan et al., 1993), sinusoidal gratings (Harrison et al., 1993), or low contrast letters (Hard et al., 1990) as targets, and also for specific night time conditions (Rubin et al., 1993). The repeatability and discriminative ability of the glare tests studied were found to be inadequate (Elliott and Bullimore, 1993, van den Berg et al., 2003, van Rijn et al., 2005). A large multicentre Prospective Evaluation of Radial Keratotomy (PERK) study omitted glare test data from the final results (Waring et al., 1990), as the glare tester was not sufficiently sensitive to detect small but significant amounts of light scattering (Waring et al., 1985, Elliott and Bullimore, 1993, Veraart et al., 1993). Due to these issues, a standard glare
measurement test was never adopted, and papers discussing glare test problems emerged (Prager et al., 1988, Rubin, 1990, van den Berg, 1991, Elliott, 1993, van den Berg, 1994, Aslam et al., 2007b). However, Cervino et al. (2008) showed high repeatability of the C-Quant, suggesting that the system is reliable and useful for detecting clinically significant stray light values. Although there are various questionnaires available, they don’t seem to be in wide use. Photographic questionnaires depicting various types of dysphotopsia have the potential for clinical use due to the quick and easy nature of use. When investigating dysphotopsia in a normal population, each study reports either objective measures or subjective complaints. It is therefore unknown how both measures are linked, if they are.

The aims of this thesis are:

- Describe the relationship between objective measures and subjective complaints of dysphotopsia and to establish a normal range of values for the first time representing the subjective grade divided by the objective grade (the glare effect ratio).
- Compare binocular and monocular halometry measures to ascertain if there is a significant difference.
- Establish how objective measures and subjective complaints of dysphotopsia change with age in healthy eyes, whilst defining a normal range of values for halometry halo area over a wide age range.
- Establish if pupil size has an effect on the halo area measured by the Aston halometer.
- Measure longitudinal changes in halo area, straylight and subjective photic effects following LASIK refractive surgery, and to determine whether both objective and subjective measures return back to normal values.
- Determine how cataract surgery impacts on objective and subjective photic effects, and to track longitudinal changes in response to cataract surgery.
CHAPTER 2

A NOVEL GLARE EFFECT RATIO TO DESCRIBE THE RELATIONSHIP BETWEEN OBJECTIVE AND SUBJECTIVE MEASURES OF DYSPHOTOPSIA

2.1. Introduction

Cataract surgery is the most commonly performed surgical procedures with approximately 19 million operations carried out per year globally (Donaldson et al., 2013). Cataract is the leading cause of avoidable blindness (World Health Organisation, 2007). In developed countries, a routine and cost-effective procedure (Asbell et al., 2005) can be carried out in which the cataract is extracted followed by implantation of an IOL within the capsule. Monofocal IOLs are currently the most commonly implanted lens type (Hovath et al., 2014), designed to provide good vision at a single focal point, typically distance, often leaving patients with poor unaided near vision, thus corrective lenses must be worn. In the UK, cataract surgery is the most frequently undertaken procedure within the National Health Service (NHS) with an estimated 330,000 operations undertaken annually in England (Trikha et al., 2013, Donachie et al., 2016). The volume of cataract surgery has increased dramatically since the 1980s (Taylor, 2000) due to growth and ageing of the population. As cataract surgery has improved, it is now offered as clear lens exchange as a refractive surgery option.

Dysphotopsia is a well-known complaint after refractive and cataract surgery (Tester et al., 2000, Souza et al., 2006, Aslam et al., 2007b, Woodward et al., 2009, Chang et al., 2012, de Vries and Nuijts, 2013). Such surgeries are becoming increasingly common since the introduction of multifocal IOLs (Davison and Simpson, 2006, Alfonso et al., 2008, van der Linden et al., 2012, Aychoua et al., 2013), which usually allow patients spectacle independence as good distance and near visual acuity are achieved. Despite good scores on traditional measures of visual acuity, patients may report poor vision or light sensations in everyday situations (Nadler et al., 1990). Multifocal IOLs create two or more focal points at different planes. For distance viewing, the distance focal point produces a spot image with the near focal point creating an out of focus blur circle on the retina. The surrounding blur results in the retinal image having less contrast against its background and therefore, also results in the halo phenomenon (Buznego and Trattler, 2009). It is recognised that patients with cataract or individuals fitted with multifocal IOLs may demonstrate excellent high contrast visual acuity, but suffer from undesirable photic phenomena such as halos and disabling glare (Schwiegerling, 2006, Aslam et al., 2007b, Calladine et al., 2012). Halos are a major cause of dissatisfaction following multifocal IOL implantation and may necessitate explantation if the effects are
severe and persistent (Galor et al., 2009, Kamiya et al., 2014). It has been reported that up to 40% of those fitted with multifocal IOLs complain of dysphotopsia, compared to only 20% with monofocal IOLs (Souza et al., 2006, Woodward et al., 2009, de Vries et al., 2011, Chang et al., 2012). However, a 2006 Cochrane review found that photic phenomena are 3.5 times more likely with multifocal IOLs than monofocal IOLs (Leyland and Pringle, 2006). Dysphotopsia (Tester et al., 2000) also increases naturally with age due to greater light scattering by the optical media.

The need to measure photic phenomena is becoming ever more important as patients are being fitted successfully with multifocal IOLs, and these have become increasingly popular amongst patients (Davison and Simpson, 2006, Alfonso et al., 2008, van der Linden et al., 2012, Aychoou et al., 2013). Hovath et al. (2014) reported that in 2011, 7.8% of European cataract surgery patients opted to receive a premium IOL, defined as multifocal, multifocal toric or accommodative IOL, compared to 14.7% in the United States. Whilst monofocal IOLs are the most commonly implanted IOL type currently, it is envisaged that the trajectory of premium IOLs, specifically multifocal IOLs, will increase at a significantly faster rate in comparison to the steady increase of monofocal IOLs.

Multifocal IOLs are not only used in cataract surgery but are becoming a common first choice for refractive lens exchange as an alternative to laser eye surgery in presbyopia (Barisic et al., 2008, Chang et al., 2012). Refractive lens exchange is becoming increasingly popular, as it is a relatively uncomplicated procedure that addresses both ametropia and presbyopia (Goes, 2008). Multifocal IOLs increase the likelihood of spectacle independence compared to monofocal designs (Pager, 2004, Hawker et al., 2005, Munoz et al., 2011, Ferrer-Blasco et al., 2012). In the UK, multifocal IOLs are a part of the private sector and are not available on the NHS unless under a clinical trial.

Since the introduction of refractive lens exchange, the purpose of the procedure is no longer to simply remove the cataractous lens and replace it with an IOL of a close pre-operative refractive error (Lichtinger and Rootman, 2012); it also comes with increased patient expectation of the best possible refractive outcome with restoration of vision for near and distance without spectacles (Aslam et al., 2004a, Pager, 2004, Hawker et al., 2005, Munoz et al., 2011, Braga-Mele et al., 2014). It has become increasingly common for emmetropic presbyopes to undergo refractive lens exchange simply to be rid of reading spectacles (Schena, 2005). In these cases, it is more evident that patients with moderate visual acuity pre-operatively are less happy with making the trade-off of good visual acuity at the cost of troublesome glare and loss of contrast sensitivity (Aslam et al., 2007b).
Chang et al. (2012) found that the most satisfied patients were those who underwent bilateral refractive lens exchange and were habitual spectacle wearers pre-operatively.

A number of halometers have been developed to measure the size of the photic scotoma (halo) surrounding a glare source (Pieh et al., 2001, Babizhayev et al., 2009, Puell et al., 2013, Buckhurst et al., 2015). Such devices allow objective quantification of halos, with newer halometers typically controlled using computer programmes, providing a high level of accuracy and avoiding the previous limitation of patients having to manually indicate the halo boundary. Halo area increases with age in healthy eyes (Puell et al., 2013) and may also be greater for cataract patients (Babizhayev et al., 2009, Palomo-Álvarez and Puell, 2015), those fitted with multifocal IOLs (Zhang et al., 2011) and following corneal refractive surgery procedures, depending on factors such as pupil diameter and ablation zone (Lackner et al., 2003, Valverde and Gonza, 2003).

Measurement of intraocular forward-scattered light, using a straylight meter such as the C-Quant (Oculus Optikgeräte, Wetzlar, Germany) represents a further objective clinical approach to evaluate visual quality. Retinal straylight, caused by light scattering in the ocular media, increases with age (van den Berg, 1995, Guber et al., 2011) and measurements may aid the diagnosis of cataract (Palomo-Álvarez and Puell, 2015) and surgical decision-making processes (van der Meulen et al., 2012), alongside conventional visual acuities. It has been suggested that straylight values could be used as an indicator for fitness to drive (van Rijn et al., 2011) in cataract patients, even when visual acuity is within acceptable limits.

Subjective dysphotopsia assessment techniques are also available; these include simple numerical scales of severity (Hofmann et al., 2009), more detailed complaint questionnaires (Arnold, 1994, Dick et al., 1999) and grading of various photic effects with reference to simulated photographs (Aslam et al., 2004a). Subjective evaluation of photic complaints may be valuable in addition to objective measures as the experience of dysphotopsia is believed to have a significant psychological component (Aslam et al., 2007a), with some surgeons recommending or making decisions regarding refractive procedures on the basis of patient personality traits (Dick et al., 1999, Pepose, 2008, Braga-Mele et al., 2014).

Although the subjective experience of dysphotopsia has a significant impact on both post-operative patient satisfaction and the need for subsequent corrective procedures, e.g. lens explantation, subjective findings are not routinely considered in light of objective measures. That is despite the fact that one study by Dick et al. (1999), which examined both objective and subjective measures of photic phenomena after monofocal and multifocal lens implantation, found a positive correlation. However, no previous study has investigated the
typical relationship between newer objective measures, such as Aston halometer and 
*C-Quant*, and subjective complaints of photic complaints using images across a broad age 
range prior to any refractive surgery. Such information could be clinically valuable at the 
pre-operative stage in the identification of individuals at risk of the worst subjective problems 
post-operatively, that is, those with a high level of subjective grievance in comparison to 
objective findings are most likely to experience extreme dissatisfaction with any undesirable 
photic phenomena.

The aims of this prospective study are:

- Describe the relationship between objective measures and subjective complaints of 
dysphotopsia.
- Establish a normal range of values for the first time representing the subjective grade divided by the objective grade (the glare effect ratio).
- Compare binocular and monocular halometry measures to see if there is a significant difference as typically, previous studies state monocular values only (Bailey and Bullimore, 1991, Pieh et al., 2001, Lackner et al., 2003, Puell et al., 2013). Binocular measures may be more representative of an individuals’ visual experience.
- Use Bangerter foils (Haag-Strait, Koeniz, Switzerland) to simulate glare conditions, 
such as those that would be experienced in a ‘cataractous’ eye, to permit 
assessment of the relationship of objective and subjective measures in these conditions.

2.2. Subjects and methods

All procedures were conducted in the Ophthalmic Research Group laboratories at Aston 
University, Birmingham, UK. Risk assessment was conducted as part of the ethics 
application. The study was reviewed by the Aston University Life and Health Sciences 
Research Ethics Committee (Application number 595). A copy of this approval can be found 
in appendix A1. The study was conducted in accordance with the tenets of the Declaration of Helsinki and all subjects gave their informed consent to take part.

Power calculations, made using GPower (version 3.1.9.2), showed that 93 participants were 
required to enable Spearman correlation to detect statistically significant medium size (0.3) 
effect at the 5 % significance level ($\alpha = 0.05$) with 80 % power. One hundred participants 
were recruited from the staff and student body in the Optometry department at Aston 
University subject to the following criteria:
Inclusion Criteria

- Healthy subjects under 35 years old as it is known that glare increases with age (Bailey and Bullimore, 1991, Vos, 2003a).
- Corrected visual acuity of logMAR 0.1 or better in the eye to be tested, and logMAR 0.3 or better in the weaker eye to allow easy viewing of the logMAR 0.4 letter on the halometer.
- Participants who are able to understand and undertake the informed consent process.

Exclusion Criteria

- Any history of ocular surgery, including laser refractive surgery as it could increase the magnitude of the glare effect (Lackner et al., 2003, Valverde and Gonza, 2003, Zhang et al., 2011).
- Participants with any pre-diagnosed ocular conditions.
- Any participants with a history of using drugs that are known to affect the eye.
- Any participants with a systemic health problem that may result in ocular complications.

Unaided visions were measured and a full subjective refraction was performed at 3 m using the Thomson Test Chart 2000 (Thomson Software Solutions, Hatfield, Herts, UK). If the participant for distance wore a habitual refractive correction, then this refractive correction was used for halometry. An Oculus Universal trial frame (Keeler Ltd, Windsor, UK) was used to house the manifest refraction; adjusted to ensure a 12 mm back vertex distance.

The full aperture trial lenses (one spherical lens and one cylindrical lens, if required) were cleaned before insertion into the trial frame to ensure that they did not increase the amount of glare experienced.

A short pilot study (n = 5) was carried out to check that the trial lens did not affect the C-Quant measurements. The investigator took 2 repeated measures for each condition: without a lens, with a dirty lens (a trial lens with any visible marks present, e.g. fingerprints), and with a lens that had been cleaned with lens cleaner solution. Dirty lenses were found to increase straylight readings compared to without a lens, whilst clean lenses did not have any effect (see Table 2.1). A one-way repeated measures ANOVA was conducted to compare the effect of a lens on straylight using no lens, a clean lens, and a dirty lens. There was a significant difference between these three conditions \[ F(2, 8) = 52.98, P < 0.001 \]. Post hoc comparison using the Tukey test indicated that the mean score for the dirty lens condition (mean 1.50 ± 0.10) was significantly different than the no lens condition.
(mean 1.17 ± 0.17; $P < 0.001$) and clean lens condition (mean 1.06 ± 0.07; $P < 0.001$). However, the clean lens condition did not significantly differ from the no lens condition ($P = 0.079$). The findings were supported by results from a previous study by de Wit (2003), who found that fingerprints, dirt, and dust increased the straylight value. The no lens condition appears to have a higher mean and SD than the clean lens condition. The cause of this could be a learning effect as the no lens condition was carried out first, which may have led to the greater variability whilst the participant adjusted to carrying out the test.

Habitual contact lens wearers kept their lenses in throughout. The lens type was not recorded, however, the lenses were inspected on the eye with a slit lamp prior to assessment to ensure the lenses were not heavily deposited. It was ensured that the participant had visions/VAs better than 0.1 logMAR in the monocular eye to be tested. The C-Quant guidelines suggest that it is difficult to perform the test with visual acuities of worse than 0.1 logMAR (van den Berg, 2004).

<table>
<thead>
<tr>
<th></th>
<th>Mean Log(s)</th>
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<tbody>
<tr>
<td>No lens</td>
<td>1.17 ± 0.17</td>
</tr>
<tr>
<td>Clean lens</td>
<td>1.06 ± 0.07</td>
</tr>
<tr>
<td>Dirty lens</td>
<td>1.50 ± 0.10</td>
</tr>
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</table>

Table 2.1: Pilot study ($n = 5$) comparing the straylight measurements with no lens, with a dirty lens, and with a clean lens in place. Log(s) is the straylight value, where the average of 2 readings were taken. One-way RM ANOVA showed that straylight values in the clean lens and no lens conditions were not significantly different.

As participants were selected to have no history of ocular problems or surgery, dysphotopsia assessment was undertaken under normal viewing conditions and under simulated glare conditions using a Bangerter foil. Bangerter foils are an effective tool for increasing light scatter due to their effect on the point spread function simulating different levels of light spread on the retina (Perez et al., 2010). Bangerter foils are available in a range of density levels (1.0, 0.8, 0.6, 0.4, 0.3, 0.2 and 0.1) that are intended to provide a graded amount of blur, and are imprinted on to a self-adhesive plastic foil for ease of application (see Fig 2.1). Bangerter foils are designed to induce mild to moderate degradation in visual acuity making them useful in the treatment of diplopia and amblyopia (Odell et al., 2008).
Figure 2.1: Bangerter foil was pressed on to the wet surface of a clean +0.12 D trial lens and left to dry until there were no air bubbles.

Perez et al. (2010) measured microbubble density at each Bangerter filter level. It was expected that a higher microbubble density level would result in more severe image degradation (Perez et al., 2010). The density of bubbles (bubbles/mm²) in the selected field was 1.5 in the 0.8 foil, 1.7 in the 0.6 foil, 2.4 in the 0.4 foil, and paradoxically, 1.7 in the 0.3 foil (Perez et al., 2010). Perez et al. (2010) identified that both the physical structure and optical properties were similar and not necessarily ordinal for their samples of the 0.3, 0.4, and 0.6 filters; only the 0.8 filter was substantially different. Odell et al. (2008) similarly stated that the amount of visual degradation did not correspond well with the density designation of the Bangerter foil. Odell et al. (2008) found that the 1.0, 0.8, and 0.4 filters degraded distance acuity to a similar degree (mean 0.22, 0.23, and 0.28 logMAR); the 0.6 filter was not selected as initial pilot testing showed it did not degrade visual acuity differently from the 0.8 filter.

A Bangerter foil was required which would cause an increase in straylight without reducing the VA to worse than 0.4 logMAR as this would cause difficulties with distinguishing the letter on the halometer. Therefore, two filters were chosen to pilot as previous research has indicated that Bangerter filters do not always degrade visual acuity consistently to the manufacturer’s specified levels (Odell et al., 2008, Perez et al., 2010). The 0.4 foil was
chosen as the website of the manufacturer states that it degrades to approximately 0.4 logMAR (Haag-Strait), whilst Odell et al. (2008) found it has an actual visual acuity of 0.3 logMAR which would be the ideal VA for this study. The 0.8 foil was chosen as it is significantly different from 0.4; whilst 0.4 and 0.6 are both physically and optically the same (Perez et al., 2010). The 0.8 foil was found to cause the least impairment but is still considerably worse than the reference Modular Transfer Function (MTF; Perez et al., 2010).

Initial work in the laboratory involved comparing the results for the halometer and C-Quant without a lens, with the 0.4 Bangerter and with the 0.8 Bangerter for two participants. It immediately became apparent that with the 0.4 Bangerter in place, the visual acuity dropped to 0.6 logMAR making it impossible to distinguish the letter on the halometer. The participant could only note when the letter was seen, removing the accuracy of determining the glare scotoma size. With the 0.8 Bangerter, visual acuity was better at 0.12 logMAR but distinguishing the letter was still quite difficult due to the drop in visual acuity. It was found that the participant had an unaided vision of -0.08 logMAR, therefore, there was a respective drop in visual acuity of 0.24 logMAR. To make the task of halometry consistent in difficulty with the 0.8 Bangerter as it is without a lens, the target letter was made 0.24 logMAR bigger, equivalent to approximately 0.6 logMAR; this improved the participants’ accuracy when distinguishing the letter, whilst still showing an increase in the glare scotoma with the 0.8 Bangerter.

2.2.1. Objective assessment of dysphotopsia

The Aston halometer device which has been described and used in previously published studies (Sheppard et al., 2013, Buckhurst et al., 2015) was used to measure monocular and binocular halo area, under natural viewing conditions and with a Bangerter foil in situ. Subjects were positioned at 2.0 m from the halometer screen with their eyes aligned with the centre of the screen and the light path of the glare source. Halometry was carried out in scotopic light conditions; the emergency light in the room was covered with a black cloth to ensure the halometer was the only light source. Prior to the examination, the halometer was switched on allowing sufficient ‘warm up’ time of 5 minutes for the output of the LED light to stabilise. During this period the subject was allowed to dark-adapt before halometry was undertaken.
Figure 2.2: Ray diagram of the experimental set-up of the halometer. The participants' eye was aligned with the centre of the screen. The screen is always set at a 90° angle.

Binocular and monocular measures (on a randomly selected eye (Armstrong, 2013)) were carried out in a random order. The participant was instructed to look at the halometer screen, which has a central bright light source, attached to a wand (see Fig 1.10) acting as the glare source. The laptop screen was always placed at a 90° angle. The halometer uses a letter height of 0.21°, equivalent to a visual acuity of 0.4 logMAR at 2 m. 0.4 logMAR or Snellen 6/15 is the visual acuity required to distinguish a 79.4 mm high letter on a number plate viewed at a distance of 20.5 m (Charman, 1997); the minimum driving requirement for the UK (Kiel et al., 2003). A letter emerges from behind the glare source (in 0.05 degree increments) in one of eight directions, and the participant was asked to focus on the letter and to distinguish the character at the earliest point. From this point, the character was moved progressively closer to the glare source- the letter was changed with each incremental movement. The closest point at which the subject could correctly identify the letter was recorded as the boundary of the halo for that meridian. The remaining 7 meridians were assessed in the same way to allow the size and shape of the glare scotoma to be determined (See Fig 2.9).

The commercially available C-Quan was used to measure the amount of straylight falling on the retina in the monocular eye as chosen previously (see Fig 2.3). C-Quan readings were taken under natural viewing conditions and with Bangerter foil in situ. Franssen et al. (2006) noted that refractive correction is not critical for the measurement; only spherical errors over 2.00 D required correction and cylindrical errors of up to 3.00 D may be corrected with the spherical equivalent (van den Berg, 2004). It is recommended to use only one trial lens for refractive correction, to reduce the possible effect on straylight readings (van den Berg, 2004). Following these guidelines, low myopes (up to -2.00 D) did not have a lens inserted. However, for hyperopes, a single lens was used where the patient habitually wore spectacles for near vision to allow for comfortable viewing of the stimulus screen at a distance of 32 cm (Franssen et al., 2006). If a cylindrical correction was required then spectacles were worn as only one trial lens fitted into the lens holder with the Bangerter foil. The spectacles were cleaned before starting the test.

The participant was directed to look at the central circular stimulus, which is split into two hemispheres, surrounded by a larger ring of bright light causing the straylight. Both of the
hemispheres flash alongside the glare source with different intensities, and the subject pressed a button corresponding to the side appearing to flash the brightest. Two repeats were taken (Coppens et al., 2006, Cervino et al., 2008). If the two values differed by greater than 0.1 log units, then a third reading was taken and averaged. A limit value of 0.1 was applied to the GLARE study when testing for reliability on 2422 patients using 2 measures and a clinically relevant limit value of 0.1 was assumed (Coppens et al., 2006). Franssen et al. (2006) found an overall SD of repeated measures between 0.06 and 0.1 log units, and Cervino et al. (2008) had findings of SD between 0.04 and 0.13 log units. The measurement of straylight was considered reliable if the estimated standard deviation (ESD) was below 0.8 and the quality factor for the psychometric sampling (Q) was above 1.00 (Coppens et al., 2006, Cervino et al., 2008). The C-Quant software highlights values considered as unreliable by displaying them in red (van den Berg, 2004).

**Figure 2.3:** Set up of C-Quant
2.2.2. Subjective assessment of dysphotopsia

Subjective grading of dysphotopsia was performed using the photographic images of photic phenomena (PIPP) plates developed by Aslam et al. (2004a) which were shown to have excellent repeatability and reliability. Eight images depict 10 types of dysphotopsia: dark arc, bright arc, serrated arc, night halos, night starburst, day halos, day starburst, central flash (glare from the sun causing excessively bright light), streams of light and ripple effect (see Fig 2.4 – 2.6). Participants are presented with the first board with a set introduction: ‘Some people can get problems in their vision with light effects or glare at different times in different places. These are pictures of the problems some people have.’ The participant is asked which, if any of the problems shown they experience. If the participant points to any particular plate they are then presented with the grading scale of four stages of severity for that plate (see Fig 2.8). The individual is then informed: ‘Some patients only get this problem in a mild form (pointing to plate 1) and some will get very severe forms (pointing to plate 4). How bad on this scale would you say you experience this?’ The score for that particular phenomenon was recorded 1 to 4, depending on the plate that they point out most appropriately correlated with the severity of their symptoms. Participants were returned to the first board and asked if they had any other visual phenomena. A grade of 0 was given to any image that they did not feel they experience; thus a scale of 0 to 4 was determined to grade the severity of each phenomenon. All of these 10 values were summed to give the overall subjective grade between 0 – 40, where 0 indicated no dysphotopsia and 40 indicated severe photic impairment.

The original document containing the images was obtained from Dr. Aslam, and with permission, the images were printed on to matt finish photographic paper. The images were mounted onto 9 A3 sized cards; the first of which displayed 8 images portraying the different types of glare most commonly experienced (see Fig 2.7).
Figure 2.4: PIPP plates (A – dark arc, B – bright arc and C – serrated arc). Images supplied and reproduced with permission from Karger Publishers.
Figure 2.5: PIPP plates (D - night halos and night starburst and E - day halos and day starburst). Images supplied and reproduced with permission from Karger Publishers.
Figure 2.6: PIPP plates (F - central flash, G - streaks of light and H - ripple effect). Images supplied and reproduced with permission from Karger Publishers.
**Figure 2.7:** Image to show the layout of the first board of *PIPP* images with the most severe of each of the 10 photic phenomena.
Figure 2.8: Night halo PIPP board showing the 4 severities of night halos that the participant may select from if they report experiencing this effect.
2.3. Data and statistical analysis

The data was stored in a password protected Excel 2016 Spreadsheet document (Microsoft, Redmond, WA). All statistical tests were performed using SigmaPlot graphing and statistical software (Version 12.0, Systat Software Inc., Chicago, Illinois, USA). The one-sample Kolmogorov-Smirnov test was used to determine if results from each measurement followed a normal distribution. All data sets deviated from a normal distribution, thus, median and range are reported and the following non-parametric statistical analyses were utilised: Wilcoxon Signed Rank Test was used when comparing two related samples; Spearman’s Rank Correlation was used to investigate the strength of association between 2 variables. Although the data are not normally distributed, a one-way ANOVA was used to compare the 8 triangle areas from halometry, as the test is not highly sensitive to deviations from the assumption of normality (McDonald, 2014). In all cases, a P value of < 0.05 was considered statistically significant.

2.3.1. Calculation of halo area from halometer

The halometer output displays the angle in degrees subtended at the eye for each of the 8 meridians (see Fig 2.9).

![Figure 2.9: Example of raw halometer output when measuring monocular halo area. Table represents the angle in degrees subtended at the eye for each of the 8 meridians.](image)

To report a single value that encompasses the whole glare scotoma, the area of glare scotoma was calculated. Thereby, allowing more accuracy in comparison than visual inspections of the plots. The glare scotoma was split into the 8 triangles that are made up from the measurements of the 8 meridians (see Fig 2.10).
Figure 2.10: The total halo area is the sum of the 8 triangles labelled a-h.

To calculate the area (cm$^2$) of these triangles, the distance, $D$, from the glare source in the centre of the screen to the centre of the letter at the edge of the glare scotoma (equivalent to the radius of the glare scotoma) was required. Equation 2.1 was used to convert the angle given by the halometer to the distance (see Fig 2.11).

$$D \text{ (cm)} = 200 \times \tan(x)$$

**Equation 2.1**

Figure 2.11: The relationship between the angular output by the halometer, $x$, and the distance, $D$, from the glare source in the centre of the screen to the centre of the letter at the edge of the glare scotoma.

$D$ values were used to calculate total areas; the areas of each of the triangles were calculated using the lengths of two adjacent meridians. For example, area a was calculated
by inserting $D(90)$ and $D(45)$ (see Fig 2.10) into Equation 2.2. All areas were summed together to give the total glare scotoma area value.

$$\text{Area} = \frac{1}{2} \times D_1 \times D_2 \times \sin 45$$

Equation 2.2

A single value was used for the total area of the glare scotoma as glare scotomas measured with the halometer were found to be symmetrical in shape in this cohort, despite present literature showing a debate that halos may not be perfectly circular (Castro et al., 2011, Meikies et al., 2013). The 8 triangular areas of the glare scotoma were analysed using a one-way ANOVA (McDonald, 2014). For the 8 triangular areas, no significant difference was found for either the binocular or monocular measurements ($[F(7, 792) = 1.799, P = 0.084]$ and $[F(7, 792) = 1.098, P = 0.363]$, respectively).

As previous studies have stated halo area using mean radii in arc min (Puell et al., 2013) and mean area in square degrees (Allen et al., 2008, Buckhurst et al., 2015), both of these were calculated for the present data. To calculate the mean radii in arc min, first, the mean radii in degrees was calculated. $x$, in Fig 2.11, shows the radii in degree, the mean of this for each of the 8 meridians was calculated. The value was converted to arc min using the following formula:

$$\text{Mean Radii (arc min)} = \frac{\text{Mean Radii (deg)}}{1/60}$$

Equation 2.3

The area in square degrees was calculated using the following formula:

$$\text{Mean Area (sq deg)} = \pi (\text{Mean Radii (deg)})^2$$

Equation 2.4

These parameters are used further in chapter 3 and subsequent chapters.

A glare effect ratio was calculated to encompass the objective results with subjective complaints by means of the following formula:

$$\text{Glare Effect Ratio} = \frac{\text{Subjective Grade}}{\text{Objective Measure}}$$

Equation 2.5

A glare effect ratio was calculated separately for objective measures using halometer and C-Quant. A low glare effect ratio would indicate a low level of subjective effect compared to
objective measure; whilst a high glare effect ratio indicates an individual who is more subjectively affected by a given objective measure. It is expected that the glare effect ratio could be used pre-operatively to ascertain those who are most likely to suffer from subjective complaints post-operatively. Individuals with higher glare effect ratio may suffer and complain of more dysphotopic effects post-surgery.

The interquartile range (IQR) was calculated for the glare effect ratio using the following formula (Simmons, 2000):

\[ IQR = \text{Third Quartile} - \text{First Quartile} \]

Equation 2.6

As the glare effect data were non-parametric, SigmaPlot was used to calculate the median, and the 25\textsuperscript{th} (first quartile) and 75\textsuperscript{th} (third quartile) percentiles. The IQR was then used to calculate outliers in the data by the following formula (Simmons, 2000):

\[ \text{Upper Outliers} > \text{Third Quartile} + (1.5 \times \text{IQR}) \]
\[ \text{Lower Outliers} < \text{First Quartile} - (1.5 \times \text{IQR}) \]

Equation 2.7

2.4. Results

One hundred participants aged 18.0 – 33.0 years (median age 21.0 years) were recruited. The cohort consisted of 65 female and 35 male volunteers. Eleven of these participants wore soft contact lenses during the assessments. Table 2.2 provides summary descriptive statistics for the entire cohort.

<table>
<thead>
<tr>
<th>Participant data</th>
<th>Median halo radius (range)</th>
<th>Median halo area (range)</th>
<th>Median straylight score (range)</th>
<th>Median subjective complaint score (range)</th>
<th>Median GE ratio based on binocular halo area (range)</th>
<th>Median GE ratio based on straylight score (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n = 100 ) (65 female)</td>
<td>Monocular: 21.0 (14.4 – 45.3) arc min</td>
<td>Monocular: 4.25 (1.97 – 19.61) cm(^2) Binocular: 3.24 (1.64 – 8.26) cm(^2)</td>
<td>0.90 (0.62 - 1.56) log(s)</td>
<td>4.0 (0.0 – 13.0)</td>
<td>1.03 (0.0 – 4.06)</td>
<td>4.97 (0.0 – 15.29)</td>
</tr>
<tr>
<td>Median age: 21.0 years (range 18.0 – 33.0 years)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2: Summary descriptive statistics for the whole cohort \( (n = 100) \). GE = Glare Effect Ratio.
Monocular halo areas (median = 4.25 cm$^2$; range 1.97 to 19.61 cm$^2$) were significantly larger than the binocular halo areas (median = 3.24 cm$^2$; range 1.64 to 8.26 cm$^2$) with halometry ($P < 0.001$). The median radius in arc min (median = 21.0; range 14.4 to 45.3) and median area in square degrees (median = 0.39; range 0.18 to 1.79) was calculated for monocular data to compare with previously published results. The median straylight score was 0.90 (range 0.62 – 1.56) log(s). The median subjective complaint score was 4.0 (range 0.0 – 13.0). A summary of the subjective grading for each dysphotopic condition is shown in Table 2.3.

There was no significant relationship between binocular halo area and subjective grade using Spearman correlation ($r_s = -0.072, r_s^2 = 0.005, P = 0.478$); monocular halo area and subjective grade ($r_s = -0.013, r_s^2 = 0.0002, P = 0.896$); C-Quant and subjective complaints ($r_s = 0.153, r_s^2 = 0.023, P = 0.128$; see Fig 2.12); halometer and C-Quant ($r_s = 0.121, r_s^2 = 0.015, P = 0.229$; see Fig 2.13).

**Figure 2.12**: Retinal straylight values determined with C-Quant versus subjective grading with PIPP (n = 100).
<table>
<thead>
<tr>
<th>Dysphotopic Condition</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Dark Arc</td>
<td>100</td>
</tr>
<tr>
<td>Bright Arc</td>
<td>98</td>
</tr>
<tr>
<td>Serrated Arc</td>
<td>96</td>
</tr>
<tr>
<td>Night Halo</td>
<td>25</td>
</tr>
<tr>
<td>Night Starburst</td>
<td>25</td>
</tr>
<tr>
<td>Day Halo</td>
<td>48</td>
</tr>
<tr>
<td>Day Starburst</td>
<td>48</td>
</tr>
<tr>
<td>Central Flash</td>
<td>39</td>
</tr>
<tr>
<td>Streams of Light</td>
<td>88</td>
</tr>
<tr>
<td>Ripple Effect</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 2.3**: Summary of the number of participants and the subjective grade of severity given to each dysphotopic condition (n =100).
Figure 2.13: Binocular halo area determined with halometry versus retinal straylight measured with C-Quant (n = 100).

The normal range for the glare effect ratio was calculated for binocular halometry (median = 1.03; range 0 – 4.06; IQR 0.55 – 1.76; see Fig 2.14) and for C-Quant (median = 4.97; range 0 – 15.29; IQR 2.50 – 7.76; see Fig 2.15). Seven outliers were identified for normal binocular halometry glare effect ratio with the following characteristics summarised in Table 2.4. No outliers were identified for the C-Quant glare effect ratio.
<table>
<thead>
<tr>
<th>Age</th>
<th>Sex</th>
<th>Monocular halo area (cm²)</th>
<th>Subjective grade</th>
<th>Glare effect ratio</th>
<th>Bangerter halo area (cm²)</th>
<th>Bangerter subjective grade</th>
<th>Monocular halo area proportional increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>F</td>
<td>3.88</td>
<td>13</td>
<td>4.01</td>
<td>22.39</td>
<td>19</td>
<td>5.8 x</td>
</tr>
<tr>
<td>24</td>
<td>F</td>
<td>2.99</td>
<td>10</td>
<td>3.75</td>
<td>14.06</td>
<td>16</td>
<td>4.7 x</td>
</tr>
<tr>
<td>23</td>
<td>M</td>
<td>3.00</td>
<td>7</td>
<td>4.26</td>
<td>12.84</td>
<td>18</td>
<td>4.3 x</td>
</tr>
<tr>
<td>22</td>
<td>F</td>
<td>2.36</td>
<td>8</td>
<td>4.41</td>
<td>14.84</td>
<td>12</td>
<td>6.3 x</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>3.60</td>
<td>10</td>
<td>3.92</td>
<td>11.19</td>
<td>19</td>
<td>3.1 x</td>
</tr>
<tr>
<td>18</td>
<td>F</td>
<td>2.76</td>
<td>7</td>
<td>3.93</td>
<td>15.16</td>
<td>17</td>
<td>5.5 x</td>
</tr>
<tr>
<td>24</td>
<td>M</td>
<td>5.47</td>
<td>10</td>
<td>3.65</td>
<td>17.01</td>
<td>12</td>
<td>3.1 x</td>
</tr>
</tbody>
</table>

*Table 2.4:* Summary of characteristics for participants who were outliers in the binocular glare effect ratio category (n = 7).
Figure 2.14: Box-and-whisker plot to show the interquartile range of the glare effect ratio with binocular halometry (n = 100). Line within box = median; upper limit of box = 75th percentile; lower limit of box = 25th percentile; upper error bar = 90th percentile; lower error bar = 10th percentile; points = outliers in the upper and lower 10th percentile.

Figure 2.15: Box-and-whisker plot to show the interquartile range of the glare effect ratio with C-Quant (n = 100). Line within box = median; upper limit of box = 75th percentile; lower limit of box = 25th percentile; upper error bar = 90th percentile; lower error bar = 10th percentile; points = outliers in the upper and lower 10th percentile.
Data collected using *Bangerter* filters were assessed (see Table 2.5). The median *Bangerter* halo area was 17.25 cm$^2$ (range 10.27 - 40.45 cm$^2$) and the median straylight score was 1.43 (range 1.29 - 1.77) log(s). The subjective score with *Bangerter* filter *in situ* was evaluated (median = 12.0; range 2.0 – 21.0; IQR 9.0 – 16.0; see Fig 2.16). A summary of the number of participants and the severity that each dysphotopic condition was graded is shown in Table 2.6. The *Bangerter* monocular halometry glare effect ratio median was 0.63 (range 0.06 – 1.70).

<table>
<thead>
<tr>
<th></th>
<th>Halo Area (range)</th>
<th>C – Quant (range)</th>
<th>Subjective Grade (range)</th>
<th>Glare Effect Ratio Monocular Halometry (range)</th>
<th>Glare Effect Ratio C-Quant (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>With Bangerter</strong></td>
<td>17.25* (10.27 – 40.45) cm$^2$</td>
<td>1.43* (1.29 – 1.77) log(s)</td>
<td>12.0* (2.0 – 21.0)</td>
<td>0.63* (0.06 – 1.70)</td>
<td>8.01* (1.47 – 14.93)</td>
</tr>
<tr>
<td><strong>Without Bangerter</strong></td>
<td>4.25* (1.97 – 19.60) cm$^2$</td>
<td>0.90* (0.62 – 1.56) log(s)</td>
<td>4.0* (0.0 – 13.0)</td>
<td>1.36* (0.0 – 4.41)</td>
<td>4.97* (0.0 – 15.29)</td>
</tr>
</tbody>
</table>

*Table 2.5.* Summary of data collected with and without *Bangerter* filters. * indicates a significant difference between normal and *Bangerter* conditions (n = 100).
Figure 2.16: Box-and-whisker plot to show the interquartile range of the Bangerter subjective grading (n = 100). Line within box = median; upper limit of box = 75th percentile; lower limit of box = 25th percentile; upper error bar = 90th percentile; lower error bar = 10th percentile; points = outliers in the upper and lower 10th percentile.
<table>
<thead>
<tr>
<th>Dysphotopic Condition</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Dark Arc</td>
<td>98</td>
</tr>
<tr>
<td>Bright Arc</td>
<td>91</td>
</tr>
<tr>
<td>Serrated Arc</td>
<td>85</td>
</tr>
<tr>
<td>Night Halo</td>
<td>11</td>
</tr>
<tr>
<td>Night Starburst</td>
<td>11</td>
</tr>
<tr>
<td>Day Halo</td>
<td>26</td>
</tr>
<tr>
<td>Day Starburst</td>
<td>26</td>
</tr>
<tr>
<td>Central Flash</td>
<td>36</td>
</tr>
<tr>
<td>Streams of Light</td>
<td>54</td>
</tr>
<tr>
<td>Ripple Effect</td>
<td>96</td>
</tr>
</tbody>
</table>

Table 2.6: Summary of the number of participants and the subjective grade of severity given to each dysphotopic condition with Bangerter foil in situ (n = 100).

No relationship was found when the glare effect ratios from normal binocular halometry readings were compared with subjective grades from participants with the Bangerter foil ($r_s = -0.054$, $r_s^2 = 0.003$, $P = 0.594$). However, when normal binocular halometry glare effect ratio was compared to halometry measurements with the Bangerter foil in place, a significant relationship was found ($r_s = -0.215$, $r_s^2 = 0.046$, $P = 0.032$; see Fig 2.17).
Figure 2.17: Binocular halometry glare effect ratio versus binocular halo area with Bangerter foils (n = 100).

The difference in halo area caused by the Bangerter filter was calculated for halometry by subtracting the monocular normal halo area from the Bangerter halo area. No significant relationship was found when binocular halo area was compared to the increase in halo area ($r_s = 0.103, r_s^2 = 0.011, P = 0.305$). However, the proportional change, calculated by dividing the Bangerter glare area by the normal halo area, showed a weak significant correlation ($r_s = - 0.477, r_s^2 = 0.228, P < 0.001$). A similar result was found when normal monocular halo areas were compared to the increase in halo area ($r_s = 0.130, r_s^2 = 0.017, P = 0.199$) and proportional change ($r_s = - 0.706, r_s^2 = 0.498, P < 0.001$). The C-Quant showed no relationship with the increase in straylight score ($r_s = - 0.028, r_s^2 = 0.0008, P = 0.780$) and proportional increase ($r_s = - 0.090, r_s^2 = 0.008, P = 0.372$).

2.5. Discussion

The present study set out to determine the typical relationship between the most common objective measures of photic effects (halo area and retinal straylight) and subjective complaints of dysphotopsia. Previous studies in the field of photic phenomena have generally reported either objective or subjective measures only (Arnold, 1994, van den Berg, 1995, Dick et al., 1999, Pieh et al., 2001, Aslam et al., 2004a, Puell et al., 2013), largely without consideration of normal values in healthy eyes. That is despite Dick et al. (1999) having investigated both objective and subjective measures after monofocal and multifocal lens implantation, and a positive association between subjective
reports of halos and the objective quantification of halo area being discovered for both lens types. Dick et al. (1999) used a method of moving a small mark from outside the central round source of light to the outer part of the halo using a computer mouse and computer program called ‘glare and halo’. The method is prone to inaccuracies as marking the edge of the halo could lead to some difficulties and thus, seems a rather crude way to measure halo area. The subjective measure is by means of a questionnaire, the modified Arnold questionnaire, targeted at post-cataract surgery patients (see section 1.6.13). It simply asks participants whether they have ‘noticed light flashes or streaks after cataract surgery not noticed before’. The question is followed up with ‘what did your light flash seem the most like’, and were given options of: a curved streak of light, a halo of light, a flare of light, a flash of light, or glare. It is arguable that a participant may not be aware of using these terms to describe the types of dysphotopsia they are experiencing. Also, those who experienced ‘light flashes or streaks’ prior to cataract surgery are omitted from being able to say whether they still experience them, whether they are worse or no longer experience symptoms of dysphotopsia. For this reason, it was decided that the relationship between newer objective measures of dysphotopsia, such as Aston halometer and C-Quant, should be investigated with an alternative subjective measure of dysphotopsia using simulated images.

Dysphotopsia is a complaint often reported by patients after corneal refractive surgery or cataract surgery/refractive lens exchange. Some patients find the symptoms reduce their quality of life with problems such as being unable to drive at night due to the glare. Such patients may request for the multifocal IOL to be removed, which in itself carries inherent risks. Since refractive surgery is becoming more common, it is important to be able to assess glare and to be able to predict those who will likely experience the adverse effect of glare. Currently, no clinical approach is in use pre-operatively to attempt to identify individuals who might be most severely affected subjectively with some surgeons refusing IOL implantation on personality traits alone in otherwise healthy individuals (Pepose, 2008, Braga-Mele et al., 2014).

Binocular and monocular measures were taken with halometry as all previous papers have taken monocular readings only and binocular measures may best represent natural viewing conditions. Monocular halo area was found to be significantly larger (31.2 %) than the binocular area in this study, indicating the effect of binocular summation on objective measures of halo area. Thus, a potential limitation of many previous studies e.g. Puell et al. (2013) and Pieh et al. (2001), is reporting of monocular halo area values only, which are not representative of an individual’s normal binocular visual experience, and may over-estimate the effects of dysphotopsia. Indeed, the correlation between subjective
complaint score and halo radius was found to be weaker for monocular, compared to binocular area.

Using the PIPP plates to grade subjective complaints of dysphotopsia found that the higher values came from day halos, day starburst, night halos, night starburst and central flash. Aslam et al. (2007a) reported a similar finding with a predominance of halos and starburst effects but also substantial symptoms of arc effect, streams of light, and central flash. These were also the more common complaint with the Bangerter lens in situ.

Despite Dick et al. (1999) finding a correlation between subjective reports of halos and halo area, this study found a lack of relationship between subjective and objective measures highlighting the difficulties in being able to predict the potential subjective complaints a patient may experience from an objective measure alone. From this, it is clear that the perception of dysphotopsia is individual to each person. Some have a high objective measure of glare, however subjectively they give a low score for glare effects. It is possible that these individuals have adapted to the glare that they experience and as such have no complaints of glare, or are less troubled by photic effects. Dick et al. (1999) did not state the r-value for the association found, and possibly related it to the complaints of halos alone rather than any dysphotopic complaint. The number of participants was only 28 in each for the monofocal and multifocal group. The study was also carried out 5 months after refractive surgery took place, which is known to increase dysphotopsia, and only those with new complaints of dysphotopsia post-surgery are included in the subjective complaints. Thus, a relationship may have been found as there were 24 monofocal and 19 multifocal participants that answered no to noticing photic phenomena not noticed before, which therefore may include participants who have dysphotopsia but had experienced it prior to surgery. In this study any dysphotopic complaint made up the subjective complaint score, which evidently varies from objective measures. The cohort in this study were mainly young, who are likely to have smaller halos. With the expected larger halo area in older individuals, it is possibly that a relationship may exist, which will be explored in the next chapter.

Puell et al. (2014) found a significant correlation between halo radius and straylight \((r = 0.45, r^2 = 0.203, P = 0.001)\) in a cohort of similarly aged participants to the present study. However, no relationship between halometry and C-Quant measurements was found here and it is likely to be due to the fact that both machines measure different aspects of glare; the C-Quant measures the amount of straylight in the eye (van den Berg, 1995), whereby, the halometer measures the actual size of the disability glare area experienced and is not based on forward scatter within the eye alone. Again, this would indicate that using one objective measure alone may not be enough to distinguish those who struggle
with dysphotopsia. The subjective/objective ratio (glare effect ratio) was calculated to give a single value that combined both measurements. Seven outliers were identified for binocular halometry glare effect ratio. Perhaps surprisingly, the outliers had a range of monocular halo areas, with only one participant having an area larger than the median monocular halo area, however, all of them had higher than the median subjective grade of 4. Supporting the fact that objective measures alone are not enough to predict the possibility of dysphotopsia after refractive surgery. These participants had an average proportional increase of 4.7 times, and had a Bangerter subjective grade of between 12 and 19, which is above the median Bangerter subjective grade for the whole cohort. A finding that supports the idea that those with higher glare effect ratios are more likely to suffer with dysphotopic complaints post-surgery. It could be possible that in this scenario, using the usual equation to calculate the upper outlier by Q3 + 1.5*IQR may not be appropriate. Only seven outliers were identified, yet a significant proportion, about 20 %, of monofocal IOL patients end up dissatisfied (Souza et al., 2006). A suggestion would be to consider anyone above the upper quartile (Q3) as suspicious. Further experimental investigation would be required to confirm this.

There were 11 participants who wore contact lenses during the assessment of halo area and straylight. The lens type was not recorded, however, all wore soft contact lenses. The lenses were assessed at the start of the examination to ensure that there were no significant deposits on the lenses as this would have caused an increased in straylight. Of the 11 contact lenses wearers, the powers were as follows: 3 x < - 2 D, 3 x – 2 D to – 4 D, 2 x – 4 D to – 6 D and 3 x > - 6 D. In this cohort, there were only 3 high myopes. However, in future studies it may be worthwhile investigating whether high powered plus and negative lenses cause increased intraocular scatter due to the edge of the optic and given that the pupils will be dilated in the dark. A limitation of this study is that participants were able to carry out the assessment either with no lenses, with trial lenses or with contact lenses. Whilst, the lenses were cleaned and contact lenses were checked for deposits, in future studies it may be wise to carry out the assessment with trial lenses for all including using plano lenses for those with no refractive error.

Simulating glare conditions using Bangerter foils meant that an estimate of subjective performance if a participant was to develop a cataract or perhaps have refractive surgery could be achieved. Glare effect ratios from binocular halometry readings (under normal viewing conditions) were plotted against subjective grading with Bangerter foils in situ, and no relationship was found. However, when glare effect ratio was compared to halometry with Bangerter foils in place, a weak negative relationship was found. Both of these findings support the fact that the glare effect ratio could be a good indicator of those who are likely
to suffer with increased dysphotopsia post-surgery. It would appear that those with a low glare effect ratio have the larger halo area with Bangerter, which may be due to them having both a high subjective and objective measure in normal viewing conditions giving a low glare effect ratio value, but a large halo area.

The normal range of subjective/objective ratios that have been found could be used for comparison purposes pre- and post-refractive surgery. It is expected that those with the highest subjective/objective ratios are most likely to perform poorly with multifocal IOLs – further studies seeing cataract patients both pre-operatively and post-operatively will be required to test this hypothesis. Having this information would be valuable to IOL manufacturers, as distance and near vision is good in multifocal IOLs with the main complaint being glare. If there is a way to reduce the number of patients who suffer from these glare effects, there may be 100 % patient satisfaction.

The next chapter will investigate both objective and subjective changes over a wider age group, as this data set was a fairly young cohort, to give normative data for halo area and glare effect ratio.
CHAPTER 3

EFFECT OF AGE ON SUBJECTIVE AND OBJECTIVE MEASURES OF DYSPHOTOPSIA

3.1. Introduction

As detailed in section 1.2, dysphotopsia is a term used to denote any light-related visual phenomenon experienced by both phakic and pseudophakic patients (Tester et al., 2000). Dysphotopsia includes flashes of light, increased light sensitivity, glare and haloes (Tester et al., 2000). Although dysphotopsia is one of the most common causes of dissatisfaction in an otherwise satisfied pseudophakic population (Schwiegerling, 2006, Galor et al., 2009, Calladine et al., 2012, Kamiya et al., 2014), it is also a common occurrence in the ageing phakic population (van den Berg, 1995, Vos, 2003a).

In an ideal eye with optically clear media and perfect optical surfaces, no backward or forward scatter would occur. However, the human eye is imperfect and each of its structures contributes to the amount of light scatter through diffraction and aberration (Piñero et al., 2010). In normal individuals, previous authors have estimated that the cornea accounts for about 30 %, the lens 40 % and retina approximately 20 % of scattered light (Yuan et al., 1993, Vos, 2003a). The cornea and crystalline lens cause scattering when their transparency is reduced by conditions including corneal haze (Lohmann et al., 1991, Braunstein et al., 1996, Corbett et al., 1996, Wang et al., 2004, De Brouwere et al., 2008), dystrophy (van den Berg et al., 1993), keratoconus, corneal surgery (Lohmann et al., 1993, Jain et al., 1995, Chang et al., 1998, Wang et al., 2006, Fankhauser, 2007) and cataracts (Delaye et al., 1982, Whitaker et al., 1993, Qian, 2000, Gilliland et al., 2001, Donnelly et al., 2004, Costello et al., 2007). Both the iris and sclera are partially responsible for intraocular scattering as they are not completely opaque, and allow some incident light to pass through (Ijspeert et al., 1990, van den Berg et al., 1991). When light reaches the retina, some of it is absorbed, whilst some is reflected back contributing the intraocular scattering (Vos, 1984, van den Berg, 1995). The vitreous humour is usually a transparent gel due to the regular structure of its fibrils. The transparency of this element may be severely affected by the presence of blood or cells in pathological conditions such as vitreous haemorrhage or posterior uveitis (Piñero et al., 2010).

The resultant increase in intraocular light scatter or straylight from a bright light source causes a veiling glare and a loss of contrast across the retinal image (Vos, 1984, van den Berg, 1995, Aslam et al., 2007b, Allen et al., 2009). A loss in contrast typically reduces the observer’s ability to distinguish detail within a visual scene. Disability glare is
usually encountered in scotopic light conditions as pupil dilation allows more intraocular scatter to occur from the glare source (Allen et al., 2009). The term dysphotopsia encompasses more phenomena than glare alone- a commonly reported complaint is halos; the subjective perception of a bright ring around a light source (Aslam et al., 2007b, Buznego and Trattler, 2009). The effect is regularly perceived when looking at a bright light source in the dark, such as street lamps on a foggy night. The halo is formed by light rays that are scattered outside the focussed image creating a dim disc of light around the light source (Allen et al., 2009).

Dysphotopsia is widely accepted to increase with age (van den Berg, 1995, Tester et al., 2000, Vos, 2003a, Puell et al., 2013), and complaints of halos with night driving are more frequent in older patients. Although visual acuity may be normal, the effect of the bright headlight can cause such a severe detriment to the vision of some that it causes individuals to stop driving, which in turn reduces quality of life (Dewaard et al., 1992, Ranney et al., 2000, Theeuwes et al., 2002). Individuals affected by dysphotopsia may complain of ‘hazy vision’, difficulties in recognising faces when looking into the light, and halos around bright lights in low light conditions (van den Berg et al., 2007). Even in photopic conditions, loss of contrast and colour can occur (Piñero et al., 2010). The age-related increase in dysphotopsia is attributable to natural ageing changes increasing ocular media irregularities such as lens opacities and vitreous floaters, and therefore increasing the amount of scatter (Wolf, 1960, Vos, 1984, Bailey and Bullimore, 1991, Dewaard et al., 1992, Elliott, 1993). The resultant increase in intraocular light scatter from a bright light source causes a veiling glare and a loss of contrast across the retinal image (Vos, 1984, van den Berg, 1995, Aslam et al., 2007b, Allen et al., 2009).

Previous studies have used different devices to study changes in dysphotopsia with age; these have been summarised in Table 3.1. One of the earlier methods of measuring straylight was the direct compensation method, as used by Ijspeert et al. (1990; n = 129, range = 20 – 82 years). The observer monocularly views a screen at a distance of 45 cm. A 1 degree radius circular test field is in the centre, surrounded by a ring shaped field with an outer radius of 1.5 cm (2 deg) of steady, homogeneous, luminance of 30 cd/m², called the separation ring. On the screen, one of four ring shaped straylight sources were projected with effective angular radii of 3.5, 7.0, 13.6 and 25.4 deg. The straylight source was intermittent at a frequency of 8 Hz by means of a chopper. The intraocular light scattering between 3.5 and 25 deg of scattering angle was determined using direct compensation method. The authors reported that straylight increased significantly (to the power of $4.3 \pm 0.2$) with age, and after 70 years the straylight doubled.
Bailey et al. (1991) used the Berkeley glare test to determine Disability Glare Index (DGI) as a measure of dysphotopsia in younger versus older individuals (Younger cohort: n = 28, mean age = 28.4 ± 7.0 years, range = 15 – 41 years; Older cohort: n = 47, mean age = 64.9 ± 9.2 years, range = 50 – 82 years). The Berkeley glare test is a low contrast (10 %) letter chart surrounded by a white background which may be transilluminated to serve as the glare source. The chart is front-illuminated by lamps to a level of 80 cd/m². The surrounding luminance can be set at 300 (low glare), 800 (medium glare) and 3000 (high glare) cd/m². Visual acuity is measured at 1 m from the chart. DGI is calculated as the difference between VA scores in the no glare and high glare conditions. In this study, a strong positive correlation between DGI values and age was found (r = 0.75).

Since the development of the psychophysical compensation comparison method, it has been favoured over the previous direct compensation method (Coppens et al., 2006, Franssen et al., 2006), and can be performed using the commercially available C-Quant. To date two studies have used the C-Quant to measure the effect of age on straylight (Rozema et al., 2010b, Puell et al., 2014). Rozema et al. (2010b) found that straylight remained constant until the age of 45 years, after which it gradually increased (n = 518 eyes of 277 subjects, mean age = 39.7 ± 13.2 years, range = 8.5 – 78 years). Puell et al. (2014), described no significant effect of age on straylight in their study cohort (n = 51, mean age = 29.3 ± 7.5 years, range = 20 – 43 years), although the age range was more limited. Thus, there is no clear consensus on the effect of age on straylight measured with the C-Quant, although it may increase beyond the middle of the fifth decade.

Measurement of halo area with age has been carried out in just two previously published studies, from the same research team (Puell et al., 2013, Puell et al., 2014). Both measured halo radius using the Vision Monitor and low luminance optotypes presented at 2.5 m. An off axis light source was used, with the participant’s head positioned with centre of monitor, whilst the LED glare source is at the edge of the screen. Optotypes arranged in three radial lines of letters appear from the periphery, moving towards the glare source. Each line contains 10 letters forming 10 rings at intervals of 33 arc min. Each letter subtends 15 arc min and corresponds to 0.5 logMAR. Monocular testing in a dark room with best spectacle correction was performed in both studies. Puell et al. (2013) investigated the change in halo radius over a range of age groups (n = 147, mean age = 48.2 ± 16.2 years, range = 20 – 77 years; 20 – 29 years n = 28; 30 – 39 years n = 17; 40 – 49 years n = 25; 50 – 59 years n = 31; 60 – 69 years n = 34; 70 – 79 years n = 12) using an optotype luminance of 5 cd/m². Mean halo radius was found to be 111.6 ± 39.8 arc min (range 66 – 220 arc min). A significant relationship between halo area and age was established (r = 0.65, r² = 0.42, P < 0.0001). Halo areas were similar in the 20 – 29, 30 – 39
and 40 - 49 age groups, and then increased beyond the age of 50 years. There was a mean halo radius difference of 72 arc min between the youngest (88.4 ± 22.1 arc min) and the oldest (160.4 ± 35.5 arc min) age groups. A limitation of this study is that the test was conducted monocularly, and as found in chapter 2, monocular glare areas are larger than binocular glare areas. Therefore, an overestimation of halo areas, as experienced by the participant, may have occurred. An off-axis light source was used, with halo radius estimated from just 3 radius measurements as only a semi circle of the halo is measured. An assumption of halo area being symmetrical has been made, despite existing literature showing a debate that halos may not be perfectly circular (Castro et al., 2011, Meikies et al., 2013). In 2014, Puell et al. conducted a further study (n = 51, mean age = 29.3 ± 7.5 years, range = 20 – 43 years) using the Vision Monitor but with a reduced optotype luminance of 1 cd/m². The lower optotype luminance meant the mean halo radius of 201.6 ± 42.7 arc min was almost double that reported in the previous study. However, no significant effect of age on halo radius was observed in this younger study sample.

The previous studies described have failed to provide information on how individuals are affected by dysphotopsia, as no subjective measures were included. It might be anticipated that both subjective and objective measures increase with age. The previous chapter highlighted the lack of a relationship between objective measures and subjective complaints of dysphotopsia. The use of the ‘glare effect ratio’ to combine the two measurements, and its potential use as a pre-operative assessment was introduced in chapter 2. The effect that the increase in both objective and possibly subjective complaints will have on the ‘glare effect ratio’ with age is unknown. The previous chapter also described normal values for halometry in a ‘young’ cohort, however, further investigation of the normative data over a wider age range would be useful when carrying out pre- and post-operative examination on the likely older cohort with cataract.
<table>
<thead>
<tr>
<th>Parameter Measured</th>
<th>Author and Technique</th>
<th>Cohort Characteristics</th>
<th>Mean Value</th>
<th>Effect of Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straylight</td>
<td>Puell et al. (2014)</td>
<td>n = 51</td>
<td>Straylight</td>
<td>No significant effect of age on straylight was observed. Highest age was 43 years.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean age = 29.3 ± 7.5 years</td>
<td>0.95 ± 0.12 (range 0.64 – 1.21) log units</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range 20 – 43 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rozema et al. (2010b)</td>
<td>n = 518 eyes of 277 subjects (257 right and 261 left)</td>
<td>N/A</td>
<td>Straylight remained constant until the age of 45 years, after which it gradually increased.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 male and 198 female</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean age = 39.7 ± 13.2 years</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range 8.5 – 78 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vos (2003)</td>
<td>N/A</td>
<td>N/A</td>
<td>Introduced age dependence into the Stiles-Holladay disability glare equation. For ages under 35 years old, the change in glare is negligible. Disability glare rapidly increases beyond the age of 60 years; it doubles by 70 years and triples by 83 years.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Theoretical study linked to disability glare</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Author(s)</td>
<td>Description</td>
<td>Younger cohort</td>
<td>Older cohort</td>
<td>Analysis</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
<td>----------------</td>
<td>-------------</td>
<td>----------</td>
</tr>
</tbody>
</table>
| Bailey *et al.* (1991) | Berkeley Glare Test- low contrast (10 %) letter chart surrounded by a white background which may be transilluminated to serve as the glare source. Visual acuity is measured at 1 m from the chart. DGI calculated as the difference between VA scores in the no glare and high glare conditions. | n = 28  
Mean age = 28.4 ± 7.0 years  
Range 15 – 41 years | n = 47  
Mean age = 64.9 ± 9.2 years  
Range 50 – 82 years | Linear regression analysis showed a correlation coefficient of r = 0.75 between DGI values and age. |
| Ijspeert *et al.* (1990) | Monocular observation of a screen at 45 cm. A 1 degree radius circular test field was in the centre, surrounded by a ring shaped field with an outer radius of 1.5 cm (2 deg). Direct compensation method determined the intraocular light scattering between 3.5 and 25 deg of scattering angle. | n = 129  
Range 20 – 82 years  
20 – 30 years n = 20 (40 eyes)  
30 – 40 years n = 21 (42 eyes)  
40 – 50 years n = 20 (40 eyes)  
50 – 60 years n = 20 (40 eyes)  
60 – 70 years n = 20 (40 eyes)  
70 – 80 years n = 8 (13 eyes) | N/A | Straylight increased to the power of 4.3 ± 0.2 with age. It doubled from the age of 70 |
| Vos (1984) | Assessment of straylight using the equivalent veil method. | N/A | N/A | Straylight increases with age by a factor of 3 between 20 and 80 years. |
### Halo Area

**Puell et al. (2014)**

Monocular halo radius measured using the Vision Monitor and low luminance (1 cd/m²) optotypes presented at 2.5 m. Off axis light source used. Optotypes arranged in three radial lines of letters appearing from the periphery towards the glare source.

- n = 51
- Mean age = 29.3 ± 7.5 years
- Range 20 – 43 years
- Halo Radius: 201.6 ± 42.7 arc min / 3.4 ± 0.7 º
- No significant effect of age on halo radius was observed in this study sample. Oldest participant was 43 years old.

**Puell et al. (2013)**

Halo radius measured using the Vision Monitor as described above. However, optotype used had a luminance of 5 cd/m².

- n = 147
- Mean age = 48.2 ± 16.2 years
- Range 20 – 77 years
- 20 – 29 years n = 28;
- 30 – 39 years n = 17;
- 40 – 49 years n = 25;
- 50 – 59 years n = 31;
- 60 – 69 years n = 34;
- 70 – 79 years n = 12.
- Halo Radius: 111.6 ± 39.8 arc min (range 66 – 220 arc min)
- Relationship between halo area and age: (r = 0.65, r² = 0.42, P < 0.0001)
- Halo areas were similar in the 20 – 29 / 30 – 39 / 40 – 49 age groups, and then increased beyond the age of 50 years. Mean halo radius difference of 72 arc min between the youngest (88.4 ± 22.1 arc min) and the oldest (160.4 ± 35.5 arc min) groups.

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**Table 3.1:** Summary of studies that have investigated the changes in dysphotopsia with age.
The effect of age on halo area is unknown, and there is a lack of information about subjective changes in dysphotopsia with age. Therefore, the aims of this prospective study are to:

- Establish how objective measures and subjective complaints of dysphotopsia change with age in healthy eyes.
- Determine how the “glare effect ratio”, introduced in chapter 2, changes with age.
- Define a normal range of values for halometry glare area and “glare effect ratio” over a wide age range to facilitate an evidence-based approach to assist with the selection, and counselling of candidates for refractive procedures which may induce post-operative photic effects.

3.2. Subjects and methods

All procedures were conducted in the Ophthalmic Research Group laboratories at Aston University, Birmingham, UK. The study was reviewed by the Aston University, Life and Health Sciences Research Ethics Committee (Application number 595). A copy of this approval can be found in appendix A1. The study was conducted in accordance with the tenets of the Declaration of Helsinki and all subjects gave their written informed consent to take part after explanation of the nature and consequences of the study.

Power calculations, made using GPower (version 3.1.9.2), showed that 135 participants were required to enable Spearman correlation to detect statistically significant medium size (0.25) effect at the 5% significance level ($\alpha = 0.05$) with 80% power. One hundred and forty-one subjects were recruited from staff and student body and Aston Research Centre for Healthy Ageing (ARCHA).

**Inclusion Criteria**

- Corrected distance visual acuity (CDVA) of 0.0 logMAR or better binocularly, with at least 0.1 logMAR monocularly in the better eye.
- Clear ocular media or with normal age related media changes on slit lamp examination; classed as posterior capsular cataract, cortical or nuclear opacities less than LOCS III classification grade 1.5 (Chylack et al., 1993, van den Berg et al., 2007, Puell et al., 2013).
Exclusion Criteria

- Any history of ocular surgery, including laser refractive procedures.
- Participants with any pre-diagnosed ocular conditions.
- Any participants with a history of using drugs that are known to affect the eye.
- Any participants with a systemic health problem that may result in ocular complications.

Unaided visions were measured and a full subjective refraction was performed at 3 m using the Thomson Test Chart 2000. Where the participant wore a distance habitual refractive correction, then this refractive correction was used for halometry and C-Quant. An Oculus Universal trial frame was used to house the manifest refraction; adjusted to ensure a 12 mm back vertex distance. The full aperture trial lenses were cleaned before insertion into the trial frame to ensure that they did not increase the amount of glare experienced.

As described in sections 2.2.1 and 2.2.2, objective and subjective measures of dysphotopsia were conducted in a random order. Halometry was carried out both binocularly and monocularly, with the eye for monocular measurement selected using a randomisation table (Armstrong, 2013). The C-Quant was used to quantify intraocular light scatter in the same eye used for monocular halometry reading. Subjective complaints of dysphotopsia were recorded using the PIPP plates to give a grade between 0 – 40, where 0 = no dysphotopsia experienced, and 40 = severe complaints in all forms of photic effects (Aslam et al., 2004a).

3.3. Data and statistical analysis

The data was stored in a password-protected Excel 2016 Spreadsheet document (Microsoft, Redmond, WA). All statistical tests were performed using SigmaPlot graphing and statistical software (Version 12.0, Systat Software Inc., Chicago, Illinois, USA). The data was checked for normality using the one-sample Kolmogorov-Smirnov test; only C-Quant glare effect ratio did not deviate significantly from a normal distribution (all $P < 0.05$). Therefore, median and range values are reported for all parameters. Monocular and binocular halo areas were compared using Wilcoxon signed rank test. Spearman’s correlation was used to determine the relationship between objective measures of dysphotopsia / subjective gradings and age. In all cases, a $P$ value of < 0.05 was considered statistically significant.
3.3.1. Calculation of halo area from halometer

The halo radius in degrees for each of the 8 meridians was recorded, and these were used to calculate the area of the triangle that is created by two adjoining meridians (see Fig 2.11). The total area of the glare scotoma was calculated. To calculate total halo area, the sum of the areas of 8 triangles resulting from the 8 medians was calculated as previously described in section 2.3.1 (see Fig 2.10). The halo radius was converted from degrees subtended to arc min using Equation 2.3. The median and range for halo radius was calculated. Glare area was also calculated in square degrees using mean radii in degrees described in Equation 2.4.

The glare effect ratio was calculated by dividing subjective grading by the objective area found for binocular halometry. In addition, a similar calculation was carried out for C-Quant measures. The glare effect ratio provides a single value to represent the combination of subjective and objective measures. A low ratio indicates a low level of subjective effect compared to the objective measure, whilst a high glare effect ratio indicates an individual who is more subjectively affected by a given objective measure. Median and IQRs glare effect ratios were calculated. The IQR was then used to calculate outliers in the data by adding 1.5 x IQR to Q3 (the upper value of the interquartile range) and by subtracting 1.5 x IQR from Q1 (the lower value of the interquartile range).

A power function was fitted using SigmaPlot graphing software (Version 12.0) to model the relationship between halo area and age.

3.4. Results

One hundred and forty one healthy volunteers aged 18.0 – 82.0 years (median age 23.0 years) participated in the study. Table 3.2 provides summary descriptive statistics for the entire cohort. It was not possible to include straylight readings for 3 participants due to the poor reliability of their readings, other data from these individuals were included in the analyses.
<table>
<thead>
<tr>
<th>Participant data</th>
<th>Median halo radius (range)</th>
<th>Median glare area (range)</th>
<th>Median straylight score (range)</th>
<th>Median subjective complaint score (range)</th>
<th>Median GE ratio based on binocular halo area (range)</th>
<th>Median GE ratio based on straylight score</th>
</tr>
</thead>
<tbody>
<tr>
<td>M = 141 (86 female)</td>
<td>Monocular: 22.7 (14.4–46.7) arc min</td>
<td>Monocular: 4.87 (1.97–20.87) cm²</td>
<td>0.99 (0.62–1.56) log(s)</td>
<td>5.0 (0.0–20.0)</td>
<td>1.28 (0.0–4.41)</td>
<td>5.63 (0.0–17.17)</td>
</tr>
<tr>
<td>Median age: 23.0 years (range 18.0–82.0 years)</td>
<td>Binocular: 19.8 (13.1–35.6) arc min</td>
<td>Binocular: 3.77 (1.64–12.11) cm²</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: Summary descriptive statistics for the whole cohort. N = 141. GE = Glare Effect Ratio.

The cohort of 141 participants consisted of 86 females and 55 males (see Table 3.2). Monocular halo areas (median = 4.87 cm²; range 1.97 to 20.87 cm²) were significantly larger than binocular halo areas (median = 3.77 cm²; range 1.64 to 12.11 cm²) with halometry (P < 0.001). The median radius in arc min (median = 22.7; range 14.4 to 46.7) and median area in square degrees (median = 0.45; range 0.18 to 1.91) was calculated for monocular data to allow comparison with previously published results. Binocular and monocular halo areas both increased with age (r = 0.449, r² = 0.202, P < 0.001 and r = 0.403, r² = 0.162, P < 0.001, respectively; see Fig 3.1). Monocular mean radii increase with age (r = 0.405, r² = 0.162, P < 0.001). A power function was fitted to the halo radius data plotted against age (see Fig 3.2), to enable comparison with that plotted by Puell et al. (2013). Straylight measured with the C-Quant also increased significantly with age (r = 0.457, r² = 0.209, P < 0.001; see Fig 3.3).
Figure 3.1: Binocular and monocular halo area measured with halometry versus age (n = 141).

Figure 3.2: Power function fitted to halo radius data plotted against age (n = 141).
Figure 3.3: $C$-Quant straylight values plotted against age ($n = 138$).

The median subjective complaint score was 5.0 (range 0.0 – 20.0). A summary of the subjective grading for each dysphotopic condition is shown in Table 3.3.
Table 3.3: Summary of the number of participants and the subjective grade of severity given to each dysphotopic condition (n = 141).

<table>
<thead>
<tr>
<th>Dysphotopic Condition</th>
<th>Grade</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Arc</td>
<td></td>
<td>140</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bright Arc</td>
<td></td>
<td>136</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Serrated Arc</td>
<td></td>
<td>137</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Night Halo</td>
<td></td>
<td>27</td>
<td>77</td>
<td>31</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Night Starburst</td>
<td></td>
<td>27</td>
<td>77</td>
<td>31</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Day Halo</td>
<td></td>
<td>73</td>
<td>18</td>
<td>29</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Day Starburst</td>
<td></td>
<td>73</td>
<td>18</td>
<td>29</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Central Flash</td>
<td></td>
<td>58</td>
<td>31</td>
<td>33</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>Streams of Light</td>
<td></td>
<td>117</td>
<td>15</td>
<td>3</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Ripple Effect</td>
<td></td>
<td>139</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

No relationship was exhibited between objective binocular halo area and subjective grade ($r_s = 0.132$, $r_s^2 = 0.017$, $P = 0.119$; see Fig 3.4); and between monocular halo area and subjective grade ($r_s = 0.148$, $r_s^2 = 0.022$, $P = 0.08$; see Fig 3.5). However, a weak correlation was found when binocular halo area was compared to subjective night halo complaints ($r_s = 0.330$, $r_s^2 = 0.109$, $P < 0.001$; see Fig 3.6). There was no relationship between any of the other PIPP plate conditions with either monocular or binocular halo area (see Table 3.4). A weak relationship was shown between C-Quant and subjective complaints ($r_s = 0.268$, $r_s^2 = 0.072$, $P = 0.002$; see Fig 3.7). Binocular halometry and C-Quant also
exhibited a weak relationship ($r_s = 0.337$, $r^2_s = 0.114$, $P < 0.001$, $N = 138$; see Fig 3.8). Overall, a weak relationship was seen between age and subjective grade ($r_s = 0.314$, $r^2_s = 0.099$, $P < 0.001$; see Fig 3.9); night halo complaints specifically increased with age, again only a weak but significant relationship ($r_s = 0.356$, $r^2_s = 0.127$, $P < 0.001$; see Fig 3.10).

**Figure 3.4:** Binocular halo area measured with halometry versus subjective grading with PIPP ($n = 141$).

**Figure 3.5:** Monocular halo area determined with halometry versus subjective grading with PIPP ($n = 141$).
**Figure 3.6:** Binocular halo area measured with halometry plotted against subjective night halo complaints with *PIPP* (n = 141).

**Figure 3.7:** Retinal straylight values with *C-Quant* versus subjective grading with *PIPP* (n = 138).
**Figure 3.8:** Binocular halo area determined with halometry versus retinal straylight measured with *C-Quant* (*n* = 138).

**Figure 3.9:** Subjective grading with *PIPP* against age (*n* = 141).
Figure 3.10: Subjective night halo complaints on PIPP against age (n = 141).

Table 3.4: Spearman correlation values for monocular and binocular halometry versus the 8 dysphotopic conditions on the PIPP plates.
The normal range for the glare effect ratio was calculated for binocular halometry (median = 1.28; range 0.0 – 4.41; IQR 0.75 – 2.15; see Fig 3.14) and for C-Quant (median = 5.63; range 0.0 – 17.17; IQR 2.72 – 7.97; see Fig 3.15). There was no significant relationship found between age and the binocular glare effect ratio for halometry ($r_s = 0.0002, r_s^2 < 0.001, P = 0.998$; see Fig 3.11); monocular halometry glare effect ratio ($r_s = -0.003, r_s^2 < 0.001, P = 0.969$; see Fig 3.12); however, a weak relationship was found with C-Quant glare effect ratio ($r_s = 0.199, r_s^2 = 0.040, P = 0.020, N = 138$; see Fig 3.13).

![Figure 3.11](image_url)

**Figure 3.11**: Binocular halometry glare effect ratios against age ($n = 141$).
**Figure 3.12:** Monocular halometry glare effect ratios against age (n = 141).

**Figure 3.13:** C-Quant glare effect ratios against age (n = 138).
As with chapter 2, the box-and-whisker plot shows the median, 25th percentile and 75th percentile (see Fig 3.14 and Fig 3.15). Outliers are calculated by adding 1.5 x IQR to the upper value of the interquartile range. For binocular halometry, glare effect ratios above 4.25 would be classed as outliers; in this cohort there were 2 outliers (see Table 3.5), according to this calculation. For C-Quant, glare effect ratios above 15.85 are outliers. Two outliers were identified in this cohort and their characteristics are summarised in Table 3.6.

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age</th>
<th>RE Rx</th>
<th>LE Rx</th>
<th>Subjective Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>23</td>
<td>Plano</td>
<td>Plano / -0.50 x 180</td>
<td>7</td>
</tr>
<tr>
<td>F</td>
<td>22</td>
<td>+1.00 / - 0.50 x 100</td>
<td>+ 1.00 / - 0.50 x 70</td>
<td>8</td>
</tr>
</tbody>
</table>

**Table 3.5:** Summary of characteristics of outliers for the binocular halometry glare effect ratio (n = 2).

<table>
<thead>
<tr>
<th>Sex</th>
<th>Age</th>
<th>RE Rx</th>
<th>LE Rx</th>
<th>Subjective Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>62</td>
<td>+ 0.25 / -1.25 x 50</td>
<td>+ 0.50 / -1.00 x 20</td>
<td>18</td>
</tr>
<tr>
<td>F</td>
<td>52</td>
<td>- 2.00 DS</td>
<td>- 3.00 DS</td>
<td>17</td>
</tr>
</tbody>
</table>

**Table 3.6:** Summary of characteristics of outliers for the C-Quant glare effect ratio (n = 2).

**Figure 3.14:** Box-and-whisker plot to show the interquartile range of the glare effect ratio with binocular halometry (n = 141). Line within box = median; upper limit of box = 75th percentile; lower limit of box = 25th percentile; upper error bar = 90th percentile; lower error bar = 10th percentile; points = outliers in the upper and lower 10th percentile.
Figure 3.15: Box-and-whisker plot to show the interquartile range of the glare effect ratio with C-Quant \((n = 138)\). Line within box = median; upper limit of box = 75\(^{th}\) percentile; lower limit of box = 25\(^{th}\) percentile; upper error bar = 90\(^{th}\) percentile; lower error bar = 10\(^{th}\) percentile; points = outliers in the upper and lower 10\(^{th}\) percentile.

3.5. Discussion

The present study set out to determine how halo area, measured with the Aston halometer, changes with age in a large cohort. The effect of age on objective measures of retinal straylight was also established, as well as the effect on subjective complaints. The influence that age has on ‘glare effect ratio’, which was introduced in chapter 2, was investigated for the first time.

Dysphotopsia is a complaint often reported by patients after corneal refractive surgery or cataract surgery/refractive lens exchange, but it is also a common occurrence in the healthy aging population (van den Berg, 1995, Vos, 2003a). Dysphotopsia is widely accepted to increase with age (van den Berg, 1995, Tester et al., 2000, Vos, 2003a, Puell et al., 2013), with frequent complaints from older patients about halos around light when driving at night. Individuals may have good visual acuity, and still find the glare to be bothersome (Dewaard et al., 1992, Ranney et al., 2000, Theeuwes et al., 2002). Some patients find the symptoms causes such a severe detriment to their vision that it reduces their quality of life, as they lose the confidence to drive at night. The literature presently concludes that straylight increase with age (Wolf, 1960, Ijspeert et al., 1990, Bailey and Bullimore, 1991, Dewaard et al., 1992, Elliott and Bullimore, 1993, Vos, 2003a, van den Berg et al., 2007, Rozema et al., 2010b, Puell et al., 2014). Only two studies have investigated how halo area
changes with age, and whilst one found a significant relationship with age ($r = 0.65$, $r^2 = 0.42$, $P < 0.0001$) and that it rapidly increased beyond 50 years old (Puell et al., 2013). The second study by Puell et al. (2014) found no effect with age in that cohort (range 20 – 43 years old). However, no studies to date have described how subjective complaints of dysphotopsia change with age.

Consistent with the findings of chapter 2, monocular halo area was also found to be significantly larger than binocular halo area in this cohort including a much wider age range. The difference was approximately 29 %, similar to the 31.2 % difference found in chapter 1. Thus, a potential limitation of previous studies, such as Puell et al. (2013) and Pieh et al. (2001), is reporting of monocular halo area values only, which are not representative of an individual’s normal visual experience, and may over-estimate the level of dysphotopsia.

It is widely accepted that even in the absence of ocular disease, normal age-related changes in dysphotopsia occur due to an increase in intraocular scatter (Ijspeert et al., 1990, Bailey and Bullimore, 1991, Vos, 2003a, Rozema et al., 2010b, Puell et al., 2014) and the current data also demonstrate an increase in straylight with age ($rs = 0.457$, $r_s^2 = 0.209$, $P < 0.001$). Bailey et al. (1991) found a correlation coefficient of $r = 0.75$ between age and straylight, however a low contrast letter chart was used to assess the DGI. The difference between VA in no glare and high glare (3000 cd/m²) conditions was used to calculate the DGI. The compensation comparison method uses a different technique to assess straylight, thus these values would not be comparable to C-Quant straylight values.

The results of the present study indicate that binocular halo area increases with age ($rs = 0.449$, $r_s^2 = 0.202$, $P < 0.001$) in individuals with healthy eyes. The finding compares favourably with studies that have used alternative halometers such as the Vision monitor (Puell et al., 2014), although the raw data values are not comparable to this data set, an issue which is discussed further later on in this section. Puell et al. (2013) reported a similar correlation for halo radius and age ($r = 0.65$, $P < 0.001$) as the monocular halometry results in the current study ($rs = 0.405$, $r_s^2 = 0.162$, $P < 0.001$). Puell et al. (2013) stated that this increase in halo area with age could be due to changes in the transparency of the ocular media.

Halometry is used to establish the limit in the visual field at which the subject is unable to identify a letter around a central light source, thus, allowing the extent of the halo to be plotted. Identifying letters is more accurate than attempting to mark on the score the limit of
a diffuse halo produced by a central glare source, which has to be viewed by the subject. In several previous studies, the task for the subject was to report when a red spot touched the edge of a possible halo at a 2 m distance (Pieh et al., 2001, Lackner et al., 2003). Alternatively, the subject had to place a marker at the outer limit of the halo using a computer mouse at a 1 m distance (Allen et al., 2008). A limitation of these methods is that if the subject does not see a defined halo or does not understand what a halo is, identification of its margin could be difficult. Differences in methodology, luminance of the glare source, distance, and measurement units make it difficult to compare the findings of the few studies that have examined halo area. In one study, halo area has been reported as its radius (mm) at 30 cm (Babizhayev et al., 2009). In others, halo area values are given in square degrees (sqd; Lackner et al., 2003, Allen et al., 2009). In LASIK patients younger than 50 years, mean pre-operative halo area was 1.97 ± 1.20 sqd. (Lackner et al., 2003). Puell et al. (2013) found a mean halo area in subjects younger than 50 years of 6.9 ± 0.4 sqd. Allen et al. (2009) found larger values of 61.3 ± 6.5 sqd, which could be due to the very close proximity of the glare source to the participant at 1 m. The limit of the halo was also defined by placing a marker at the outer limit using a computer mouse, which could have led to a gross overestimation. The median halo area in the present study was 0.45 sqd (range 0.18 – 1.91). Puell et al. (2013) recorded mean halo radii in arc min and found a mean of 100 ± 43 and 93.4 ± 41.6 for their first and second sessions, whilst the median radii in the present study was 22.7 arc min (range 14.4 – 46.7). The difference could be explained by the difference in light brightness, light source size, test distance or the position of glare source as Puell et al. (2013) positioned it peripherally. Puell et al. (2013) also had intervals of 33 min of arc that is the equivalent of 0.55 degree steps, whilst the Aston halometer uses increments of 0.05 degrees, making it more sensitive to small differences in halo area. Halo radius is estimated from only 3 radius measurements as only a semi circle of the halo is measured. An assumption of the halo area being symmetrical has been used, despite present literature showing a debate that halos may not be perfectly circular (Castro et al., 2011, Meikies et al., 2013).

Similar to findings in chapter 2, no relationship was exhibited between objective binocular halo area and subjective grade \( (r_s = 0.132, \ r_s^2 = 0.017, \ P = 0.119) \); and between monocular halo area and subjective grade \( (r_s = 0.148, \ r_s^2 = 0.022, \ P = 0.08) \). However, a weak correlation was found when binocular halo area was compared to subjective night halo complaints \( (r_s = 0.330, \ r_s^2 = 0.109, \ P < 0.001) \); whilst no other dysphotopic conditions exhibited a relationship. It may be that the night halo image on the PIPP plates is most similar to the appearance of the halo, and therefore, some correlation lies there for the measurement of similar photic phenomena.
Subjective grading showed only a weak relationship with age \( (r_s = 0.314, r_s^2 = 0.099, P < 0.001) \), indicating that although both objective measures of dysphotopsia increased with age, subjective complaints do not concur with this finding. Substantially highlighting the fact that it is possible for individuals to have high objective measures but not have significant complaints of glare. Night halo complaints had a slightly stronger relationship with age, again only a weak but significant relationship \( (r_s = 0.356, r_s^2 = 0.127, P < 0.001) \); it may be that it is a specific complaint that individuals feel they can relate to. In chapter 2, the glare effect ratio was introduced as a way of incorporating objective and subjective measures of dysphotopsia. Both binocular and monocular halometry glare effect ratios displayed no relationship with age \( (r_s = 0.0002, r_s^2 < 0.001, P = 0.998 \text{ and } r_s = -0.003, r_s^2 < 0.001, P = 0.969, \text{ respectively}) \); and C-Quant glare effect ratio presented a very weak relationship with age \( (r_s = 0.199, r_s^2 = 0.040, P = 0.020) \). It is widely accepted that objective measures increase with age, therefore, it can be difficult to establish if an older patient has a high objective measure due to age alone. The glare effect ratio is independent of age, and as suggested in chapter 2, a high glare effect ratio would indicate an individual more subjectively affected by a given objective measure. Along with the two outliers on halometry according to the IQR formula, those at the top of the box and whisker plot would be more susceptible to subjective effects. The outlier formula may not be appropriate here, as it is known that up to 50% of patients may complain of dysphotopsia post-operatively, therefore, in a cohort of 141, a significant number of outliers would have been expected. So, whilst those that are classed as outliers would be most problematic, it is likely that there are others who would also be troubled by dysphotopsia. In the current cohort, 2 participants were also identified as outliers for the C-Quant glare effect ratio. Looking at the characteristics of all the individuals, there were 2 males and 2 females; who had a subjective grade from 7 to 18. There was no obvious trend of refractive error with the outliers.

Factors such as translucency of the wall of the eye can allow straylight to enter the eye depending on the individuals’ pigmentation. Therefore, a potential limitation of this study was not recording the ethnicity or iris colour of the participants. However, many papers have evaluated glare and they have not considered ethnicity or iris colour, despite the likelihood that it would impact on the levels of ocular pigmentation (Puell et al., 2013, Buckhurst et al., 2017, Pieh et al., 2001). The point is explored further in chapter 7.

In summary, this study has found that monocular and binocular halo area increases with age. Subjective complaints were only very weakly associated to age. Glare effect ratio was also independent of age. Indicating that the use of glare effect ratio may be a more suitable pre-operative test to establish those likely to suffer from complaints of dysphotopsia. A future study described in this thesis will examine glare effect ratios measured
pre-operatively in cataract patients, and compare them to subjective complaints post-operatively.
CHAPTER 4
HOW DOES PUPIL DIAMETER IMPACT ON HALO AREA?

4.1. Introduction

As detailed in earlier chapters, dysphotopsia describes unwanted light sensations, and including glare and halos. The scatter of intraocular straylight from the various surfaces within the eye, such as the cornea, lens and vitreous, is the cause of dysphotopic effects. Dysphotopsia can cause severe problems for people when driving at night due to the bright light source of car headlights and streetlamps (Dewaard et al., 1992, Ranney et al., 2000, Theeuwes et al., 2002). Many different techniques exist to measure the amount of glare or straylight; although currently there is no gold standard (Neumann et al., 1988, Elliott and Bullimore, 1993, Aslam et al., 2007b). Often dysphotopsia is measured by placing a bright light source in the subjects' field of view (Williamson et al., 1992, Elliott and Bullimore, 1993), and pupil diameter is known to decrease with increasing luminance (Laughlin, 1992, Winn et al., 1994, Loewenfeld, 1999, Watson and Yellott, 2012, Orr et al., 2015). Therefore, one might argue that pupil size will be affected in these assessments of dysphotopsia, as less retinal illuminance will occur. It leads to the question of whether pupil size should be measured or controlled in the measurement of dysphotopsia.

The iris is a thin, contractile, pigmented, disc-shaped diaphragm (Snell and Lemp, 1997). The iris is suspended in the aqueous humour between the cornea and crystalline lens and is attached to the anterior surface of the ciliary body (Zinn, 1972, Pipe et al., 1997, Snell and Lemp, 1997, Kaufman et al., 2003; see Fig 4.1). The pupil is an aperture located in the centre of the iris of the eye that allows light to strike the retina. It appears black because light rays entering the pupil are either absorbed by the tissues inside the eye directly, or absorbed after diffuse reflections within the eye that mostly miss exiting the narrow pupil.

The anterior surface of the iris is divided into a central pupillary zone and a peripheral ciliary zone (Pipe et al., 1997, Snell and Lemp, 1997). Muscles control the size of the pupil. Fig 4.2 shows that the sphincter pupillae muscle is located in the pupillary zone of the iris (Pipe et al., 1997, Snell and Lemp, 1997). It forms a ring of smooth muscle fibres running parallel to the pupil margin, measuring about 1 mm wide, and is located in the stromal layer. When the sphincter pupillae contracts, the iris diaphragm reduces in size making the pupil constrict (Snell and Lemp, 1997). The nerve supply of the sphincter pupillae is from the parasympathetic postganglionic fibres in the short ciliary nerves; derived from the autonomic Edinger-Westphal nucleus of the third cranial nerve.
Figure 4.1: Anatomical section through the globe showing the relative position of the iris and pupil.

Figure 4.2: Diagram showing the arrangement of the fibres of the dilator pupillae and the sphincter pupillae of the iris.
The dilator pupilæ, shown in Fig 4.2, is a thin layer of myo-epithelium that extends from the iris root as far as the sphincter pupilæ (Pipe et al., 1997, Snell and Lemp, 1997). When the dilator pupilæ contracts, the pupil dilates (Snell and Lemp, 1997). The nerve supply of the dilator pupilæ is from the postganglionic fibres of the superior cervical sympathetic ganglion via the long ciliary nerves (Pipe et al., 1997).

Changes in pupil diameter are under the control of the two branches of the autonomic nervous system (Alexandridis et al., 2012). As with other autonomically-innervated muscles, the pupil cannot be controlled voluntarily, although it is susceptible to the influence of the central nervous system (Pipe et al., 1997). The iris muscles are innervated by the sympathetic and parasym pathetic pathways (Alexandridis et al., 2012). The dilator muscles of the iris are part of the sympathetic innervation pathway, whilst the sphincter muscles are para-sympathetically innervated.

There are three reflex pupil responses; known as the light reflex, the near reflex and psycho-sensory reflex (Walker et al., 1983). The main function attributed to the pupillary light reflex is regulating the amount of light reaching the retina (Woodhouse and Campbell, 1975). Therefore, the light reflex regulates retinal illumination to minimise disabling effects on vision, caused by excessive bleaching of the photoreceptors at high luminances, and to facilitate retinal adaptation following rapid changes in incident light levels (Woodhouse and Campbell, 1975). In accordance with this theory, it is known that pupil size decreases with increased retinal illumination (Watson and Yellott, 2012, Orr et al., 2015), and as such, it is important to know whether the pupil size affects halo area measurements.

The near reflex involves constriction of the pupil, which occurs when viewing close objects. A smaller pupil diameter increases the depth of focus of the eye, reducing the detrimental effects of the optical aberrations (Westheimer, 1964, Loewenfeld, 1999, Atchison and Smith, 2000). The near pupil reflex occurs simultaneously with accommodation and convergence (Loewenfeld, 1999). Lastly, psycho-sensory reflex describes when intense emotion can produce mydriasis (Alexandridis et al., 2012). Loud noises can cause dilation of the pupil along with strong emotional or physical stimuli and states of heightened central nervous system arousal (Loewenfeld, 1999).

Normal pupil size has been reported to be 2 to 4 mm in diameter in bright light and 4 to 8 mm in the dark (Walker et al., 1983). The pupil diameter also decreases with increasing age (Kadlecova et al., 1958, Schaeffel et al., 1993, Winn et al., 1994, Watson and Yellott, 2012). As halometry is used to measure halo area, and this is a common problem in the ageing population (van den Berg, 1995, Puell et al., 2013); it is
likely that many participants will have senile miosis. When pupils are small, vision may be adversely affected by loss of retinal illumination (Campbell and Gubisch, 1966). Equally, a smaller pupil can have a positive effect on visual acuity as it may result in less retinal illumination, and thus, VA improves with small pupils (Atchison et al., 1979).

The existing literature shows debate on whether pupil size affects the amount of dysphotopsia that is measured (summarised in Table 4.1). It could be reasoned that in darkness, pupil dilation allows more glaring light to enter the pupil and scatter on the retina. Franssen et al. (2007) believed this argument was misleading, as larger pupils also allow more of the dark scenery to reach the retina, thus counteracting the effect of the glaring light. The more likely reason for increased glare with large pupils could be due to the impact of the extreme periphery of the lens (Cahane et al., 1993, Franssen et al., 2007) - previous work has demonstrated that for pupil diameters greater than 8 mm, the zonular area scatters light much more than the central parts of the lens (van den Berg, T, unpublished data, 1992 as cited in Franssen et al. 2007). Franssen et al. (2007) showed that for pupil diameters between 2 and 7 mm, straylight measured with C-Quant weakly but not significantly depended on pupil size. On average, the change was +0.025 log units per mm of pupil diameter increase. The authors concluded that straylight values measured with photopic pupils are also valid under mesopic and scotopic pupils, such as night driving. Whitaker et al. (1994) hypothesised that there should not be an increased amount of forward light scatter related to a larger pupil diameter as pupil size change affects retinal illuminance of the stimulus and the glare source equally. Contrarily, Masket (1992) used the Miller–Nadler glare tester (Miller et al., 1972, Nadler et al., 1984) to measure glare before and after dilation. The results indicated that pupillary enlargement is associated with increased glare disability.

Due to the nature of most the tests, it might be expected that the bright glare source used would cause pupil constriction. Investigators found that the reduction in disability glare results produced by the BAT were possibly due to pupil miosis from the increased illumination from the glare source (Tan et al., 1998). The study measured glare with the BAT before and after Nd:YAG capsulotomy for posterior capsule opacification (PCO). It is therefore possible that pupil miosis caused some PCO to be excluded from the pupil, effectively reducing glare, thus, potentially giving an underestimate of the amount of glare experienced. However, Whitaker et al. (1994) postulated that the decrease in pupil size with a bright glare source would mean that the PCO would take up a much greater proportion of the pupillary area, therefore, increasing the glare experienced. Boxer-Wachler et al. (1999) found a similar improvement in visual acuity and contrast threshold measures with a glare source. The VectorVision CSV-1000 (VectorVision, Dayton, Ohio) used to measure VA and
contrast sensitivity simulates mesopic conditions, which allows natural pupil dilation. It is a self-calibrated, internally illuminated light box. In this scenario, it could be argued that the ablation zone would be between 4.5 – 5 mm in size. Thus, the non-operated area outside of the ablation zone will have an increased power, and therefore, increase peripheral spherical aberrations. However, when the glare source is present in the field of view, the pupil size reduces, masking the transition zone and decreasing the visual degradation, leading to improved vision or less dysphotopsia.
<table>
<thead>
<tr>
<th>Author and methods</th>
<th>Effect of pupil size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Franssen <em>et al.</em> (2007)</td>
<td>For pupil diameters of 2 - 7 mm, straylight weakly (but not significantly) depends on pupil diameter. On average, the change was + 0.025 log units per mm of pupil diameter increase. In normal eyes, straylight values measured with photopic pupils are by approximation also valid for mesopic and scotopic pupils (e.g. night driving).</td>
</tr>
<tr>
<td>Boxer-Wachler <em>et al.</em> (1999)</td>
<td>Reported an increase in both measures when tested under a glare condition. Visual acuity under glare conditions was significantly higher in the photorefractive keratectomy group by one letter (<em>P</em> = 0.02). Pupils were significantly smaller under glare conditions (PRK, <em>P</em> = 0.002; RK, <em>P</em> &lt; 0.001). Hypothesised that the glare source reduced the pupil size, masking the transition zone in the entrance pupil and accounted for results of improved visual acuity and contrast sensitivity with glare testing.</td>
</tr>
<tr>
<td>Tan <em>et al.</em> (1998)</td>
<td>Glare was significantly improved (Straylightmeter, <em>P</em> &lt; 0.001; BAT, <em>P</em> &lt; 0.014) following capsulotomy. BAT – 18.8% of patients with PCO had improved VA with glare testing prior to capsulotomy. Aberrant disability glare results produced due to pupil miosis from the bright light source.</td>
</tr>
<tr>
<td>Masket (1992)</td>
<td>Pre-dilation mean pupillary size of 2.8 mm, and Miller-Nadler glare disability score of 15 %. Post-dilation mean pupillary size of 5.4 mm and Miller-Nadler glare disability score of 28.1 %. Difference in pupil size and glare disability were statistically significant (pupil size <em>P</em> &lt; 0.001; glare score <em>P</em> &lt; 0.004).</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of previous work investigating the effect of pupil size on glare and measurements of dysphotopsia.
There is a lack of consensus over whether pupil size affects the amount of glare measured. It seems that it may be dependent on which device is used to measure glare; whilst, C-Quant results are not affected by pupil size, BAT and Miller–Nadler results are affected. No previous study has investigated whether pupil size needs to be controlled when assessing the size of the halo area using halometry. Halometry plays an important part in accurately assessing the size of a glare scotoma, and is becoming a popular choice (Piej et al., 2001, Sheppard et al., 2013, Puell et al., 2014, Buckhurst et al., 2015). It has easy clinical use in the assessment of dysphotopsia post-refractive surgery, both laser and IOLs (Sheppard et al., 2013). Therefore, it is essential to know whether results are robust without controlling the pupil size.

The aim of this prospective study was to establish whether pupil size impacts on halo area (measured using the Aston halometer), and if necessary, determine how pupil diameter should be controlled during the technique.

4.2. Subjects and methods

All procedures were conducted in the Ophthalmic Research Group laboratories at Aston University, Birmingham, UK. Risk assessment was conducted as part of the ethics application. An amendment was made to the ethical application (Number 595) to allow the use of mydriatic drugs to dilate the pupil for halometry measures. The principal investigator was a UK registered Optometrist and followed the College of Optometrists' guideline on dilation (College of Optometrists, 2015). The amendment was reviewed by the Aston University Life and Health Sciences Research Ethics Committee (Application number 595). A copy of this approval can be found in the appendix A2. The study was conducted in accordance with the tenets of the Declaration of Helsinki and all subjects gave their written informed consent to take part.

Power calculations, made using GPower (version 3.1.9.2), showed that 24 participants were required to enable Friedman repeated measures ANOVA on Ranks to detect statistically significant large size (0.7) effect at the 5% significance level (α = 0.05) with 80% power. Twenty-five participants were recruited from the staff and student body in the Optometry department at Aston University subject to the following criteria:
**Inclusion Criteria**

- Corrected visual acuity of logMAR 0.1 or better in the eye to be tested, and logMAR 0.3 or better in the weaker eye to permit easy viewing of the logMAR 0.4 letter targets on the halometer.
- Participants who are able to understand and undertake the informed consent process.

**Exclusion Criteria**

- Any history of ocular surgery, including laser refractive surgery as it may increase the magnitude of the glare effect (Gutierrez *et al.*, 2003, Lackner *et al.*, 2003).
- Participants with any pre-diagnosed ocular conditions.
- Any participants with a history of using drugs that are known to affect the eye.
- Any participants with a systemic health problem that may result in ocular complications.

Unaided visions were measured and a full subjective refraction was performed at 3 m using the *Thomson Test Chart 2000*. Where the participant wore a distance habitual refractive correction, then this refractive correction was used for halometry. An *Oculus Universal* trial frame was used to house the manifest refraction; adjusted to ensure a back vertex distance as small as possible to allow the pupil aperture to be close to the eye. The full aperture trial lenses were cleaned before insertion into the trial frame to ensure that they did not increase the amount of glare experienced.

Initially, halometry was carried out monocularly on a randomly selected eye (using a randomisation table) in its undilated state. Subjects were positioned at 2.0 m from the halometer screen. Halometry was conducted in scotopic light conditions. The technique is described in full in Section 2.2.1.

Tropicamide is a drug commonly used in practice to dilate patients’ pupils. Prior to dilation, intraocular pressures (IOPs) were measured using Reichert 7 (Haag-Streit, UK). Van Herrick’s angle was assessed and any history of previous reactions was established. If deemed safe to do so, the participant was dilated, and warned not to drive for 6 hours post-dilation. One drop of 0.5 % tropicamide was used for light irides, whilst, one drop of 1 % was used for dark irides as per College of Optometrists guidance. Participants were also advised of the possibility of an adverse effect, and that in the case of a red or painful eye, a visit to eye casualty would be required. IOPs were also checked at the end of the data collection to check for the occurrence of an adverse reaction, and a College of
Optometrists leaflet on Tropicamide was given (College of Optometrists). Participants waited 20 minutes for dilation to occur, and following this; dilation was classed as complete when the pupil size was greater than 7.5 mm measured with a ruler, as this was the largest pupil size tested.

Pupil size was controlled by exact diameter holes being drilled into occluders. The same method has been used to simulate different pupil size in the clinical evaluation of the WAM-5500 (Sheppard and Davies, 2010; see Fig 4.3). 3 pupil sizes were chosen: 4.5 mm, 6.0 mm and 7.5 mm. Previous studies have found the mean night time driving pupil diameter at 2.5 cd/m² was 5.76 mm (Guillon et al., 2016). The mean scotopic pupil diameter was 6.61 ± 0.92 mm when measured with Wavescan, and 6.40 ± 0.90 mm with Procyon pupilometer (Wickremasinghe et al., 2005). The scotopic pupil size of 6.0 mm was chosen to replicate night-time driving, as it is when most people complain of glare problems. A pupil size of 4.5 mm was chosen as pre–presbyopic individuals (18 – 39 years; n = 166) have a mean pupil diameter of 4.21 ± 1.61 mm (Guillon et al., 2016). The largest pupil diameter of 7.5 mm was chosen based on the study of MacLachlan and Howland (2002), which reported a typical pupil size of 7.5 mm in 15 – 18 year olds. The chosen pupil sizes allow a linear increase and decrease around the scotopic pupil diameter.

![Fig 4.3: Image to show the pupil size difference by creating exact 4.5 mm, 6.0 mm and 7.5 mm holes in occluders.](image)

Halometry was conducted for each of the 3 pupil sizes in a random order. A randomisation table was used to decide which of the pupil sizes would be tested first, secondly and thirdly for each participant. The participant wore a trial frame, set up to ensure central positioning of any lenses or occluders to the eye, both vertically and horizontally. The occluder with the fixed pupil size hole was placed in front the eye to be tested. It was inserted in to the back
cell, to minimise the back vertex distance without touching the eyelashes. The fellow eye was occluded to allow for monocular testing. Subjects were given a break (5 minutes) between halometry measurements to enable recovery from the glare source.

4.3. Data and statistical analysis

The data was stored in password-protected Excel 2016 Spreadsheet document (Microsoft, Redmond, WA). All statistical tests were performed using SigmaPlot graphing and statistical software (Version 12.0, Systat Software Inc., Chicago, Illinois, USA). The one-sample Kolmogorov-Smirnov test was used to determine if results from each measurement followed a normal distribution. Only the pre-dilation halo area followed a normal distribution, therefore, to aid comparison, median and range are reported for all data sets. Due to the non-parametric data sets, to compare the halo area from the different pupil sizes, a Friedman repeated measures ANOVA on Ranks was used. In all cases, a P value of < 0.05 was considered statistically significant.

4.4. Results

Twenty-five participants aged 18.0 – 41.0 years (median age 20.0) were recruited. Summary descriptive data are detailed in Table 4.2. The summary details of the median refraction results for the eye that was tested are displayed in Table 4.3. No adverse effects occurred with dilation of the pupil. The median halo area for each of the pupil conditions were calculated: pre-dilation 4.47 cm$^2$ (range 2.28 – 11.94); 4.5 mm pupil 4.07 cm$^2$ (range 1.64 – 11.90); 6.0 mm pupil 3.89 cm$^2$ (range 1.70 – 11.45); 7.5 mm pupil 4.19 cm$^2$ (range 1.78 – 9.51). The median and IQR of halo areas for each pupil size are shown in Table 4.4 and Fig 4.4.

<table>
<thead>
<tr>
<th>Number of Participants</th>
<th>Median Age (Years)</th>
<th>Age Range (Years)</th>
<th>Gender</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>20.0</td>
<td>18.0 – 41.0</td>
<td>16 females; 9 males</td>
</tr>
</tbody>
</table>

Table 4.2: Summary descriptive data for cohort.
<table>
<thead>
<tr>
<th>Tested Eye Median Sph Rx (range)</th>
<th>Tested Eye Median Cyl Rx (range)</th>
<th>Tested Eye Median Axis (range)</th>
<th>Median unaided vision or VA of eye when tested (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00 (- 6.25 – 5.50) D</td>
<td>-0.50 (- 2.75 – 0.00) D</td>
<td>130 (5 – 180) deg</td>
<td>0.00 (- 0.10 - 0.30) logMAR</td>
</tr>
</tbody>
</table>

**Table 4.3:** Summary of median refraction results for cohort.

<table>
<thead>
<tr>
<th>Pupil Size</th>
<th>Median Halo Area (range)</th>
<th>Median Halo Radius (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural – Pre-dilation</td>
<td>4.47 (2.28 – 11.94) cm²</td>
<td>21.6 (15.4 – 35.4) arc min</td>
</tr>
<tr>
<td>4.5 mm</td>
<td>4.07 (1.64 – 11.90) cm²</td>
<td>20.6 (13.1 – 35.4) arc min</td>
</tr>
<tr>
<td>6.0 mm</td>
<td>3.89 (1.70 – 11.45) cm²</td>
<td>20.3 (13.2 – 34.5) arc min</td>
</tr>
<tr>
<td>7.5 mm</td>
<td>4.19 (1.78 – 9.51) cm²</td>
<td>20.7 (13.7 – 31.5) arc min</td>
</tr>
</tbody>
</table>

**Table 4.4:** Median halo area for the various pupil conditions: natural pupil, 4.5 mm, 6.0 mm and 7.5 mm simulated artificial pupils. N = 25.
Figure 4.4: Box-and-whisker plot to show the interquartile range of halo area with halometry for each of the set pupil diameters (n = 25). Line within box = median, upper limit of box = 75th percentile; lower limit of box = 25th percentile; upper error bar = 90th percentile; lower error bar = 10th percentile; points = outliers in the upper and lower 10th percentile.

No significant relationship was found between the pre-dilation halo area and unaided vision or VA in the eye used for halometry assessment ($r_s = 0.09$, $r_s^2 = 0.008$, $P = 0.665$). There was also no relationship between the mean equivalent sphere and the pre-dilation halo area ($r_s = 0.10$, $r_s^2 = 0.010$, $P = 0.630$). The simulated artificial pupil size was compared to the halo area, which found no significant relationship ($r_s = 0.03$, $r_s^2 = 0.001$, $P = 0.769$).

A non-parametric Friedman test of differences amongst repeated measures was conducted to compare the effect of pupil size on halo area with natural pupil size, 4.5 mm, 6.0 mm and 7.5 mm pupils (see Table 4.5 for descriptive statistics used). There was no significant difference between these four conditions ($\chi^2_{(3)} = 7.56$, $P = 0.056$).

<table>
<thead>
<tr>
<th>Pupil Size</th>
<th>%</th>
<th>N</th>
<th>Percentiles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>25th</td>
</tr>
<tr>
<td>Pre-dilation</td>
<td>25</td>
<td>3.81</td>
<td>4.47</td>
</tr>
<tr>
<td>4.5 mm</td>
<td>25</td>
<td>3.41</td>
<td>4.07</td>
</tr>
<tr>
<td>6.0 mm</td>
<td>25</td>
<td>3.10</td>
<td>3.89</td>
</tr>
<tr>
<td>7.5 mm</td>
<td>25</td>
<td>3.47</td>
<td>4.19</td>
</tr>
</tbody>
</table>

Table 4.5: Descriptive statistics used for the non-parametric Friedman test, showing the median and IQR for halo area.
4.5. Discussion

It is becoming more important to measure dysphotopsia due to the relatively high prevalence of complaints (10 – 50 %) linked to the phenomena in post-refractive surgery eyes (Applegate and Gansel, 1990, Aslam et al., 2007b). Despite it being imperative to be able to measure dysphotopsia, currently a gold standard does not exist. Many techniques, including C-Quant, Miller–Nadler glare tester and halometry, are carried out in a dark room, potentially increasing pupil size, but use a bright light source in visual field, causing constriction of the pupil. There is likely to be an effect on the measurement, as individuals will have a different pupil size, which is true even in mesopic conditions without a bright light source. The present literature shows debate on whether pupil size affects the amount of dysphotopsia measured. With C-Quant, straylight was not significantly dependent on pupil size (Franssen et al., 2007), with an average change of + 0.025 log units per mm of pupil diameter increase. Whilst, Masket (1992) found an increase in glare disability with pupillary enlargement, using the Miller–Nadler glare tester. Thus, with halometry becoming a more popular choice in the assessment of dysphotopsia (Pieh et al., 2001, Sheppard et al., 2013, Puell et al., 2014, Buckhurst et al., 2015), it leads to the question of whether the pupil size should be measured or controlled in the assessment of dysphotopsia with halometry. This is the first study to report empirical data on whether pupil size impacts on halo measurements.

The median halo area pre-dilation was 4.47 cm² (range 2.28 – 11.94 cm²) in this cohort, which is in line with the median for monocular halometry previously reported in chapter 3 of 4.87 cm² (range 1.97 – 20.87 cm²) and within the IQR of 3.70 – 6.62. From this, it could be said that the cohort in this study are a good representation of ‘normal’ values of halo area. No significant relationship was found between the pre-dilation halo area and the unaided vision or VA used for halometry assessment (rs = 0.09, rs² = 0.008, P = 0.665). There was also no relationship between the mean equivalent sphere and the pre-dilation halo area (rs = 0.10, rs² = 0.010, P = 0.630). Therefore, confirming that there is no secondary effect influencing the halo area in this cohort.

The simulated artificial pupil size was compared to the halo area, with no significant relationship identified (rs = 0.03, rs² = 0.001, P = 0.769). From Fig 4.2, it is apparent that there is a wide spread of halo areas for each pupil size. The non-parametric Friedman test of differences amongst repeated measures showed no significant difference in halo area with the different pupil sizes. Assessment with halometry is carried out in a dark room. Pupil dilation occurs in darkness, and therefore, could potentially allow more glaring light to enter the eye and cause more scatter on the retina. The results here appear to support the
argument that whilst a larger pupil allows more glaring light from the glare source to enter, the retinal illuminance is also changed by the stimulus (Whitaker et al., 1994, Fransssen et al., 2007). More dark scenery enters the eye, thus counteracting the effect of the glaring light. Fransssen et al. (2007) indicated that the pupil size would affect the overall light intensity, but not the quality of the retinal image. Therefore, the amount of glare that is experienced is more dependent on the individual and the optics of their eye creating the straylight, such as cornea, crystalline lens and vitreous rather than the pupil size alone. The more likely reason of increased glare with large pupils may be due to the extreme periphery of the lens (Cahane et al., 1993, Fransssen et al., 2007). This hypothesis is supported by previous work by van den Berg et al. (1992; cited in Fransssen et al., 2007), which demonstrated that for pupil diameters of greater than 8 mm, the zonular area scatters light much more than the central region of the lens.

Factors such as translucency of the wall of the eye can allow straylight to enter the eye depending on the individuals’ pigmentation. Fransssen et al. (2007) reported a translucency value average of 0.30 mm² in four more lightly pigmented subjects, compared to 0.00 mm² in the brown-eyed individual. The effect of translucency was more apparent for small pupil sizes when the scattering angle increases (Fransssen et al., 2007), thus, negating the expected reduction in glare entering the eye. Fransssen et al., (2007) measured the pupil reflex in the presence of 1-second flashes of glaring light. The investigators found that the glare effect invokes significant pupillary contraction, and that the contraction makes the pupil size approach daylight situations.

Whilst most studies of conventional and wavefront-guided LASIK have not shown a relationship between the diameter of the low light pupil and night vision symptoms post-operatively (Schallhorn et al., 2003, Pop and Payette, 2004, Tuan and Liang, 2006, Villa et al., 2007, Chan and Manche, 2011), Tan et al. (1998) and Boxer-Wachler et al. (1999) reported unusual findings where both found an improvement in measurements when the glare source was present. An explanation of these findings is due the presence of PCO, where the pupil miosis has excluded some of the PCO area from the pupil, effectively reducing the amount of source for light scatter to occur. Boxer-Wachler et al. (1999) investigated individuals post-laser surgery. The ablation zone is likely to be more exposed when in mesopic conditions; therefore, increased light scatter would occur at the periphery of the pupil where the remaining spherical error is still present. Pupil miosis due to the glare source would have masked the transition zone, and thus reduced the visual degradation.
The use of artificial pupil holes creates a limitation in this study, despite ensuring that the artificial pupil was central, and in the closest cell of the trial frame to the eye. There is debate about whether the centre of a pharmacologically-dilated pupil corresponds to the centre of the undilated pupil (Yang et al., 2002), therefore having the artificial pupil central to the real pupil may not have been effective. A contact lens to act as a pupil block may be a good alternative, but that also brings its own problems due to movement of the lens on the eye.

The pre- and post-dilation pupil size was not measured. Instead, before starting the assessment, the pupil was measured to ensure it was bigger than 7.5 mm as that is the largest pin hole being used. Having the pupil sizes could have been useful. Measuring the pupils with a ruler was a limitation, and perhaps an infrared pupilometer could be used in future studies for this task to increase accuracy.

The results of the present study indicate that the pupil size has no effect on the glare area measured with the Aston halometer, analogous to findings when straylight is measured with C-Quant (Franssen et al., 2007). Thus, similarly as the authors concluded that straylight values measured with photopic pupils are also valid under mesopic and scotopic pupils, such as night driving, this stands true for the Aston halometer. The likely cause for this is because both the direct light from the scenery and scattered light veil from a headlamp would increase in direct proportion to each other with increasing pupil size. In other words, the ratio between the useful and disturbing light, and thus the contrast in the scenery, would remain constant. The Aston halometer is a robust way to measure dysphotopsia without measuring or controlling the pupil size.
5.1. Introduction

Refractive surgery encompasses various elective procedures that modify the optical status of the eye. Procedures that involve altering the cornea may be referred to as keratorefractive surgery, refractive keratoplasty, or corneal refractive surgery (American Academy of Ophthalmology, 2013). The most frequently performed procedures for low to moderate myopia utilise the excimer laser (Sakimoto et al., 2006, American Academy of Ophthalmology, 2013), with millions of procedures performed worldwide each year (Market Scope, 2016). The US FDA first approved the excimer laser for this purpose in 1995 (Bailey and Zadnik, 2007).

A surface ablation technique, PRK, was the first excimer laser refractive procedure performed (Marshall et al., 1985). It uses a non-thermal ultraviolet wavelength excimer laser to reshape corneal tissue following removal of the epithelium. LASIK surgery has since overtaken PRK to become one of the most common operations performed worldwide (Sekundo et al., 2003, O'Doherty et al., 2006). LASIK utilises the excimer laser to reshape the cornea beneath its surface after a superficial corneal flap is fashioned using either a femtosecond laser or a manual microkeratome. Both make corneal flaps of very high quality and consistency, approximately 100 – 140 µm in thickness (Ruth et al., 2008, Ahn et al., 2011). Although both PRK and LASIK use the excimer laser to ablate the cornea, they differ in the layers of corneal tissue remaining after ablation. PRK removes the epithelium and Bowman layer, whereas in LASIK, these layers are preserved with the repositioning of the corneal flap (Ivarsen et al., 2009). Replacing the epithelium post-operatively is thought to be the cause of decreased pain and faster visual recovery in LASIK procedures (Ambrosio and Wilson, 2003). PRK declined in popularity during the late 1990s, however, the use of surface ablation has seen a partial resurgence in patients with thinner corneas and low to moderate myopia, due to the avoidance of lamellar flap creation and associated risks (Sakimoto et al., 2006). Other keratorefractive procedures to correct low to moderate myopia include variations of PRK such as LASEK (Tobaigy et al., 2006) and epi-LASIK (American Academy of Ophthalmology, 2013).

Approximately 1.4 million patients undergo corneal refractive surgery each year in the United States alone (Harmon, 2011), whilst an estimated 8.5 million people in the United States underwent refractive surgery between 1995 and 2010 (Market Scope, 2010: cited by
the UK in 2009 reported that Optimax surgeons have performed over 300,000 procedures 
since 1991 whilst Ultralase, the UK’s longest established provider, quoted in 2008 that they 
had carried out 175,500 treatments to date. Optical Express reports its surgeons have a 
combined experience of over 600,000 procedures (Ewbank, 2010).

Refractive error affects approximately 60 – 80 % of the adult population in the United States 
(Vitale et al., 2008, Solomon et al., 2009), with a similar proportion of UK adults likely to be 
affected. Refractive surgery may be considered when an individual wishes to be less 
dependent on spectacles or contact lenses. It may also enable people to enter occupations 
previously closed to them because of their ametropia. A meta-analysis of outcomes of 
treatments with US FDA approved LASIK platforms reported that 93.1 % of patients 
achieved monocular uncorrected visual acuity (UCVA) of 20/40 and 62.5 % of patients 
achieved monocular UCVA of 20/20 (Bailey and Zadnik, 2007); whilst about 20 % 
complained of glare, halos and night driving problems post-operatively. Research released 
by the American Society of Cataract and Refractive Surgeons analysed 19 studies from 13 
countries involving 2198 subjects who underwent LASIK from 1988 to 2008; 95 % of 
patients were satisfied with the results (Solomon et al., 2009). Patient satisfaction is linked 
to the ease and comfort of the procedure for the patients, the excellent UCVA outcomes, 
and the relatively low complication rate, with complications leading to permanent visual loss 
occurring very rarely (Sugar et al., 2002, Varley et al., 2004, Schallhorn et al., 2017). The 
excimer laser seems set to continue to be a primary means of refractive surgery, despite 
phakic and accommodative IOLs growing in popularity and clinical use (Sakimoto et al., 2006).

Although high contrast visual acuity outcomes following refractive surgery are usually 
excellent, problematic photic effects may occur. Even after uneventful surgery, glare 
sensitivity is increased (Veraart et al., 1992, Butuner et al., 1994, Niesen et al., 1997, 
Ghaih et al., 1998, Katlun and Wiegand, 1998, Fan-Paul et al., 2002). Whilst anecdotal 
evidence suggests that subjective photic effects reduce with time following laser refractive 
surgery, there is a lack of empirical data to support this viewpoint past 6 months. It is also 
unclear how much of the apparent improvement is due to a subjective acceptance of the 
disturbances (by neural adaptation) or an actual physical reduction in halo area 
(Fan-Paul et al., 2002) and straylight.

Studies acquiring objective measures of straylight using the C-Quant following laser 
refractive surgery have provided conflicting evidence regarding whether there is an increase 
or decrease in values post-operatively (see Table 5.1). Overall, Lapid-Gortzak et al. (2010b)

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found no significant increase in straylight at 3 months, compared to pre-operative levels in a LASIK group of 39 eyes and in a LASEK group of 26 eyes. However, in some individuals, notable increases in straylight occurred. In some affected eyes, haze or debris could be seen, whilst in others, the cause could not be determined. A second report from the same research group examining myopic eyes found on average, a significant improvement in straylight values post-operatively (Lapid-Gortzak et al., 2010a). The mean decrease was \(-0.016\) log(s) in the LASIK group and \(-0.026\) log(s) in a LASEK group. Straylight improved in 62 of 102 eyes in a LASIK group \((P < 0.001)\) and 78 of 137 eyes in the LASEK group \((P < 0.02)\) and deteriorated in 35 eyes and 58 eyes, respectively. Rozema et al. (2010a) found a significant decrease in base and age-corrected straylight from 0.15 ± 0.14 log units to 0.00 ± 0.14 log units in a LASEK group. The base and age corrected (BAC) straylight subtracts a reference value of 0.931 from the measured straylight to compensate for the base constant and the effect of the age-related increase in straylight. Lorente-Velazquez et al. (2010) reported an initial improvement in straylight values post-surgery, which later worsened. Straylight values (mean ± SD) were 0.99 ± 0.03, 0.88 ± 0.03, and 0.93 ± 0.03 log(s) before, 15 days and 6 months after LASIK surgery, respectively. The 15 days values were significantly better than pre-operatively, although at 6 months, there was no difference compared to the pre-operative measures.

LASIK is undoubtedly a very successful refractive procedure, however, it may be associated with unwanted and disabling dysphotopsia. There has been limited research to date on longitudinal photic effects post-laser refractive surgery. Those that have reported on post-operative effects have typically used the C-Quant and report conflicting findings, usually following participants for a maximum of 6 months. Some authors report an improvement in straylight post-surgery, although usually by just a small amount and it is debatable how clinically significant these improvements may be. No previous studies have investigated longitudinal changes in subjectively reported and objectively measured (including halometry) photic effects following refractive surgery.
<table>
<thead>
<tr>
<th>Author and study details</th>
<th>Key results</th>
</tr>
</thead>
<tbody>
<tr>
<td>He and Manche (2014)</td>
<td>Patients experienced less night-time glare from 6 months onward ($P &lt; 0.03$). Halos, double vision, and visual clarity were initially worse ($P &lt; 0.025$) but not significantly different after 1 month.</td>
</tr>
<tr>
<td>Lapid-Gortzak et al. (2010a)</td>
<td>No significant increase in straylight at 3 months, compared to pre-operative levels in the LASIK and LASEK group.</td>
</tr>
<tr>
<td>Lapid-Gortzak et al. (2010b)</td>
<td>On average, there was a significant improvement in straylight values post-operatively. Straylight improved in 62 eyes in the LASIK group ($P &lt; 0.001$) and 78 eyes in the LASEK group ($P &lt; 0.02$) and deteriorated in 35 eyes and 58 eyes, respectively.</td>
</tr>
<tr>
<td>Lorente-Velazquez et al. (2010)</td>
<td>Straylight values significantly improved from pre-operative levels to those recorded 15 days after LASIK ($P = 0.03$), although values at 6 months failed to differ from baseline ($P &gt; 0.05$).</td>
</tr>
<tr>
<td>Rozema et al. (2010)</td>
<td>After LASEK a significant decrease in base and age-corrected straylight, corrected to negate the effect of increasing straylight with age.</td>
</tr>
</tbody>
</table>

Table 5.1: Previous studies available at the time of writing that have reported longitudinal changes in dysphotopsia after laser refractive surgery.
The aims of this prospective study are:

- To measure longitudinal changes in halo area, straylight and subjective photic effects following bilateral LASIK refractive surgery in young adults.
- To compare results obtained with those of an age-matched control group.

5.2. Subjects and methods

All procedures were conducted in the Ophthalmic Research Group laboratories at Aston University, Birmingham, UK. Risk assessment was conducted as part of the ethics application. The study was reviewed by the Aston University Life and Health Sciences Research Ethics Committee (Application number 595). A copy of this approval can be found in appendix A1. The study was conducted in accordance with the tenets of the Declaration of Helsinki and all subjects gave their written informed consent to take part.

Power calculations, made using GPower (version 3.1.9.2), showed that 16 participants were required to enable Friedman repeated measures ANOVA on ranks to detect statistically significant large size (1.0) effect at the 5 % significance level ($\alpha = 0.05$) with 80 % power. Sixteen participants (32 eyes) were recruited from the student body at Aston University subject to the following criteria:

**Inclusion Criteria**

- Underwent uncomplicated bilateral LASIK refractive surgery within the last 3 months.
- Uncorrected visual acuity of logMAR 0.1 or better in both eyes to allow easy viewing of the logMAR 0.4 letter on the halometer.
- Able to understand and undertake the informed consent process.

**Exclusion Criteria**

- Any history of ocular surgery other than recent LASIK.
- Participants with any pre-diagnosed ocular conditions.
- Any participants with a history of using drugs that are known to affect the eye.
- Any participants with a systemic health problem that may result in ocular complications.

The LASIK patients came from a cohort of ‘pick and mix’ surgeries, where there was no access to key surgery information such as flap diameter, flap thickness, and pre-op information. Participants were seen at the following time points: within 3 months, 6 months
and 12 months post-surgery. At the < 3 months visit, unaided visions were measured and a full subjective refraction was performed at 3 m using the Thomson Test Chart 2000. All had unaided visions of 0.00 logMAR or better monocularly and required no spectacle correction for distance tasks.

**Objective Measures**

As described in section 2.2.1, objective measures of dysphotopsia were acquired in a random order from participants. Halometry was carried out both binocularly and monocularly, with the eye for monocular measurement selected using a randomisation table (Armstrong, 2013). The C-Quant was used to quantify intraocular light scatter in the same eye used for the monocular halometry reading.

**Subjective Assessment**

Subjective complaints have been measured using questionnaires in previously published studies (Arnold, 1994, Dick et al., 1999, Aslam et al., 2004a, Pepose et al., 2007, Hofmann et al., 2009), however, there is questionable value in simple questionnaires which may just ask individuals, ‘do you suffer from glare?’, or to grade severity on a scale of 1 - 10. Aslam et al. (2004a) stated that questionnaire assessments provide scores that are perhaps closest to patient’s perceived morbidity but have poor specificity and are subject to interpretation errors, ambiguity, use of jargon and biases in responding. Hunkeler et al. (2002) developed a series of images and illustrations that depict various night-time visual phenomena including halo and starburst (see Fig 5.1 and Fig 5.2). The images have been successfully used in a previously published study, and received good feedback as participants felt they could relate to the images (Hunkeler et al., 2002). Based on previous chapters, of the 10 types of dysphotopsia shown, most were reported only at a low level. The Hunkeler images are in line with the night halos most reported. In the present study, with reference to the Hunkeler images (shown in Fig 5.1), the participant was asked which image best related to how they perceive the headlights of oncoming traffic. A value ranging from 1 – 6 was recorded. With Hunkeler illustrations (shown in Fig 5.2), the participant was asked which image best represented the way that a point source light would look. For these images a 2 digit number is recorded, the first of which is from 1 – 4 and represents the type of glare experienced. The second number from 1 – 3 indicates the severity of the symptom. A final subjective score was calculated from the sum on the Hunkeler image grade, and the second number for Hunkeler illustration, giving a value between 1 and 9; where 1 indicates no problems, and 9 indicates severe dysphotopsia.
Figure 5.1: Hunkeler images grading halo effects as seen around car headlights. Images supplied and reproduced with permission from Elsevier Ltd.

Figure 5.2: Hunkeler Illustrations depicting varying levels of halos and starburst experienced from a point source light. Images supplied and reproduced with permission from Elsevier Ltd.
Participants returned for repeat measures within 6 months and 12 months after their surgery date. At these visits, unaided visions were checked, and if there was a reduction in vision of 0.1 logMAR or more, a full subjective refraction was carried out. Repeat measures were taken with the halometer, C-Quant and subjective images as per the first visit.

5.2.2. Age matched control group

An age-matched control group underwent the same procedures outlined above at a single visit, for comparison with the treatment group.

5.3. Data and statistical analysis

The data was stored in a password protected Excel 2016 Spreadsheet document (Microsoft, Redmond, WA). All statistical tests were performed using SigmaPlot graphing and statistical software (Version 12.0, Systat Software Inc., Chicago, Illinois, USA). The one-sample Kolmogorov-Smirnov test was used to determine if results from each measurement followed a normal distribution; results for binocular halo area at visit 2, monocular halo area at visit 1, C-Quant at visit 3, subjective grading at visit 1, control group age, control group binocular halo area and control group subjective grading. Where data followed a normal distribution, the following parametric analyses were performed: - paired t-test was used when comparing two related samples, and t-test for comparing the control group to the laser group. For those data sets where one or both groups deviated from a normal distribution, Mann-Whitney Rank Sum Test was used for comparing the control group to the laser group. As there were some non-normally distributed data sets, median and range are reported for all data sets allowing for comparison between groups. Although the data are not normally distributed, a one-way ANOVA was used to compare the 8 triangle areas from halometry, as the test is not highly sensitive to deviations from the assumption of normality (McDonald, 2014). For repeated measures, due to some non-parametric data sets, to compare the halo area, straylight values and subjective grade over time, a Friedman repeated measures ANOVA on Ranks was used. In all cases, a P value of < 0.05 was considered statistically significant.

5.3.1. Calculation of halo area from halometer

Halo area was calculated in cm$^2$ as described in Section 2.3.1 and to aid comparison with published data on halo area, halo radius in arc min was also calculated.

Although it was previously determined (see Section 2.3.1) that a single halo area would suffice for the normal participants, due to the nature of refractive laser surgery and the possibility of it inducing asymmetry in monocular halo area; the 8 triangular areas of the glare scotoma were analysed using a one-way ANOVA (McDonald, 2014). For the
8 triangular areas, no significant difference was found for either the binocular or monocular measurements ([F(7, 120) = 0.137, P = 0.995] and [F(7, 120) = 0.101, P = 0.998], respectively), suggesting symmetry in glare scotoma shape.

5.4. Results

Sixteen refractive surgery patients and 16 control participants took part in the study. The median age of the control group was 22.0 years (range 20.0 – 29.0 years); this was not significantly different from the age of the laser group (median 21.5 years; range 18.0 – 31.0 years; P = 0.410). The cohort descriptive data is summarised in Table 5.2. The data collected from the control group is summarised in Table 5.3.

<table>
<thead>
<tr>
<th>Group Type</th>
<th>Number of Participants</th>
<th>Median Age (Years)</th>
<th>Age Range (Years)</th>
<th>Gender</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>16</td>
<td>21.5</td>
<td>18.0 – 31.0</td>
<td>12 females; 4 males</td>
</tr>
<tr>
<td>Control</td>
<td>16</td>
<td>22.0</td>
<td>20.0 – 29.0</td>
<td>10 females; 6 males</td>
</tr>
</tbody>
</table>

Table 5.2: Summary descriptive data for entire cohort.

<table>
<thead>
<tr>
<th>Median Binocular Halo Area (range)</th>
<th>Median Binocular Halo Radius (range)</th>
<th>Median Monocular Halo Area (range)</th>
<th>Median Monocular Halo Radius (range)</th>
<th>Median C-Quant (range)</th>
<th>Median Subjective Grade (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.13 (2.64 – 5.50) cm²</td>
<td>18.1 (16.6 – 23.9) arc min</td>
<td>4.28 (2.69 – 6.76) cm²</td>
<td>21.2 (16.8 – 26.6) arc min</td>
<td>0.86 (0.76 – 1.21) log(s)</td>
<td>5.0 (2.0 – 6.0)</td>
</tr>
</tbody>
</table>

Table 5.3: Summary descriptive statistics for age-matched control group. N = 16.

Twelve of sixteen participants returned for the all visits; one participant did not attend the 6 month visit, but did the 12 month visit, and 4 were unable to return for the 12 month visit. Objective and subjective data from the laser group from the < 3 months, 6 months and 12 months are summarised in Tables 5.4, 5.5, and 5.6, respectively.
<table>
<thead>
<tr>
<th>Median Binocular Halo Area (range)</th>
<th>Median Binocular Halo Radius (range)</th>
<th>Median Monocular Halo Area (range)</th>
<th>Median Monocular Halo Radius (range)</th>
<th>Median C-Quant (range)</th>
<th>Median Subjective Grade (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.93* (2.79 – 17.91) cm²</td>
<td>24.8 (16.8 – 43.1) arc min</td>
<td>7.35* (3.99 – 27.86) cm²</td>
<td>27.7 (20.3 – 53.9) arc min</td>
<td>0.93 (0.72 – 1.35) log(s)</td>
<td>5.0 (2.0 – 7.0)</td>
</tr>
</tbody>
</table>

Table 5.4: Summary descriptive statistics for laser group at visit 1 (< 3 months post-operatively). N = 16. * indicates significant difference compared to the age-matched control group.

<table>
<thead>
<tr>
<th>Median Binocular Halo Area (range)</th>
<th>Median Binocular Halo Radius (range)</th>
<th>Median Monocular Halo Area (range)</th>
<th>Median Monocular Halo Radius (range)</th>
<th>Median C-Quant (range)</th>
<th>Median Subjective Grade (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.52 (1.88 – 6.42) cm²</td>
<td>19.2 (14.0 – 25.9) arc min</td>
<td>6.32* (2.75 – 8.07) cm²</td>
<td>25.7 (17.0 – 29.0) arc min</td>
<td>0.93 (0.75 – 1.49) log(s)</td>
<td>5.0 (2.0 – 7.0)</td>
</tr>
</tbody>
</table>

Table 5.5: Summary descriptive statistics for laser group at visit 2 (6 months post-operatively). N = 15. * indicates significant difference compared to the age matched control group.

<table>
<thead>
<tr>
<th>Median Binocular Halo Area (range)</th>
<th>Median Binocular Halo Radius (range)</th>
<th>Median Monocular Halo Area (range)</th>
<th>Median Monocular Halo Radius (range)</th>
<th>Median C-Quant (range)</th>
<th>Median Subjective Grade (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.97 (1.78 – 7.19) cm²</td>
<td>17.7 (13.7 – 27.2) arc min</td>
<td>4.14 (2.07 – 11.0) cm²</td>
<td>20.3 (15.0 – 32.6) arc min</td>
<td>0.90 (0.74 – 1.46) log(s)</td>
<td>5.0* (3.0 – 8.0)</td>
</tr>
</tbody>
</table>

Table 5.6: Summary descriptive statistics for laser group at visit 3 (12 months post-operatively). N = 12. * indicates significant difference compared to the age matched control group.
5.4.1. Monocular halo area

A non-parametric Friedman test of differences amongst repeated measures was conducted to compare the halo area at < 3 months, 6 months and 12 months post-operatively. There was a significant difference between these three conditions ($\chi^2 (2) = 13.17$, $P < 0.001$). Post hoc Tukey test showed monocular halo area significantly reduced between visits 1 and 3 ($P = 0.009$), and between visits 2 and 3 ($P = 0.027$). There was no significant difference between visits 1 and 2 ($P = 0.051$). For monocular halo area, a significant difference was found at 3 months (median 7.35 cm$^2$; range 3.99 – 27.86; $P < 0.001$, N = 16), and at 6 months (median 6.32 cm$^2$; range 2.75 – 8.07; $P = 0.027$, N = 15) compared to the control group. At 12 months post-operatively, no significant difference was found.

Consistent with previous findings, in chapter 2 and chapter 3, monocular halo area is greater than binocular halo area in both the laser group and the control group (Wilcoxon Signed Rank Test $P = 0.018$ and $P < 0.001$).

5.4.2. Binocular halo area

A non-parametric Friedman test of differences amongst repeated measures was conducted to compare the halo area at < 3 months, 6 months and 12 months post-operatively. There was a significant difference between these three conditions ($\chi^2 (2) = 16.17$, $P < 0.001$). Post hoc Tukey test shows binocular glare area significantly reduces between visits 1 and 2 ($P = 0.003$), and between visits 1 and 3 ($P < 0.001$). There was no significant difference between visit 2 and 3 ($P = 0.880$).

In the laser group, the binocular halo area at 3 months (median 5.93 cm$^2$; range 2.79 – 17.91) was significantly larger than the control group (median 3.13 cm$^2$; range 2.64 – 5.50; $P = 0.001$, N = 16). However, by 6 months there was no significant difference in binocular halo area between the laser group and control group ($P = 0.199$, N = 15).

5.4.3. C-Quant

A one-way repeated measures ANOVA was conducted to compare the effect of time on straylight at < 3 months, 6 months and 12 months post-operatively. There was a significant difference between these three conditions [$F(2, 15) = 5.91$, $P = 0.008$]. Post hoc comparison using the Tukey test indicated that there was significant difference between visits 1 and 3 ($P = 0.009$). However, straylight was not significantly different between visits 1 and 2 ($P = 0.051$) and visits 2 and 3 ($P = 0.658$). The C-Quant values did not vary significantly from the control group for any of the visits.
5.4.4. Subjective grading

A one-way repeated measures ANOVA was conducted to compare the effect of time on subjective complaints of dysphotopsia at < 3 months, 6 months and 12 months post-operatively. There was no significant difference in subjective score between these three visits \( F_{(2, 15)} = 0.107, P = 0.899 \). Subjective complaints at visits 1 and 2 do not show a significant difference between the laser and control group. At 12 months, the median subjective grade in the laser group was significantly greater than the control group.

Figure 5.3: Box-and-whisker plot to show the magnitude of the binocular glare area measured with halometry at visits 1, 2 and 3. N = 16. Line within box = median; upper limit of box = 75\(^{th}\) percentile; lower limit of box = 25\(^{th}\) percentile; upper error bar = 90\(^{th}\) percentile; lower error bar = 10\(^{th}\) percentile; points = outliers in the upper and lower 10\(^{th}\) percentile.
Figure 5.4: Box-and-whisker plot to show the magnitude of the monocular glare area measured with halometry at visits 1, 2 and 3. N = 16. Line within box = median; upper limit of box = 75th percentile; lower limit of box = 25th percentile; upper error bar = 90th percentile; lower error bar = 10th percentile; points = outliers in the upper and lower 10th percentile.

Figure 5.5: Box-and-whisker plot illustrating C-Quant values at visits 1, 2 and 3. N = 16. Line within box = median; upper limit of box = 75th percentile; lower limit of box = 25th percentile; upper error bar = 90th percentile; lower error bar = 10th percentile; points = outliers in the upper and lower 10th percentile.
Figure 5.6: Box-and-whisker plot illustrating subjective grading at visits 1, 2 and 3. N = 16.
Line within box = median; upper limit of box = 75\(^{th}\) percentile; lower limit of box = 25\(^{th}\) percentile; upper error bar = 90\(^{th}\) percentile; lower error bar = 10\(^{th}\) percentile; points = outliers in the upper and lower 10\(^{th}\) percentile.

5.5. Discussion

LASIK is widely used across the world in the correction of different degrees of ametropia (Sekundo et al., 2003, O’Doherty et al., 2006). It usually provides patients with excellent visual acuity (Bailey and Zadnik, 2007), however, a well-known complaint is disappointment due to unwanted glare and halos around lights when driving at night (Veraart et al., 1992, Butuner et al., 1994, Niesen et al., 1997, Ghaith et al., 1998, Katlun and Wiegand, 1998, Fan-Paul et al., 2002). Light scattering within the eye causes such complaints. The light spreading can have two origins (van den Berg et al., 2009), a refractive one, caused by wave front aberrations spreading light over small angular distances, and a diffractive one, due to small irregularities in the ocular media scattering light over large angular distances. Many conditions can cause this diffractive process, such as the corneal epithelial healing process, corneal haze, superficial scars, and post-operative flap positioning (Rozema et al., 2010a).

Previous studies have tracked changes in straylight up to 6 months post-surgery, and only one study has looked at subjective complaints by questionnaire up to a year after surgery (He and Manche, 2014). There appears to be debate on how straylight values are affected with one study finding no significant difference between pre-operative and 3 month post-surgery values (Lapid-Gortzak et al., 2010b), whilst the same research group found an
improvement in straylight between pre-operative and 3 months post-surgery (Lapid-Gortzak et al., 2010a). Another study by Lorente-Velazquez et al. (2010) found an initial improvement 15 days after surgery, which reduces back to baseline by 6 months post-surgery. The present study is the first time that a longitudinal investigation has used simulated images to monitor changes in subjective complaints, and measured objective halo area up to a year after refractive laser surgery. The aim of the study was to measure longitudinal changes in halo area, straylight and subjective photic effects following bilateral LASIK refractive surgery in young adults. These values were then compared to an age-matched control group to ascertain when it returns back to normal levels.

Similar to chapter 2, when comparing the 8 triangular areas, no significant difference was found for both binocular and monocular measurements ($P = 0.995$ and $P = 0.998$, respectively). It indicates that despite corneal surgery, there is a symmetrical halo shape, which may be expected with a regular, circular flap. Also, consistent with findings in chapter 2 and 3, binocular glare areas were approximately 24% smaller than monocular measurements due to the effects of binocular summation.

At the 3 month post-operative visit, median binocular and monocular halo areas (5.93 cm$^2$ and 7.35 cm$^2$, respectively) are significantly larger than the control group median (3.13 cm$^2$ and 4.28 cm$^2$, respectively). By 6 months, the binocular glare area is not significantly different from the control group, however, monocular glare is, further evidence that binocular summation is present and able to reduce the effects of dysphotopsia. There is a reduction in halo area over time, so that by 12 months, there is no significant difference to the control group. The median binocular halo area is 2.97 cm$^2$ and median monocular area is 4.14 cm$^2$, which also compares well to median data in chapter 2 (3.24 cm$^2$ and 4.25 cm$^2$, respectively).

The other objective assessment, C-Quant, showed no significant difference between visits 1 and 2, and between 2 and 3. However, there was a small but significant reduction in straylight between visits 1 (median 0.93 log(s)) and 3 (median 0.90 log(s)), suggesting a gradual reduction in straylight in the 12 months following laser refractive surgery. Consistent with Lapid-Gortzak et al. (2010b), where a significant difference was not found between pre-operative levels and 3 months after surgery in hyperopic eyes. The same research group did find a significant reduction at 3 months compared to pre-operative levels in a myopic group (Lapid-Gortzak et al., 2010a).

Subjective findings by 3 months (median 5.0) are the same as the control group (median 5.0), indicating that laser patients are no more bothered by dysphotopsia than
normal individuals of the same age soon after surgery. These results tie in with previous work by He and Manche (2014) where halos significantly reducing by 1 month post-surgery. The authors found that night-time glare was experienced less from 6 months onwards. It is likely that a neural adaptation is occurring post-surgery (Fan-Paul et al., 2002).

An unusual finding is present in the subjective grading at 12 months as there is a significant increase. The anomaly could be due to the visit being in December/January time. At this time of year, it gets darker earlier and therefore, night driving issues would become more apparent. Participants would also be more familiar with the images at the final visit, so they may be more aware of the symptoms. The cohort is smaller by 4 participants so any small differences would have more of an effect. In this cohort, at visit 3, 3 participants reported a value of 8.

Due to the nature of the recruitment, the participants came from a cohort of ‘pick and mix’ surgeries. Little pre-operative information was known, and that information could have been useful. For example, pre-operative glare effect ratio could not be calculated, and flap diameter and thickness were unknown. A limitation was that a control group had to be used to ascertain when halo area and subjective complaints reduced back to normal levels.

The study findings indicate that the halo shape is symmetrical even after laser refractive surgery. Both halo area and C-Quant increase post-laser surgery, but this effect reduces over 12 months. Subjective results, however, are comparable to the control group by 3 months. In patients undergoing uneventful bilateral LASIK refractive surgery, a transient increase in objectively measured dysphotopsia occurs. It reduces over time and does not seem to cause significant subjective complaints for patients.
CHAPTER 6
A LONGITUDINAL EVALUATION OF CHANGES IN PHOTIC PHENOMENA FOLLOWING CATARACT SURGERY

6.1. Introduction

Cataract is a common problem in the ageing eye; according to the World Health Organisation (WHO; Pascolini and Mariotti, 2012), age-related cataract is responsible for 51 % of world blindness, which represents about 20 million people. Straylight increases with age in the perfectly healthy eye, but to a greater extent with disturbances to the optical media, including cataract (Vos, 1984, van den Berg, 1986, Elliott and Bullimore, 1993). Quality of vision loss because of media disturbances is not limited to visual acuity reduction, but includes other effects such as those caused by straylight (van den Berg et al., 2007). Straylight is the known cause of disability glare (Vos, 1984, van den Berg, 1986, Elliott and Bullimore, 1993), leading to problems with glare while driving at night, hindrance from a low sun during the daytime, facial recognition difficulties, reports of hazy vision and colour and contrast loss (van den Berg et al., 2007).

Undesirable optical phenomena such as negative and positive dysphotopsia are also a well-known side effect following modern cataract surgery (Tester et al., 2000, Mamalis, 2010, Hood and Sugar, 2015). Previous studies have reported the primary cause of post-surgical dissatisfaction in a normal pseudophakic population was dysphotopsia (Welch et al., 2010, Kinard et al., 2013). Negative dysphotopsia is defined as the perception of a shadow obscuring the temporal field of vision, while positive dysphotopsia is characterized as halos, arcs or streaks around point light sources (Davison, 2000, Mamalis, 2010). It is difficult to gauge the prevalence of dysphotopsia- studies report a range from as low as 1.5 % up to 67 % for positive dysphotopsia, with most authors identifying more moderate values of 12 % to 35 % (Tester et al., 2000, Ellis, 2001, Meacock et al., 2002). Negative dysphotopsia is less common and estimated to occur in only 0.5 % to 2.4 % of patients (Meacock et al., 2002, Osher, 2008). In the majority of cases, dysphotopsia resolves or diminish over time (Makhotkina et al., 2015). It has been suggested that this is due to neuroadaptation (Kershner, 2011) although, in 0.2 % to 1 % of pseudophakic patients severe symptoms will persist (Davison, 2000) and additional surgery may be required.

For negative dysphotopsia implantation of a secondary IOL in the bag or in the ciliary sulcus has been proposed as an option to alleviate the problem (Masket and Fram, 2011, Zeldovich, 2012). Other available treatment options for severe and persistent negative
dysphotopsia include implantation of a supplementary IOL, reverse optic capture and Nd:YAG laser anterior capsulectomy (intended to eliminate a sector along the nasal aspect of the anterior capsule overlying the IOL optic); however, in some cases the symptoms may persist after treatment (Davison, 2000, Trattler et al., 2005, Masket and Fram, 2011, Weinstein, 2012, Zeldovich, 2012, Cooke et al., 2013, Folden, 2013, Burke and Benjamin, 2014). Successful treatment of positive dysphotopsia appears less common, despite it being the more frequent form of photic effect. There is currently no widely accepted management strategy for positive dysphotopsia (Chandramani and Riaz, 2017). If severe symptoms persist after four to six weeks, IOL exchange may be considered; however, it should be the last resort (Sukhovolskiy, 2015). The IOL may develop a strong adherence to the capsule, making it difficult to dissect it from the capsular bag (Leysen et al., 2009). Therefore, there is an importance in being able to distinguish those individuals who are more likely to encounter subjective problems prior to surgery.

Dysphotopsia occurs with IOLs of different materials (Davison, 2000) with either rounded or squared edges (Davison, 2000, Trattler et al., 2005). PMMA was the first widely used IOL material (Chehade and Elder, 2009). PMMA lenses cause little or no dysphotopsia, which is supported by the fact that dysphotopsia were virtually unknown when PMMA was the IOL material of choice (Schwiegerling, 2006), although at the time designs were all monofocal which have less incidence of photic effects. The lack of foldability of PMMA, requiring a large incision during surgery, and the high rate of PCO due to the round edge design has resulted in these lenses rarely being used today (Cheng et al., 2007). Flexible acrylic and silicone materials with vertical, sharp-edged designs were introduced with great success (Sukhovolskiy, 2015). The sharp edge design greatly reduced the rate of PCO (Hollick et al., 1999, Yan et al., 2005). However, acrylic lens materials increased the incidence of dysphotopia (Schwiegerling, 2006). IOLs of PMMA and silicone with rounded edges, along with square-edge acrylic IOLs with non-reflective surfaces, appear less likely to cause clinically significant pseudophakic dysphotopsia (Davison, 2000).

Lens design also affects the amount of dysphotopsia experienced. Multifocal IOLs are significantly more likely to induce photic phenomena than monofocal IOLs (Leyland and Pringle, 2006). Souza et al. (2006) reported values of 13 % and 20 % of glare and halos respectively in 30 eyes fitted with monofocals; these values increased to 40 % and 50 % of 50 eyes, respectively with multifocals. Woodward et al. (2009) reported 42 % of 43 eyes fitted with multifocal IOLs complained of photic phenomena, although in 8 of these 18 eyes effects were attributed to posterior capsular opacification. In a study by de Vries et al. (2011), 38.2 % of 76 eyes receiving multifocal IOL implantations had dysphotopsia. Chang et al. (2012) investigated 45 eyes for complaints of halo, night glare
and starburst; with 48 %, 15 % and 22 %, respectively, experiencing moderate to severe symptoms. A 2006 Cochrane review of multifocal IOLs found that photic phenomena are 3.5 times more likely with multifocal IOLs than with monofocal IOLs (Leyland and Pringle, 2006).

van den Berg et al. (2007) measured visual acuity using logMAR, straylight using C-Quant and scored lens opacity using the Lens Opacities Classification System III (LOCS III; Chylack et al., 1993) in 220 pseudophakic eyes, 3182 non cataractous eyes (average LOCS III score < 1.5) and 134 cataractous eyes (average LOCS III score > 3) of 2422 subjects aged between 20 and 90 years. Participants were recruited among drivers in a wide area around five participating clinics in Amsterdam, Salzburg, Tubingen, Barcelona, and Antwerp. The investigators reported that pseudophakic eyes performed better on C-Quant than the cataract eyes, as expected, as well as the age-normal eyes. The study, however, did not look at pre- and post-operative changes in the same group; it compared a cataract group to a different group that underwent cataract surgery and did not report any longitudinal effects.

Bournas et al. (2007) assessed the risk of dysphotopsia after phacoemulsification with the use of four different IOLs in 600 individuals (mean age 70.48 years, range 58 – 84 years). In week 1, 117 participants (19.5 %) reported dysphotopsia. The number of individuals still reporting phenomena declined to 15, 12 and 7 (1.52 %) at 1, 3, 6 months, respectively, indicating a reduction in symptoms over time. However, this study only takes in to account subjective complaints, there is a lack of objective measures to support the findings.

Buckhurst et al. (2017) investigated 45 patients (aged 61.8 ± 8.9 years) 4 – 6 months after bilateral implantation with Tecnis ZM900 (diffractive multifocal), Lentis MPIlus MF30 (segmented refractive multifocal) or Softec-1 (monofocal) IOLs (each n = 15). Each reported their dysphotopsia symptoms subjectively, identified its form (EyeVisPod illustrations), quantified retinal straylight (C-Quant) and halo area (Aston halometer). There was no significant correlation between the subjective dysphotopsia severity and the straylight ($r_s = -0.103, P = 0.503$). Similarly, no significant correlation was found between the subjective scores and the monocular ($r_s = 0.246, P = 0.103$) and binocular ($r_s = 0.241, P = 0.111$) halometry scores. There was also no significant correlation found between the straylight scores and the halometry area both monocularly ($r = 0.051, P = 0.739$) and binocularly ($r = 0.153, P = 0.315$). The findings from this study are comparable to the findings in chapter 2 with the young normal cohort. Whilst these results indicate that subjective and objective measures do not relate post-operatively, there was no consideration of pre-operative values to understand how they change in response to
surgery. Aslam et al. (2007a) similarly reviewed 55 individuals more than a year after cataract surgery to assess subjective complaints using photographic images (PIPP plates). Dysphotopsia in the operated eye was still common more than a year later, with 18 participants (32.7 %) complaining of some level of dysphotopsia, mainly halos and starburst effects. However, the authors also did not assess participants prior to surgery to get baseline data.

Although phacoemulsification cataract surgery has improved visual outcomes and patient satisfaction, some patients with excellent acuity report that they are unhappy even with uncomplicated surgical results (Tester et al., 2000, Radmall et al., 2015). There is limited published data regarding changes in objective and subjective measures in response to cataract surgery. Numerous studies have reported post-operative effects, but are lacking pre-operative measures and are usually not on a longitudinal basis (Aslam et al., 2007a).

The aims of this prospective study are:

- To determine how cataract surgery impacts on objective and subjective photic effects.
- To track longitudinal photic effects in response to cataract surgery for the first time with halometry and subjective assessment.

### 6.2. Subjects and methods

This prospective study included patients undergoing routine cataract surgery and implantation of the Rayner 600S monofocal IOL (described in section 6.2.1) between March 2016 and January 2017. All study procedures were performed in the Ophthalmology Outpatients clinic at Queen Elizabeth Hospital, Birmingham, United Kingdom. The University Hospitals Birmingham (UHB) Research and Development Governance Office of the UHB NHS Foundation Trust reviewed the study (UHB Ref: RRK5260; see appendix A3 and A4). The study was conducted in accordance with the tenets of the Declaration of Helsinki. After receiving an explanation of the nature and possible consequences of the study, all subjects gave their written informed consent to take part.

Power calculations, made using GPower (version 3.1.9.2), showed that 30 participants were required to enable Friedman repeated measures ANOVA on ranks to detect statistically significant large size (0.6) effect at the 5 % significance level (α = 0.05) with 80 % power. Thirty-nine patients with bilateral visually significant cataract scheduled for routine phacoemulsification cataract surgery and IOL implantation at the Queen Elizabeth Hospital were enrolled in the study, subject to the following criteria:
**Inclusion Criteria**

- Over 18 years of age.
- Cataract for which phacoemulsification extraction and posterior IOL implantation has been planned for the operative eye.
- Listed for monocular surgery, or it is the first eye of those requiring binocular treatment.
- Calculated IOL power requirement within the range of + 8.0 to + 34.0 D.
- Clear intraocular media other than cataract.
- Able to understand and undertake the informed consent process.
- Able to perform halometry at 2 metres.

**Exclusion Criteria**

- Prior surgery on the selected eye, glaucoma-filtering surgery, retinal detachment surgery or laser treatment.
- Previous uveitis or trauma to the selected eye, anterior or posterior synechiae.
- Previous eye trauma.
- Potential for best-corrected visual acuity worse than logMAR 0.30.
- Partial or total paralysis, Parkinson syndrome, cerebrovascular accident or other condition that could impact on the results of the study.
- Insufficient physical and/or mental condition to allow participation.
- Participants with any pre-diagnosed ocular condition other than cataract.
- Any participants with a history of using drugs that are known to affect visual function measures.

**6.2.1. Intraocular lens**

The IOL used in the study is based on the traditional Rayner C-flex design and material but has a 6.00mm platform diameter. Other lens features include:

- Hydrophilic acrylic aspheric monofocal IOL.
- 360 degree square edge.
- Aberrations neutral aspherical lens.
- Square edge is on both anterior and posterior surfaces.
- Available in powers from + 8.0 D to + 34.0 D.
- Can be delivered through a 2.2 mm mini incision.
6.2.2. Surgical technique

All patients were having monocular surgery, or it was the first eye of binocular surgery. All patients had cataract surgery under topical anaesthesia performed by the same experienced surgeon (S.K.). A standard suture less micro incision phacoemulsification technique was used. The IOL was implanted in the capsular bag with a single-use injection system. Post-operatively, topical therapy included a standard combination of antibiotic and steroidal agents.

6.2.3. Assessments

At the pre-operative assessment, an optometrist and ophthalmologist examined participants to judge their suitability for cataract surgery. A slit-lamp examination of the anterior segment and funduscopy of the optic nerve head and macular region were performed. The condition of the lens was scored using the LOCS III system (Chylack et al., 1993). Unaided vision or visual acuity in their current spectacles or with pinhole was recorded using a LogMAR chart.

Objective measures of dysphotopsia were acquired using a newer halometer comparable to that described in section 2.2.1, but using an iPad (Apple Inc, California, USA) to run the software, with the light source mounted directly to the tablet screen (see Fig 6.1). An iPhone (Apple Inc, California, USA) acted as the remote to control the movement and randomization of the letter. Halo radius was measured in 8 directions monocularly in the eye to be operated on. The images used to subjectively grade dysphotopsia were also installed on to a programme on the iPad, and measurements were conducted as described in 2.2.2. The Aslam PIPP plates provide an overall subjective grade between 0 (no dysphotopsia) – 40 (most severe dysphotopsia).

In addition to routine post-operative assessments, participants were evaluated at 1 month and 3 - 6 months post-surgery. Unaided visions or best-corrected visual acuity were recorded at these visits, along with objective and subjective assessments of dysphotopsia, as outlined above.
Figure 6.1: iPad halometer with custom built attachment and arm for the central light source. iPhone with a program to control the direction and distance that the letter moves, with the ability to randomise the letter.

6.3. Data and statistical analysis

The data was stored in a password protected Excel 2016 Spreadsheet document (Microsoft, Redmond, WA). All statistical tests were performed using SigmaPlot graphing and statistical software (Version 12.0, Systat Software Inc., Chicago, Illinois, USA). The one-sample Kolmogorov-Smirnov test was used to determine if results from each measurement followed a normal distribution. As there were some non-normally distributed data sets (e.g. halo area in cm² and halo radii in arc min at 3 – 6 month visit and subjective grading at all 3 visits), median and range are reported for all data sets allowing for comparison. For correlation between two data sets, if both data sets followed a normal distribution, Pearson’s Correlation was used. For those data sets where one or both groups deviated from a normal
distribution, Spearman’s Correlation was used. To track changes in objective and subjective measures over time, for parametric data sets a one-way repeated measures ANOVA was used, and for non-parametric data sets a Friedman repeated measures ANOVA on Ranks was used. In all cases, a $P$ value of $< 0.05$ was considered statistically significant.

### 6.3.1. Calculation of halo area from halometer

The halo radius in degrees for each of the 8 meridians was recorded, and these were used to calculate the area of the glare scotoma as previously described in section 2.3.1. The halo radius was converted from degrees subtended to arc min. The median and range for halo radius and halo area were calculated.

### 6.4. Results

All patients underwent uncomplicated phacoemulsification extraction and IOL implantation. Table 6.1 provides descriptive statistics for the entire cohort.

<table>
<thead>
<tr>
<th>No of Participants</th>
<th>Median Age (Years)</th>
<th>Age Range (Years)</th>
<th>Gender</th>
<th>Median pre-operative VA in operative eye</th>
<th>Median final VA in operative eye</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>74.3</td>
<td>52.8 – 86.3</td>
<td>25 female; 14 male</td>
<td>0.50 (range 0.20 – 1.0)</td>
<td>0.00 (range 0.10 – 0.30)</td>
</tr>
</tbody>
</table>

*Table 6.1:* Summary descriptive data for the cohort.

Participants were assessed prior to surgery, and at 1 month and 3 - 6 months post-operatively. One participant missed the 1 month visit, but returned for the 3 - 6 month visit. Four participants were unable to attend the 3 – 6 month visit.

Median halo area pre-operatively was 190.29 cm$^2$ (range 63.74 – 297.86), and 66.33 cm$^2$ (range 22.71 – 117.69) and 32.49 cm$^2$ (range 15.08 – 107.48) at the 1 month and 3 – 6 month post-operative stages, respectively. Median halo radius was 141.0 arc min (range 81.75 – 176.25) pre-operatively, 83.25 arc min (range 48.75 – 111.0) at 1 month and 57.75 arc min (range 39.75 – 104.25) at 3 – 6 month visit.

The median overall subjective grade was 3.0 (range 0.0 – 12.0) pre-operatively, 0.0 (range 0.0 – 6.0) at 1 month and 0.0 (range 0.0 – 8.0) at 3 – 6 month. The median halo
area, halo radius and subjective grade pre-operatively, and at 1 month and 3 - 6 months post-surgery are recorded in Tables 6.2, 6.3 and 6.4. Box-and-whisker plots show the median and interquartile ranges at each visit halo area (Fig 6.2) and subjective grade (Fig 6.3).

<table>
<thead>
<tr>
<th>Median Halo Area (range)</th>
<th>Median Halo Radius (range)</th>
<th>Median Overall Subjective Grade (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>190.29 (63.74 – 297.86) cm²</td>
<td>141.0 (81.75 – 176.25) arc min</td>
<td>3.0 (0.0 – 12.0)</td>
</tr>
</tbody>
</table>

Table 6.2: Summary descriptive statistics for the cohort at the pre-operative assessment (n = 39).

<table>
<thead>
<tr>
<th>Median Halo Area (range)</th>
<th>Median Halo Radius (range)</th>
<th>Median Overall Subjective Grade (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>66.33 (22.71 – 117.69) cm²</td>
<td>83.25 (48.75 – 111.0) arc min</td>
<td>0.0 (0.0 – 6.0)</td>
</tr>
</tbody>
</table>

Table 6.3: Summary descriptive statistics for the cohort 1 month post-surgery (n = 38).

<table>
<thead>
<tr>
<th>Median Halo Area (range)</th>
<th>Median Halo Radius (range)</th>
<th>Median Overall Subjective Grade (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.49 (15.08 – 107.48) cm²</td>
<td>57.75 (39.75 – 104.25) arc min</td>
<td>0.0 (0.0 – 8.0)</td>
</tr>
</tbody>
</table>

Table 6.4: Summary descriptive statistics for the cohort 3 - 6 month post-surgery (n = 35).
**Figure 6.2:** Box-and-whisker plot to show the interquartile range of the halo area at the three time points. $n = 39$ at pre-operative, 38 at 1 month and 35 at 3–6 months. Line within box = median; upper limit of box = 75th percentile; lower limit of box = 25th percentile; upper error bar = 90th percentile; lower error bar = 10th percentile; points = outliers in the upper and lower 10th percentile.

A non-parametric Friedman test of differences amongst repeated measures was conducted to compare the median halo area at the three time points used in the study. There was a significant difference in halo area between these three time points ($\chi^2 (2) = 58.69, P < 0.001$). Post hoc comparison using the Tukey test indicated that halo area pre-operatively (median 190.29 cm$^2$, IQR 148.54 – 226.18 cm$^2$) was significantly greater than at one month post-surgery (median 66.33 cm$^2$, IQR 45.55 – 81.55 cm$^2$) and 3 - 6 month post-surgery (median 32.49 cm$^2$, IQR 28.01 – 43.65 cm$^2$). There was also a significant reduction in halo area between one month and 3 - 6 month post-operatively ($P < 0.05$).
Figure 6.3: Box-and-whisker plot to show the interquartile range of the subjective grading at the three time points. $n = 39$ at pre-operative, 38 at 1 month and 35 at 3 – 6 months. Line within box = median; upper limit of box = 75th percentile; lower limit of box = 25th percentile; upper error bar = 90th percentile; lower error bar = 10th percentile; points = outliers in the upper and lower 10th percentile.

A non-parametric Friedman test of differences amongst repeated measures was conducted for the same time intervals for subjective complaints of dysphotopsia. There was a significant difference between the three time points ($\chi^2(2) = 40.96, P < 0.001$). Post hoc comparison using the Tukey test indicated that the subjective complaints scores pre-operatively (median 3.0, IQR 0.0 – 6.0) was significantly greater than one month post-operatively (median 0.0, IQR 0.0 – 0.0; $P < 0.001$) and 3 - 6 month post-operatively (median 0.0, IQR 0.0 – 0.0; $P < 0.001$). There was no significant difference between one month and 3 - 6 months post-operatively ($P = 0.997$). Fig 6.4 and 6.5 show the proportion of participants complaining of each type of dysphotopsia pre-operatively and 1 month post-operatively, respectively.
Figure 6.4: Diagram showing the proportion of participants complaining of each type of dysphotopsia using PIPP plates pre-operatively, where 0 indicates no dysphotopsia and 4 indicates severe photic symptoms.

Figure 6.5: Diagram showing the proportion of participants complaining of each type of dysphotopsia using PIPP plates 1 month post-operatively, where 0 indicates no dysphotopsia and 4 indicates severe photic symptoms.

Pre-operatively there was no relationship between VA and halo area ($r_s = 0.140$, $r_s^2 = 0.020$, $P = 0.391$). Subjective grade was also not related to VA ($r_s = -0.062$, $r_s^2 = 0.004$, $P = 0.705$).
Pearson’s correlation exhibited no relationship between age and halo area prior to surgery \((r = 0.152, \ r^2 = 0.023, \ P = 0.355)\); whilst at 1 month post-surgery a weak relationship was found \((r = 0.339, \ r^2 = 0.115, \ P = 0.035)\; \text{see Fig 6.6} \).

\[ r = 0.339; \ r^2 = 0.115; \ P = 0.035 \]

**Figure 6.6:** Monocular halo area determined with halometry 1 month post-surgery plotted against age \((n = 38)\).

No relationship was shown between halo area and subjective grade prior to surgery \((r_s = -0.054, \ r_s^2 = 0.003, \ P = 0.741)\) or at 1 month \((r_s = -0.124, \ r_s^2 = 0.015, \ P = 0.454)\) and 3 – 6 month post-surgery \((r_s = 0.002, \ r_s^2 < 0.001, \ P = 0.993)\).

There was no correlation between pre-operative halo area and halo area at the 3 – 6 months visit \((r_s = 0.198, \ r_s^2 = 0.039, \ P = 0.253)\). However, a weak relationship was found between pre-operative subjective complaints and those at the 3 – 6 months visit \((r_s = 0.401, \ r_s^2 = 0.161, \ P = 0.017)\).

The glare effect ratio was calculated at the pre-operative appointment \((\text{median 0.0151, range 0.0 – 0.141})\). No significant relationship was found between the glare effect ratio and the halo area at one month \((r_s = 0.006, \ r_s^2 < 0.001, \ P = 0.971)\) or the halo area at the 3 – 6 month visit \((r_s = -0.132, \ r_s^2 = 0.017, \ P = 0.448)\). However, a weak association was found between the pre-operative glare effect ratio and the 1 month subjective grading \((r_s = 0.419, \ r_s^2 = 0.176, \ P = 0.009; \text{see figure 6.7})\). It was also related to the 3 – 6 month subjective grading \((r_s = 0.366, \ r_s^2 = 0.134, \ P = 0.031; \text{see figure 6.8})\).
Pre-operative Monocular Glare Effect Ratio

Subjective grading with PIPP one month post-operatively

Figure 6.7: Pre-operative monocular halometry glare effect ratio against subjective grading with PIPP one month post-operatively.

Pre-operative Monocular Glare Effect Ratio

Subjective grading with PIPP 3–6 months post-operatively

Figure 6.8: Pre-operative monocular halometry glare effect ratio against subjective grading with PIPP 3 – 6 months post-operatively.
6.5. Discussion

Modern cataract surgery is extremely successful at improving patients' vision and quality of life. However, there are a small percentage of patients who remain dissatisfied after the procedure, even with good visual acuity. Dysphotopsia is a chief complaint after otherwise successful cataract surgery (Tester et al., 2000, Welch et al., 2010, Kinard et al., 2013). Considering this, there are few studies that have investigated the change in objective and subjective measures of dysphotopsia in response to cataract surgery. Whilst some studies have reported post-operative effects, they are rarely on a longitudinal basis (Aslam et al., 2007a) with no pre-operative measures for comparison.

There is some evidence that glare improves after surgery presented by van den Berg et al. (2007), who assessed straylight in pseudophakic eyes, non-cataractous eyes and cataractous eyes. It was previously known that straylight increases with age. The cataract eyes had a relatively mild increase in straylight compared to non-cataract eyes. Surprisingly, in pseudophakia, straylight values were better than in the non-cataract group. However, the study did not compare the pre- and post-operative measures in the same participants, but instead compared a group with cataract to a different post- cataract surgery group. The lens starts to change colour from colourless at age 20 to 25 years, to slight yellow, up to brown at around 65 years and over (van den Berg et al., 2007). The lens continues to grow throughout life, creating more and more optical distortions (Augusteyn, 2010). The retained anatomic layers of the crystalline lens from the embryonic stage to the adult may be one of the causes of light scattering in the eye (Michael and Bron, 2011). A likely reason why pseudophakic participants performed better than the non-cataractous group is that even without the presence of a significant cataract there will be some degree of normal age-related scattering occurring compared to the colourless IOL.

Participant halometry data from chapter 3 was converted to match the iPad halo values; by multiplying each angle subtended by 2 as recommended by the developers of both the Aston halometer and the iPad version. Therefore, based on the converted participant data from chapter 3, a median halo area of 34.87 cm$^2$ (IQR 22.10 – 50.30 cm$^2$) was calculated for participants aged between 51 and 82 years to provide an indication of expected normal values for an older age group. Perhaps unsurprisingly, the pre-operative halo areas (median 190.29 cm$^2$) were almost 5.5 times larger than the older age group values from chapter 3. The presence of cataract causes more scattering of light as it enters the eye (Vos, 1984, van den Berg, 1986, Elliott, 1993). The halo area significantly reduces during the month after surgery (66.33 cm$^2$), and return to values of over 55 year olds, from chapter 3, by 3 - 6 months (32.49 cm$^2$).
Subjective complaints significantly reduced from the pre-operative visit (median 3; range 0.0 – 12.0) to 1 month post-surgery (median 0.0; range 0.0 – 6.0) as may be expected. There was no significant difference between 1 month and 3 – 6 months post-surgery (median 0.0; range 0.0 – 8.0), indicating that all subjective complaint improvements occur within the first month. There may be an aspect of neuroadaptation as the subjective grade reduces by 1 month, whereas it takes 3 – 6 months for the objective measures to return to normal. The subjective values post-surgery were generally low with many participants reporting zero complaints, which could be a consequence of dramatic and sudden improvement in visual quality after cataract surgery meaning participants are on the whole very happy with their quality of vision. Due to patient expectations, in cases of clear lens exchange there may be higher values for subjective grading post-surgery for a longer duration. Bournas et al. (2007) reported from a group of 600 who had undergone cataract surgery, 117 participants (19.5 %) reported some level of dysphotopsia in week 1. There was a significant reduction to only 7 (1.52 %) complaining at 6 months post-surgery.

Relatively little work to date has used simulated images to grade types and severity of subjective photic complaints following cataract surgery with monofocal IOL implantation. Aslam et al. (2007a) reported higher levels of post-operative photic effects in monofocal IOL recipients at a minimum of 12 months post-surgery. The types of effects reported were more diverse than in the present study, whilst the severity was also greater, with around 20 % of individuals affected by each of night halos, night starburst, day starburst, day halos and central flash. The reasons for this difference may be due to the longer time interval post-operatively used by Aslam et al. (2007a), meaning that posterior capsular opacification may have a greater effect, or the initial elation following a substantial improvement in visual quality with cataract surgery declines and individuals become aware of undesirable photic effects.

Pre-operatively, there was a lack of relationship between VA and measured dysphotopsia, both objective halo area ($P = 0.391$) and subjective grade ($P = 0.705$). This finding is concurrent with several previously published studies reporting that the two measures are independent of each other with dysphotopsia often present despite excellent visual acuity (van den Berg et al., 2007, Welch et al., 2010, Kinard et al., 2013).

It is well documented that straylight increases with age (Ijspeert et al., 1990, Bailey and Bullimore, 1991, Vos, 2003a, Puell et al., 2014). Presumably due to cataracts increasing halo area, there was no correlation between age and halo area pre-operatively ($r = 0.152$, $r^2 = 0.023$, $P = 0.355$). However, 1 month after the cataract surgery, a weak but significant relationship was established between age and halo area ($r = 0.339$, $r^2 = 0.115$, $P = 0.035$)
indicating that even without the presence of lens opacities, other ocular media changes with age cause an increase in straylight.

Objective and subjective grades do not exhibit a relationship at any time interval pre- ($P = 0.741$) or post-surgery ($P = 0.454$ and $P = 0.993$). The findings are similar to those reported in chapter 2. Recently, Buckhurst et al. (2017) also described no relationship between subjective scores and straylight ($P = 0.503$), subjective scores and monocular halo area ($P = 0.103$). Therefore, glare effect ratio may be a better predictor of outcomes, as it will identify those with high subjective complaints compared to objective metrics.

There appears to be a weak relationship between glare effect ratio pre-operatively, and subjective complaints post-operatively. Indicating that indeed high glare effect ratios prior to surgery are likely to indicate higher subjective complaints post-operatively and vice versa.

The participants were only seen up to 3 – 6 months after their surgery in this study. To see how things continue to change, tracking these patients further would be useful. Also, a limitation was the fact that the participants seen received monofocal IOLs of a particular material, edge design and optic zone size. For future studies, investigating post-operative effects after multifocal IOLs would be interesting, as well as comparing different lens materials or edge designs.

To conclude, this study has shown that both objective and subjective measures of dysphotopsia improve significantly in the month after uncomplicated cataract surgery. Halo area continues to reduce up to 6 months post-operatively. Objective and subjective measures are not related in participants with cataracts or after cataract surgery. The proposed glare effect ratio may be used to highlight individuals with a significantly high subjective complaint score compared to objective measures; these individuals may need additional counselling prior to surgery or recommendation of alternative procedures.
7.1. General conclusions

The central experimental theme of the thesis has been objective and subjective assessment of dysphotopsia. Dysphotopsia is still only vaguely familiar to optometrist; however, with the incidence on the rise (Sukhovolskiy, 2015) and occurrence with normal ageing, it is important that the condition is more widely understood. Tester et al. (2000) first used the term *dysphotopsia* in 2000 to describe the visual phenomena encountered by phakic and pseudophakic patients, including flashes of light, glare, and light sensitivity. Dysphotopsia is generally divided into two categories: positive and negative. Positive visual changes involve symptoms of bright artefacts, whilst negative dysphotopsia are perceived as shadows or dark areas in the visual field (Hood, 2015). Patients may report glare, starbursts, halos or shadows when describing their visual symptoms (Sukhovolskiy, 2015).

Dysphotopsia is widely accepted to increase in the ageing phakic population (van den Berg, 1995, Tester et al., 2000, Vos, 2003a, Puell et al., 2013). The age-related increase in dysphotopsia is attributable to natural ageing changes increasing ocular media irregularities such as lens opacities and vitreous floaters, and therefore increasing the amount of scatter (Wolf, 1960, Vos, 1984, Bailey and Bullimore, 1991, Dewaard et al., 1992, Elliott, 1993). The resultant increase in intraocular light scatter from a bright light source causes a veiling glare and a loss of contrast across the retinal image (Vos, 1984, van den Berg, 1995, Aslam et al., 2007b, Allen et al., 2009). The direct compensation method and the *Berkeley Glare* Test have been reported to show an increase in glare (Ijspeert et al., 1990, Bailey et al., 1991). However, the *C-Quant* has been shown to remain stable until the age of 45 years and then gradually increase (Rozema et al., 2010) in one study, and is not related with age in another (Puell et al., 2014). Thus, there is no clear consensus on the effect of age on straylight measured with the *C-Quant*, although it may increase beyond the middle of the fifth decade. The data presented in chapter 3, demonstrated a significant increase in straylight with age ($r = 0.457, r^2 = 0.209, P < 0.001$).

Chapter 3 also investigated the effect of age on halo area using the Aston halometer for the first time. The results indicate that binocular halo area increases with age ($r = 0.449, r^2 = 0.202, P < 0.001$) in individuals with healthy eyes. The finding compares favourably with studies that have used alternative halometers such as the Vision monitor (Puell et al., 2014). Puell et al. (2013) reported a similar correlation for halo radius and age ($r = 0.65, r^2 = 0.42, P < 0.001$) as the monocular halometry mean radii results in the current study ($r_s = 0.405$,
In Chapter 3, subjective grading exhibited only a weak relationship with age ($r = 0.314$, $r^2 = 0.099$, $P < 0.001$), indicating that although both objective measures of dysphotopsia increased with age, subjective complaints do not concur with this finding. This important finding highlights the fact that photic effects may not subjectively trouble individuals with significant objective measures of dysphotopsia.

Dysphotopsia is a common cause of dissatisfaction after both corneal refractive surgery (Veraart et al., 1992, Butuner et al., 1994, Niesen et al., 1997, Ghaith et al., 1998, Fan-Paul et al., 2002), and cataract surgery/refractive lens exchange (Tester et al., 2000, Mamalis, 2010). Even after uneventful surgery, glare sensitivity is increased. For pseudophakic patients, multifocal IOLs cause increased complaints compared to monofocal IOLs (Leyland and Zinicola, 2003, Souza et al., 2006, Woodward et al., 2009, de Vries et al., 2011, Chang et al., 2012). There is a lack of data showing the time frame for improvement in visual quality after the various types of refractive surgery, with most studies only tracking changes to 6 months (Bournas et al., 2006, Lapid-Gortzak et al., 2010a, Rozema et al., 2010). In Chapter 5, post-corneal refractive surgery, the data presented indicate that objectively, the process takes 12 months to recover (to levels observed in age-matched controls), whilst subjective recovery occurs in only 3 months. It is likely that a neural adaptation is occurring post-surgery (Fan-Paul et al., 2002). Clinically, the findings indicate that patients could be informed that by 3 months post-surgery, they are likely to be completely happy with their visual quality. In Chapter 6, participants’ halo area was assessed pre- and post-cataract surgery. As expected, there was a significant improvement in objective and subjective measures following cataract surgery with improvements in halo area continuing up to 6 months.

Despite the availability of many objective and subjective methods to measure dysphotopsia, no single method is in common use, nor are photic effects commonly measured prior to cataract or refractive surgery. The chapters in this thesis predominantly used C-Quant to measure straylight and the Aston halometer to quantify the size of the halo area. Where many previously published studies have carried out monocular halometry (Pieh et al., 2001, Puell et al., 2013), in Chapters 2 and 3, both binocular and monocular measures were taken with halometry. Monocular halo area was found to be significantly larger (approximately 29 %) than the binocular area in this programme of research, indicating the effect of binocular summation on objective measures of halo area (Chapter 2 and 3). Binocular measures may be more appropriate and representative of an individual’s typical visual experience.
Often dysphotopsia is measured by placing a bright light source in the subjects’ field of view (Williamson et al., 1992, Elliott and Bullimore, 1993), and pupil diameter is known to decrease with increasing luminance (Laughlin, 1992, Winn et al., 1994, Loewenfeld, 1999, Watson and Yellott, 2012, Orr et al., 2015). Therefore, one might argue that pupil size will affect the assessments of dysphotopsia, as less retinal illuminance will occur. The pupil diameter also decreases with increasing age (Watson and Yellott, 2012; Kadlecova et al., 1958; Schaeffel et al., 1993; Winn et al., 1994). Many of the participants that will undergo dysphotopsia assessment are likely to be older adults, and will therefore be affected by senile miosis. When pupils are small, vision may be adversely affected by loss of retinal illumination (Campbell and Gubisch, 1966; Donnelly and Roorda, 2003). Equally, a smaller pupil may result in less retinal illumination, and VA improves with small pupils (Atchinson et al., 1979). This led to the question of whether pupil size should be measured or controlled in the measurement of dysphotopsia. The existing literature showed debate on whether pupil size affects the amount of dysphotopsia that is measured (Masket, 1992, Cahane et al., 1993, Whitaker et al., 1994, Franssen et al., 2007). It was apparent that it may be dependent on the device that is used to measure glare. In Chapter 4, for the first time, the study investigated whether pupil size has an effect on the size of the halo area when measured using halometry. No significant difference in halo area with the different simulated pupil sizes was detected. The results support the assertion that whilst a larger pupil allows more glaring light from the glare source to enter, the retinal illuminance is also changed by the stimulus (Whitaker et al., 1994, Franssen et al., 2007). More dark scenery enters the eye, thus counteracting the effect of the glaring light. The Aston halometer is a robust way to measure dysphotopsia without measuring or controlling pupil size. The findings are also likely to be more widely applicable to other halometers, which work on the principle of measuring the size of the glare scotoma arising from a glare source.

Subjective complaints of dysphotopsia were assessed using PIPP plates in the studies described in chapters 2, 3, 4 and 6. Using the PIPP plates to grade subjective experience of dysphotopsia found that the most common complaints were day halos, day starburst, night halos, night starburst and central flash (chapter 2). Aslam et al. (2007) reported a similar finding with a predominance of halos and starburst effects but also substantial symptoms of arc effect, streams of light, and central flash. The types of effects reported were more diverse than in chapter 2, whilst the severity was also greater. The reasons for this difference may be due to the longer time interval post-operatively used by Aslam et al. (2007), meaning that posterior capsular opacification may have a greater effect,
or the initial elation following a substantial improvement in visual quality with cataract surgery declines and individuals become aware of undesirable photic effects.

Previous studies in the field of photic phenomena have generally reported either objective or subjective measures only (Arnold, 1994, van den Berg, 1995, Dick et al., 1999, Pieh et al., 2001, Aslam et al., 2004a, Puell et al., 2013), largely without consideration of normal values in healthy eyes. The relationship between objective measures and subjective complaints is unknown in a normal population; despite conflicting evidence post IOL exchange where Dick et al. (1999) reported a correlation between subjective reports of halos and halo area, although very recently Buckhurst et al. (2017) stated that there is no correlation in pseudophakes. Chapter 2 established a lack of relationship between subjective and objective measures highlighting the difficulties in being able to predict the potential subjective complaints a patient may experience from an objective measure alone. Chapter 3 reported a weak relationship between halo area and grading of night halos severity. From this, it is clear that the perception of dysphotopsia is individual to each person. Some have a high objective measure of glare, however subjectively they may give a low score for glare effects. It is possible that these individuals have adapted to the glare that they experience and as such have no complaints of glare, or are less troubled by photic effects.

No relationship between halometry and C-Quant measurements was discovered in chapter 2, and it is likely to be due to the fact that both machines measure different aspects of glare; the C-Quant measures the amount of straylight in the eye (van den Berg, 1995), whereby, the halometer measures the actual size of the disability glare area experienced and is not based on forward scatter within the eye alone. Again, this would indicate that using one objective measure alone may not be enough to distinguish those who struggle with dysphotopsia. However, Puell et al. (2014) found a significant correlation between halo radius and straylight ($r = 0.45$, $r^2 = 0.203$, $P = 0.001$) in a cohort of similarly aged participants to the present study. This finding could be due to the fact that they measure halo area monocularly, or due to the difference in taking measurements of halo area, such as size of glare source, size of target and distance from glare source.

The subjective/objective ratio (glare effect ratio) was calculated to give a single value that combined both forms of measurement and indicated the level of subjective complaint compared to an objective measure. It is widely accepted that objective measures increase with age, therefore, it can be difficult to establish if an older patient has a high objective measure due to age alone. The glare effect ratio is independent of age, and as suggested
in chapter 2, a high glare effect ratio would indicate an individual more subjectively affected by a given objective measure.

The normal range of glare effect ratios that have been found could be used for comparison purposes pre- and post-refractive surgery as suggested in chapter 2 and 6. A larger study on subjective satisfaction after cataract surgery may be required as the individuals in chapter 6 were all very happy post-operatively. Further studies would confirm if this is a typical finding across NHS cataract patients. If cataract severity is graded at the pre-operative appointments, then it could be established whether there is a relationship between severity and subjective complaints post-surgery, as there is likely to be a larger improvement in symptoms for individuals with severe cataracts. Additionally, further work on how disabling photic effects due to cataracts are would provide valuable information. Therefore, clinically expected values of dysphotopsia with different types or varying levels of cataract could be complied and would provide additional information to VA measures. How photic effects change as cataracts develop is currently not well understood.

It has been noted that both the iris and sclera are partially responsible for intraocular scattering as they are not completely opaque, and allow some light to pass through (Ijspeert et al., 1990, van den Berg et al., 1991). The amount of light that can pass through is dependent on the level of pigmentation, whereby blue/green eyes with lower amounts of pigmentation would transmit and scatter more light than dark brown eyes (van den Berg et al., 1991). When light reaches the retina, some of it is absorbed, whilst some is reflected back contributing to the intraocular scattering (van den Berg et al., 1991); this type of scattering is also dependent on the subjects’ level of pigmentation. This would lead you to believe that a participant’s ethnicity or iris colour would affect the level of straylight and therefore, dysphotopsia experienced. Many papers have investigated dysphotopsia and glare, but they have not recorded nor taken into account ethnicity or iris colour. It could be said that ethnicity would likely impact on the levels of ocular pigment, but I would say that iris colour is the important detail to note as a few ethnicities may have brown or blue eyes. Franssen et al. (2007) reported a translucency value average of 0.30 mm² in four more lightly pigmented subjects, compared to 0.00 mm² in the brown-eyed individual. However, it was noted that the effect of translucency was more apparent for small pupil sizes when the scattering angle increases. Due to this, as we carry out halometry in the dark, and pupil sizes would be larger, the translucency may not have an effect. A future study comparing the levels of dysphotopsia in various coloured eyes or ethnic backgrounds would be interesting to ascertain if an effect is present.
A further study using multifocal IOLs may be a good comparison, as the cohort in chapter 6 were implanted with monofocal IOLs, and it is known that multifocal IOLs cause more dysphotopsia, therefore a comparison with monofocal IOLs may be nice. An alternative is to investigate the efficacy of the glare effect ratio in predicting post-operative dissatisfaction is by using multifocal contact lenses; this way glare effect ratios could be determined prior to lens wear and could be compared to subjective complaints of dysphotopsia with multifocal contact lens in situ. Therefore, allowing for a larger cohort as the effects will be reversible, unlike with multifocal IOL implantation.

Various limitations were present amongst the studies that were carried out. In future studies, it would be wise to avoid the use of contact lenses amongst glasses wearers when taking measurements, and perhaps, all should wear a trial frame, using plano lenses for those with no refractive error. A study investigating high powered contact lenses and their effect on measurements of dysphotopsia would be useful to find if there is an effect caused by the edge of the optic. If pupil sizes are to be controlled, then perhaps occluding contact lenses may work, but this is dependent on them sitting stably on the eye. It also suggested to measure the pupil size pre- and post-dilation, as it may give another dimension of analysis, and these should be measured with a pupilometer.

The glare effect ratio concept could be used by other researchers, if they establish normal values dependent on the objective measure (e.g. type of halometer) they employed.

7.2. Concluding statement

The investigations detailed in the thesis have explored some of the various ways to measure dysphotopsia both objectively and subjectively, which remain poorly understood, despite vast literary coverage of the subject. There is currently no gold standard to quantify dysphotopsia. Whilst this is the case, halometers are soon becoming a popular choice to calculate amounts of dysphotopsia objectively (Pieh et al., 2001, Puell et al., 2013, Sheppard et al., 2013, Buckhurst et al., 2015). The Aston halometer is a robust, relatively quick and easy to perform technique. The use of simulated images of dysphotopsia proved favourable amongst patients to establish their subjective complaints.

New information regarding linking objective and subjective grades to give a glare effect ratio could be useful to predict outcomes of refractive surgery if measures are taken pre-operatively. Using a combination of objective and subjective grades removes the variability in measurements that are associated with using subjective measures alone. Those with the highest glare effect ratios are most likely to perform poorly with multifocal IOLs. Having this information would be valuable to IOL manufacturers as distance and near
vision is good in multifocal IOLs, the only problematic effect is glare. Glare effect ratio can be used to predict subjective outcomes post-surgery; this could be an effective tool for surgeons. If there is a way to reduce the number of patients who suffer from these glare effects, there could be almost 100% patient satisfaction. Subjective complaints reduce by 3 months post-refractive surgery, objective halo area take 6 months to resolve post-cataract surgery and up to 12 months post-corneal surgery. In addition to providing greater insight into several aspects of dysphotopsia associated with refractive surgery which are not fully understood, the findings detailed form a platform for numerous future investigations in an exciting and expansive field of research, the ultimate goal of which is the prediction of dysphotopsia complaints post-surgery and to better provide information on time scale of resolution of symptoms.
REFERENCES


Fankhauser, F., 2nd (2007). Postoperative Follow up by Dynamic Light Scattering: Detection of Inflammatory Molecular Changes in the Cornea, the Vitreous and the Lens.


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Life and Health Sciences Research Ethics Committee’s Decision Letter

To: Dr Amy Sheppard  
Cc: Rachel Giles, administrator to the Life and Health Sciences Research Ethics Committee  
From: Dr Corinne M. Spickett  
Chair of the Life and Health Sciences Research Ethics Committee  
Date: 19/12/2013  
Subject: Project #595. Subjective and objective dysphotopsia in normal and post-refractive surgery eyes

Thank you for your resubmission. The additional information for the above proposal has been considered by the Chair of the LHS Ethics Committee. Please see below for details of the decision and the approved documents.

Reviewer’s recommendation: Approved

Please see the tabled list below of approved documents:

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After starting your research please notify the LHS Research Ethics Committee of any of the following: Substantial amendments. Any amendment should be sent as a Word document, with the amendment highlighted. The amendment request must be accompanied by all amended documents, e.g. protocols, participant information sheets, consent forms etc. Please include a version number and amended date to the file name of any amended documentation (e.g. “Ethics Application #100 Protocol v2 amended 17/02/12.doc”).

New Investigators  
The end of the study

Please email all notifications and reports to lhs_ethics@aston.ac.uk and quote the original project reference number with all correspondence.

Ethics documents can be downloaded from: [http://www.ethics.aston.ac.uk/documents-all](http://www.ethics.aston.ac.uk/documents-all). Please note that these documents can ONLY be opened using Mozilla Firefox or the latest Internet Explorer version (IE9).

Statement of Compliance  
The Committee is constituted in accordance with the Government Arrangements for Research Ethics Committees (July 2001) and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK. In accord with University Regulation REG/11/203(2), this application was considered
to have low potential risk and was reviewed by three appropriately qualified members, including the Chair of the Life and Health Sciences Ethics Committee.

Yours sincerely,

Dr Corinne M Spickett
Chair of the LHS Ethics Committee
A2: Amendment to Ethics Application 595

MEMORANDUM

DATE: 13th December 2015

TO: Dr Amy Sheppard

FROM: Dr Leon N Davies

SUBJECT: Project # 595 Subjective and objective dysphotopsia in normal and post-refractive surgery eyes

I am writing to inform you that the minor proposed changes to the above project as described in your email and attachment of 9th December 2015 have been approved.

List of Amended Items approved:

Ethics Application 595 Revised Protocol V3 08.12.15 (dated 08/12/15)
Ethics Application 595 Consent Form V3 Amended 08.12.2015 (dated 08/12/15)
Ethics Application 595 Notice of Substantial Amendment (dated 12/11/15)

The Ethics Committee's approval applies only to research conducted in accordance with the amended protocol and documentation approved by the LHS EC; any change to the protocol must be approved by the Committee prior to its implementation.

The details of the investigation will be placed on file. You should notify me of any difficulties experienced by the volunteer subjects, and any significant changes which may be planned for this project in the future.

Dr Leon N. Davies
Chair, LHS Ethics Committee
A3: NHS Ethics (LOA) Approval

**Birmingham Clinical Research Office**

**Miss Aujla**

**UHB: letter of access for researchers who do not require an honorary research contract - Form RPL 2**

Miss M Aujla

Vision Sciences

Aston University

Aston Triangle

Birmingham B4 7ET

R&D Office (UHB)

Education Centre (office 17), 1st Floor

Queen Elizabeth Hospital Birmingham

Mindelsohn Way,

Edgbaston

Birmingham B15 2WB

Tel. 0121 371 4185

Fax 0121 371 4204

Date: 11/05/2015

Dear Miss Aujla

**Letter of access for research**

This letter confirms your right of access to specified areas to conduct research through University Hospitals Birmingham NHS Foundation Trust for the purpose and on the terms and conditions set out below. This right of access commences on 01-May-2015 and ends on 06-Oct-2016 unless terminated earlier in accordance with the clauses below. Your entitlement to access to the specified area will automatically end on the date specified. It is your responsibility to seek an extension of time for access should it become necessary.

Your right of access is granted to undertake the following activities:

Consenting and measurement of visual function

or other duties agreed with the R&D office in the Delegated Duties Log for the following study/studies:

Study Title: Evaluating the subjective and objective performance of instrumentation used and intraocular devices implanted during routine ocular surgery

UHB Reference: RRK5260. Principal Investigator: Dr S Kolli

You have the right of access to conduct such research as confirmed in writing in the letter of permission for research from this NHS organisation. Please note that you cannot start the research until the Principal Investigator for the research project has received a letter from us giving permission to conduct the project. This Letter of Access is issued on the understanding that your activities will have no direct impact on the quality of care provided to patients of the Trust.

You are considered to be a legal visitor to UHB NHS Foundation Trust premises. You are not entitled to any form of payment or access to other benefits provided by this NHS organisation to employees and this letter does not give rise to any other relationship between you and this NHS organisation, in particular that of an employee.

While undertaking research through UHB NHS Foundation Trust you will remain accountable to your employer **Aston University** but you are required to follow the reasonable
instructions of Dr S Kolli in this NHS organisation or those given on her/his behalf in relation to the terms of this right of access.
Where any third party claim is made, whether or not legal proceedings are issued, arising out of or in connection with your right of access, you are required to co-operate fully with any

**Birmingham Clinical Research Office**

**Miss Aujla**

**UHB: letter of access for researchers who do not require an honorary research contract - Form RPL 2**

investigation by this NHS organisation in connection with any such claim and to give all such assistance as may reasonably be required regarding the conduct of any legal proceedings.
You must act in accordance with UHB NHS Foundation Trust policies and procedures, which are available to you upon request, and the Research Governance Framework.
You are required to co-operate with UHB NHS Foundation Trust in discharging its duties under the Health and Safety at Work etc Act 1974 and other health and safety legislation and to take reasonable care for the health and safety of yourself and others while on UHB NHS Foundation Trust premises. You must observe the same standards of care and propriety in dealing with patients, staff, visitors, equipment and premises as is expected of any other contract holder and you must act appropriately, responsibly and professionally at all times.
You are required to ensure that all information regarding patients or staff remains secure and **strictly confidential** at all times. You must ensure that you understand and comply with the requirements of the NHS Confidentiality Code of Practice ([http://www.dh.gov.uk/assetRoot/04/06/92/54/04069254.pdf](http://www.dh.gov.uk/assetRoot/04/06/92/54/04069254.pdf)) and the Data Protection Act 1998. Furthermore you should be aware that under the Act, unauthorised disclosure of information is an offence and such disclosures may lead to prosecution.
Please note that you are not regarded as a member of the healthcare team and are not entitled to access information about patients of the Trust without their consent.
You should ensure that, where you are issued with an identity or security card, a bleep number, email or library account, keys or protective clothing, these are returned upon termination of this arrangement. Please also ensure that while on the premises you wear your ID badge at all times, or are able to prove your identity if challenged. Please note that this NHS organisation accepts no responsibility for damage to or loss of personal property.
We may terminate your right to attend at any time either by giving seven days’ written notice to you or immediately without any notice if you are in breach of any of the terms or conditions described in this letter or if you commit any act that we reasonably consider to amount to serious misconduct or to be disruptive and/or prejudicial to the interests and/or business of this NHS organisation or if you are convicted of any criminal offence. Your substantive employer is responsible for your conduct during this research project and may in the circumstances described above instigate disciplinary action against you.
UHB NHS Foundation Trust will not indemnify you against any liability incurred as a result of any breach of confidentiality or breach of the Data Protection Act 1998. Any breach of the Data Protection Act 1998 may result in legal action against you and/or your substantive employer.
If your current role or involvement in research changes, or any of the information provided in...
your Research Passport changes, you must inform your employer through their normal procedures. You must also inform your nominated manager in this NHS organisation.

Yours sincerely

Christopher Counsell, PhD
Head of R&D (Governance)
UHB NHS Foundation Trust

11 May 2015

Birmingham Clinical Research Office
Miss Aujla
UHB: letter of access for researchers who do not require an honorary research contract - Form RPL 2
cc: Supervisor
UHB HR Department

HR Department of the substantive employer
A4: NHS Ethics (LOA) Extension
R&D Governance Office

Miss Aujla
UHB: letter of access for researchers who do not require an honorary research contract - Form RPL 2
Miss M Aujla
Vision Sciences
Aston University
Aston Triangle
Birmingham B4 7ET
UHB Research Governance Office
1st Floor, Institute of Translational Medicine
Heritage Building
Queen Elizabeth Hospital Birmingham
Mindelsohn Way
Edgbaston
Birmingham B15 2WG
Tel. 0121 371 4185
Date: 24/04/2017
Dear Miss Aujla

Letter of access for research
This letter confirms your right of access to specified areas to conduct research through University Hospitals Birmingham NHS Foundation Trust for the purpose and on the terms and conditions set out below. This right of access commences on 01-May-2015 and ends on 06-Oct-2016 unless terminated earlier in accordance with the clauses below. Your entitlement to access to the specified area will automatically end on the date specified. It is your responsibility to seek an extension of time for access should it become necessary. Your right of access is granted to undertake the following activities:
Consenting and measurement of visual function
or other duties agreed with the R&D office in the Delegated Duties Log for the following study/studies:

RRK5260 Evaluating the subjective and objective performance of instrumentation used and intraocular devices implanted during routine ocular surgery
PI: Kolli,S
You have the right of access to conduct such research as confirmed in writing in the letter of permission for research from this NHS organisation. Please note that you cannot start the research until the Principal Investigator(s) for the research project(s) has received a letter from us giving permission to conduct the project. This Letter of Access is issued on the understanding that your activities will have no direct impact on the quality of care provided to patients of the Trust.
You are considered to be a legal visitor to UHB NHS Foundation Trust premises. You are not entitled to any form of payment or access to other benefits provided by this NHS organisation to employees and this letter does not give rise to any other relationship between you and this NHS organisation, in particular that of an employee.
While undertaking research through UHB NHS Foundation Trust you will remain accountable to your employer Aston University but you are required to follow the reasonable instructions of Mr S Kolli in this NHS organisation or those given on her/his behalf in relation to the terms of this right of access.
Where any third party claim is made, whether or not legal proceedings are issued, arising
out of or in connection with your right of access, you are required to co-operate fully with any

R&D Governance Office
Miss Aujla
UHB: letter of access for researchers who do not require an honorary research contract - Form RPL 2

investigation by this NHS organisation in connection with any such claim and to give all such assistance as may reasonably be required regarding the conduct of any legal proceedings.

You must act in accordance with UHB NHS Foundation Trust policies and procedures, which are available to you upon request, and the Research Governance Framework. You are required to co-operate with UHB NHS Foundation Trust in discharging its duties under the Health and Safety at Work etc Act 1974 and other health and safety legislation and to take reasonable care for the health and safety of yourself and others while on UHB NHS Foundation Trust premises. You must observe the same standards of care and propriety in dealing with patients, staff, visitors, equipment and premises as is expected of any other contract holder and you must act appropriately, responsibly and professionally at all times.

You are required to ensure that all information regarding patients or staff remains secure and strictly confidential at all times. You must ensure that you understand and comply with the requirements of the NHS Confidentiality Code of Practice (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/200146/Confidentiality-_NHS_Code_of_Practice.pdf) and the Data Protection Act 1998. Furthermore you should be aware that under the Act, unauthorised disclosure of information is an offence and such disclosures may lead to prosecution.

Please note that you are not regarded as a member of the healthcare team and are not entitled to access information about patients of the Trust without their consent. You should ensure that, where you are issued with an identity or security card, a bleep number, email or library account, keys or protective clothing, these are returned upon termination of this arrangement. Please also ensure that while on the premises you wear your ID badge at all times, or are able to prove your identity if challenged. Please note that this NHS organisation accepts no responsibility for damage to or loss of personal property.

We may terminate your right to attend at any time either by giving seven days’ written notice to you or immediately without any notice if you are in breach of any of the terms or conditions described in this letter or if you commit any act that we reasonably consider to amount to serious misconduct or to be disruptive and/or prejudicial to the interests and/or business of this NHS organisation or if you are convicted of any criminal offence. Your substantive employer is responsible for your conduct during this research project and may in the circumstances described above instigate disciplinary action against you.

UHB NHS Foundation Trust will not indemnify you against any liability incurred as a result of any breach of confidentiality or breach of the Data Protection Act 1998. Any breach of the Data Protection Act 1998 may result in legal action against you and/or your substantive employer.
If your current role or involvement in research changes, or any of the information provided in your Research Passport changes, you must inform your employer through their normal procedures. You must also inform your nominated manager in this NHS organisation.

Yours sincerely

Christopher Counsell, PhD
Head of R&D (Governance)
UHB NHS Foundation Trust
cc: Supervisor
UHB HR Department
HR Department of the substantive employer

24 April 2017
SUPPORTING PUBLICATIONS

Poster presentation at ARVO 2015, Denver (Based on chapter 2 data)

Halo size and subjective complaints of dysphotopsia in a normal population

SECTION:

Purpose: Dysphotopsia including glare and haloes is the most common cause of dissatisfaction post cataract surgery with implantation of multifocal intraocular lenses (IOL). Despite good distance and near visual acuity, quality of life may be affected if activities such as night driving are compromised. There is currently no standardised method of measuring dysphotopsia. The aim of this prospective study was to investigate the relationship between objective measures and subjective complaints of dysphotopsia. The normal range of subjective/objective grade (the glare effect ratio) will be determined.

Methods: Measurements were taken both binocularly and monocularly from 100 healthy participants (mean age: 22 ± 3.21 years; range 18 to 33 years). A bespoke halometer device gave an objective measure by accurately quantifying the extent of the glare area in 8 meridians. The commercially available C-Quant objectively assessed the amount of straylight falling on the retina using the compensation comparison method. Subjective grading of glare was performed using simulated images found on the Photographic Images of Photic Phenomena plates.

Results: Monocular glare areas (median: 4.25 cm$^2$; range 1.97 to 19.61 cm$^2$) were found to be significantly larger than the binocular glare areas (median: 3.24 cm$^2$; range 1.64 to 8.26 cm$^2$) with the halometer ($P < 0.001$). There was no significant relationship found between halometer glare area and subjective complaints ($r_s = -0.048$, $r_s^2 = 0.002$, $P = 0.635$); C-Quant and subjective complaints ($r_s = 0.109$, $r_s^2 = 0.012$, $P = 0.279$); halometer and C-Quant ($r_s = 0.121$, $r_s^2 = 0.015$, $P = 0.231$). The normal range for the glare effect ratio was calculated for both halometry (median: 0.87; range 0 – 2.47) and for C-Quant (median: 3.23; range 0 – 9.41).

Conclusions: Binocular summation was evident with binocular halos being smaller than monocular halos; suggesting halometry should be performed binocularly. The lack of relationship between subjective and objective measures highlights the difficulties in being able to predict the potential subjective complaints a patient may experience from an objective measure alone. The normal range of the glare effect ratio could be used for comparison purposes pre and post refractive surgery, as individuals with the highest glare effect ratios may be less suitable for refractive surgery procedures that may induce glare.
Poster presentation at ARVO 2016, Seattle (Based on chapter 3 data)

Age-related objective and subjective dysphotopsia

SECTION:

Purpose: Dysphotopsia including glare and haloes is the most common cause of dissatisfaction post cataract surgery with implantation of multifocal intraocular lenses (MIOLs). The aim of this prospective study was to determine the relationship between objective measure and subjective complaints which could be used to identify those most likely to experience post-operative problems. The normal range of subjective/objective grade (the glare effect ratio) was determined over a wide age range.

Methods: Measurements were acquired monocularly and binocularly from 141 healthy participants (range 18 to 82 years). A bespoke halometer gave an objective measure by quantifying the extent of the glare area in 8 meridians. The C-Quant objectively assessed the amount of straylight falling on the retina using the compensation comparison method. Grading of subjective dysphotopsia was performed using simulated images (Photographic Images of Photic Phenomena plates).

Results: Monocular glare areas (median: 4.87 cm²; range 1.97 to 20.87 cm²) were larger than the binocular glare areas (median: 3.77 cm²; range 1.64 to 12.11 cm²) with halometry ($P < 0.001$). Binocular glare area increased with age ($r = 0.673$, $r^2 = 0.453$, $P < 0.001$). Objective findings explained only a small percentage of the variance in subjective measures; halometer glare area vs subjective complaints $r = 0.287$, $r^2 = 0.082$, $P < 0.001$; C-Quant vs subjective complaints ($r = 0.228$, $r^2 = 0.052$, $P = 0.007$). The normal range for the glare effect ratio was calculated for both halometry (median: 0.77; range 0 – 2.52) and for C-Quant (median: 3.45; range 0 – 10.62).

Conclusions: Binocular summation was evident with binocular halos being smaller than monocular halos, suggesting halometry should be performed binocularly. The lack of a strong relationship between subjective and objective measures highlights the difficulties in predicting a patient’s likely subjective complaints from an objective measure alone. The normal range of the glare effect ratio could be used for screening purposes pre-refractive surgery, as individuals with the highest ratios may be the most likely to complain of subjective dysphotopsia symptoms.