Contrast Sensitivity in Emmetropic Presbyopes with Small-Aperture Inlay Implantation: Normative Values and Postoperative Outcomes

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Introduction

Contrast Sensitivity (CS) is an important measure to research quality of vision, complementing high-contrast visual acuity which assesses visual quantity, and it integrates both optical and neural processing components of vision in a single function [1-2]. CS under different lighting conditions provides particularly important information about quality of vision for post-surgery populations and for presbyopia patients as they are affected by age-related changes to both crystalline lens and neural processing [2-5]. Presbyopia is the most common eye disease, naturally occurring for every person as a result of aging, currently affecting 1 billion adults worldwide [6]. It is an age-related loss of accommodation resulting from the crystalline lens’ inability to focus at near vergence [7]. The KAMRA® inlay (AcuFocus Inc., Irvine, CA, USA), a small-aperture in-corneal inlay medical device aiming at correcting presbyopia, can be monocularly implanted into a lamellar pocket in the non-dominant eye of a patient. Its mechanism of action is to restrict unfocused peripheral light rays to provide increased depth of focus and an extended range of continuous vision expanding from near to far [8,9].

The CS function is generally measured using a chart comprised of sine wave gratings at various contrast levels [e.g. the Functional Acuity Contrast Test (FACT) chart in the Optec 6500 Vision Tester (Stereo Optical Co., Chicago, IL, USA), the CSV-1000 Contrast Testing Instrument (VectorVision, Greenville, OH, USA)] at a set of spatial frequencies under photopic or mesopic lighting with or without a glare source. Despite a large body of literature on CS [1,10-13], there is an unmet need for a normative CS database that covers all contrast testing conditions for the presbyopia population, as most reported CS norms either do not pertain to presbyopia population or do not test under mesopic or with-glare conditions. The study aims to establish normative CS curves for emmetropic presbyopes tested monocularly and binocularly under photopic and mesopic conditions with and without glare and to use the normative curves to compare to postoperative outcomes in KAMRA inlay implanted subjects.

Materials and Methods

Subjects and inlay design

In this prospective, multi-center, open-label, single-arm US IDE clinical trial (http://www.clinicaltrials.gov, NCT00819299 and NCT00850031), 507 subjects at 24 clinical sites (15 US and 9 non-US) were implanted with the KAMRA intra-corneal inlay in their non-dominant eyes. Pre-determined subgroup of 335 subjects (47% females and 53% males; mean age, 51.6 ± 3.6 years; race, 90% Caucasian, 7% Asian, 2% Hispanic and less than 1% African American and others) participated in the CS sub-study that was analyzed and presented in this paper. The study was approved by the institutional review board or the ethics committee of each investigational site and was performed in accordance with the Declaration of Helsinki. Subjects provided informed consent before screening and participation.

The inclusion criteria included age between 45 and 60 years, distance visual acuity correctable to 20/20 in both eyes, uncorrected near visual acuity between 20/40 and 20/100 and a preoperative spherical equivalent cyclogeic refraction between +0.50 to -0.75 D with no more than 0.75 D of refractive cylinder in the study eye.

The design of small-aperture KAMRA inlay, the surgical preparation and the technique for KAMRA inlay implantation have been reported in detail [14]. The inlay from the anterior angle is depicted in Figure 1. The inlay is made from a highly biocompatible material polyvinylidene difluoride (PVDF). The inlay is 6 microns thick, 3.8 mm in outer diameter, 1.6 mm in inner diameter, 7.5 mm in spherical radius, and microperforated with 8,400 holes between 5 and 11 µm in diameter allowing for 5% light transmission through the annulus of the inlay.
Contrast sensitivity testing

Contrast sensitivity (CS) was measured using slides of the FACT chart within the Optec 6500 Vision Tester [15]. The back-lit chart was calibrated to 85 cd/m$^2$ and 3 cd/m$^2$ for photopic and mesopic testing in luminance, respectively. The FACT chart and the CS measurement process have been discussed in detail [15].

Testing was performed under best distance vision. Five CS conditions were measured (monocular and binocular photopic CS without glare, monocular and binocular mesopic CS without glare, and binocular mesopic CS with glare) and four spatial frequencies were tested in each condition (3, 6, 12, and 18 cycles per degree (cpd) for photopic conditions, 1.5, 3, 6, and 12 cpd for mesopic conditions). Preoperative data were collected and compared to 12, 24, and 36 months postoperatively. Test results were represented in log10 unit of CS (logCS). A logCS score of 0.3 less than the lowest logCS score for a spatial frequency on the FACT chart was assigned when no patches were seen [11,16].

Data analysis

Statistical analysis was performed using the JMP 11.2 (SAS Institute, Inc, Cary, NC, USA). Postoperative mean logCS changes and their upper limits of 95% confidence interval were compared to the preoperative mean logCS values with a non-inferiority margin of -0.15 logCS. This analysis is further confirmed by calculating the within-subject changes and comparing their means to the non-inferiority margin of -0.15 logCS. Mean logCS values from postoperative visits were compared with each other in each combination of spatial frequency and testing condition using Tukey-Kramer HSD test to protect overall error rate across tests between visits. A p-value less than 0.05 were considered statistically significant.

Results

Table 1: The mean logCS values from preoperative to 12, 24 and 36 month postoperative visits and the lower and upper limits of normative values developed from preoperative means in various contrast testing conditions.

| Spatial Frequency | Pre-op (n=335) | Month 12 (n=313) | Month 24 (n=286) | Month 36 (n=282) | Low Normal | High Normal |
|-------------------|----------------|------------------|------------------|------------------|------------|-------------|
|                   |                |                  |                  |                  |            |             |
|                   |                |                  |                  |                  | Monocular Photopic without glare |            |
| 3                 | 1.85           | 1.81             | 1.83             | 1.81             | 1.43       | 2.26        |
| 6                 | 1.94           | 1.88             | 1.87             | 1.86             | 1.54       | 2.34        |
| 12                | 1.65           | 1.52             | 1.52             | 1.49             | 1.19       | 2.11        |
| 18                | 1.23           | 1.00             | 1.01             | 0.99             | 0.66       | 1.8         |
|                   |                |                  |                  |                  | Binocular Photopic without glare |            |
| 3                 | 1.98           | 2.02             | 2.01             | 1.98             | 1.66       | 2.3         |
| 6                 | 2.08           | 2.11             | 2.1              | 2.08             | 1.77       | 2.39        |
| 12                | 1.8            | 1.78             | 1.79             | 1.79             | 1.4        | 2.21        |
| 18                | 1.41           | 1.36             | 1.36             | 1.36             | 0.92       | 1.9         |
|                   |                |                  |                  |                  | Monocular Mesopic without glare |            |
| 1.5               | 1.68           | 1.61             | 1.64             | 1.63             | 1.29       | 2.07        |
| 3                 | 1.87           | 1.74             | 1.74             | 1.73             | 1.49       | 2.25        |
| 6                 | 1.86           | 1.63             | 1.65             | 1.62             | 1.41       | 2.3         |
| 12                | 1.41           | 1.12             | 1.13             | 1.12             | 0.83       | 2           |
The upper and lower limits of normative values were developed from preoperative CS measurements by taking 1.96 standard deviations (SD) from the mean at each spatial frequency in each testing condition [15] and they demonstrated that the postoperative mean logCS values were well within the high and low normative curves across all postoperative visits (Table 1). The analyses examining changes from preoperative to postoperative revealed that none of the three binocular conditions showed a significant change from baseline: the largest mean change in any condition was -0.08 logCS, half of the clinically significant mean change threshold of -0.15 logCS. In the monocular conditions, the high spatial frequencies in monocular mesopic without glare condition showed the significant loss from preoperative (-0.20 to -0.24 logCS at 6 cd/p and 0.29 to -0.30 logCS at 12 cd/p across 12-36 months), and the highest spatial frequency in monocular photopic without glare condition also showed a significant loss from preoperative (-0.22 to -0.24 logCS at 18 cd/p). The low to intermediate spatial frequencies in both monocular conditions did not show significant losses compared to preoperative mean logCS values with a non-inferiority margin of -0.15 logCS. These results were confirmed by within-subject change analyses. Furthermore, comparisons of mean logCS values between postoperative visits yielded no statistically significant differences (p>0.05), indicating stability in CS through three years after surgery.

**Discussion**

**Floor effects in CS testing**

The floor and ceiling effects of the FACT chart are well-documented in the literature [13,17]. This study measured mesopic CS from 1.5 to 12 cd/p and photopic CS from 3 to 18 cd/p to maximize sensitivity and to minimize floor and ceiling effects in all conditions. This study further assigned a score of the lowest CS score minus 0.3 at each spatial frequency when a subject could not see any contrast patches to alleviate the impact of the floor effect and closely estimate the CS population means. This method was applied in similar sinusoidal grating contrast test such as CSV-1000 Contrast Testing Instrument [11,16]. Another method assigning half of the lowest logCS value to subjects with zero patches seen [12,18] uses the same principle even though deriving slightly different logCS scores. Some other methods to treat the floor effect could overestimate the group means if they exclude subjects who couldn’t see any patches or assign them with the lowest logCS score, and some other methods could underestimate the group means if they assign those subjects a zero value.

**CS after KAMRA inlay surgery**

The results showed some mild reductions at the highest spatial frequencies in monocular CS following KAMRA inlay surgery, but showed CS maintained in low to intermediate spatial frequencies in monocular CS conditions and across all spatial frequencies in binocular conditions. Additionally, the postoperative CS was maintained within normative range established from preoperative means in all CS conditions throughout 36 months. These results were generally comparable to a report on another presbyopia-correcting intra-corneal device [19]. Whitman et al. reported that there was some CS loss in the Raindrop Near Vision Inlay (“Raindrop”) eye at high spatial frequencies (-0.19 logCS at 12 cd/p and -0.23 logCS at 18 cd/p) in monocular photopic condition and a smaller loss at high spatial frequencies in monocular mesopic condition. That study [19] also measured CS using Optec 6500 Vision Tester but did not specify how they scored subjects who could not see any patches to account for the floor effect. The postoperative CS loss in KAMRA inlay eyes was smaller compared to Raindrop eyes in the photopic condition, and was a little bigger in mesopic conditions. This reversed impact from lighting condition can be explained by the different mechanisms of action of these two inlays: KAMRA inlay is a 3.8 mm opaque annular ring with a 1.6 mm central aperture and provides extended depth of focus from near through far by restricting unfocused light from reaching the retina; Raindrop Near Vision Inlay is a 2 mm meniscus-shaped inlay whose volume biomechanically raises anterior corneal surface over the inlay and it creates a profocal power profile to provide near vision in the most steeply curved central area, intermediate vision around the central area, and distance vision.

| Binocular Mesopic without glare |
|---------------------------------
| 1.5 | 1.62 | 1.8 | 1.82 | 1.8 | 1.48 | 2.17 |
| 3   | 1.96 | 1.96 | 1.97 | 1.94 | 1.62 | 2.3 |
| 6   | 1.96 | 1.92 | 1.94 | 1.91 | 1.56 | 2.36 |
| 12  | 1.52 | 1.48 | 1.49 | 1.47 | 0.99 | 2.05 |

| Binocular Mesopic with glare |
|-------------------------------
| 1.5 | 1.65 | 1.61 | 1.63 | 1.6 | 1.2 | 2.1 |
| 3   | 1.79 | 1.76 | 1.79 | 1.75 | 1.34 | 2.24 |
| 6   | 1.8 | 1.74 | 1.74 | 1.72 | 1.33 | 2.28 |
| 12  | 1.37 | 1.28 | 1.3 | 1.32 | 0.75 | 1.98 |

**Note:** The lower and upper normative values are derived from preoperative logCS means ± 1.96 standard deviations at each spatial frequency. The standard deviations are generally between 0.15 to 0.30 logCS and are not presented [15]. Copyright 2016 by SLACK Incorporated. Adapted with permission.
in the periphery beyond approximately a 3-mm diameter [19]. Theoretically, KAMRA inlay eyes may experience only a very mild impact on distance vision and photopic distance CS due to diffraction from the 1.6 mm central aperture, similar to the report of constricted pupils mildly reducing CS [20], and the reduced illumination on the retina in KAMRA inlay eyes may additively exemplify its impact on CS under low light. In comparison, Raindrop inlay implanted corneas are multifocal, similar to central multifocal LASIK [21], with an area of central corneal steepening splitting light energy between near and far and inducing approximately 1 diopter myopic shift along with negative spherical aberration [22]. As shown in simulations, this hydrogel inlay creates a pupil-dependent trade-in image quality in exchange for enhanced depth of focus [23] similar to what has been found with center near multifocal contact lenses [24] thus affects distance vision and photopic distance CS. With this optical design, however, the negative impact on CS may be less evident under mesopic conditions where the pupil enlarges, because distance vision is viewed through the periphery of the cornea, that is, the area of available peripheral distance zone increases with larger pupils and as a result reduces the loss of mesopic distance CS [19].

The CS results in KAMRA inlay eyes appear to be on the same scale as those after other corneal refractive surgeries. Significant and prolonged CS reduction was reported after radial keratotomy (RK) and photorefractive keratectomy (PRK) through six months or even one year after surgery [25,26]. Some CS reduction after laser in situ keratomileusis (LASIK) was reported from 6 to 18 cpd in one month postoperative while showing the most loss at 12 cpd [27]. When compared to intraocular lens (IOL), KAMRA inlay subjects demonstrated better monocular CS than multifocal IOL eyes and better binocular CS than multifocal IOL subjects and Crystalens Advanced Optics accommodative IOL subjects [28].

Conclusion

We established the CS normative values in monocular and binocular mesopic with and without glare conditions for the young presbyopia population based on a large sample. We demonstrated that the mild reductions in monocular CS in KAMRA inlay eyes were within the normative ranges and were comparable to those from other presbyopia-correcting procedures such as shape-changing corneal inlay [19]. Binocular CS in KAMRA inlay subjects were well maintained after surgery and CS has been stable through three years postoperatively. Practitioners in the ophthalmic care community can use these results as reference CS curves for their patients if their patients are in similar age range and are being measured with sinusoidal grating contrast-based test such as FACT CS chart.

References

1. Pesudovs K, Marsack JD, Donnelly WJ, Thibos LN (2004) Applegate RA. Measuring visual acuity–mesopic or photopic conditions, and high or low contrast letters? J Refract Surg 20: 5508-514.
2. Ginsburg AP (2003) Contrast sensitivity and functional vision. Int Ophthalmol Clin 43: 5-15.
3. Elliott DB (1987) Contrast sensitivity decline with ageing: a neural or optical phenomenon? Ophthalmic Physiol Opt 7: 415-419.
4. Elliott D, Whitaker D, MacVeigh D (1990) Neural contribution to spatiotemporal contrast sensitivity decline in healthy ageing eyes. Vision Res 30: 541-547.
5. Drum B, Calogero D, Rorer E (2007) Assessment of visual performance in the evaluation of new medical products. Drug Discov Today Technol 4: 55-61.
6. Holden BA, Fricke TR, Ho SM (2008) Global vision impairment due to uncorrected presbyopia. Arch Ophthalmol 126: 1731-1739.
7. Benjamin JW (1998) Borish’s Clinical Refraction. Refraction (1st Ed). WB Saunders Company, Philadelphia, pp 109-115.
8. Yilmaz OF, Bayraktar S, Agca A, Yilmaz B, McDonald MB (2008) Intracorneal inlay for the surgical correction of presbyopia. J Cataract Refract Surg 34: 1921-1927.
9. Seyeddaei O, Bacherneeg A, Riha W (2013) Femtosecond laser-assisted small-aperture corneal inlay implantation for corneal compensation of presbyopia: two-year follow-up. J Cataract Refract Surg 39: 234-241.
10. Ginsburg AP, Evans DW, Cannon MW Jr, Owseley C, Mulvanny P (1984) Large-sample norms for contrast sensitivity. Am J Optom Physiol Opt 61: 80-84.
11. Pomerance G, Evans D (1994) Test-retest reliability of the CSV-1000 contrast test and its relationship to glaucoma therapy. Invest Ophthalmol Vis Sci 35: 3357-3361.
12. Hohberger B, Laemmer R, Adler W, Juennemann AG, Horn FK (2007) Measuring contrast sensitivity in normal subjects with OPTEC 6500: influence of age and glare. Graefes Arch Clin Exp Ophthalmol 245: 1805-1814.
13. Hong YT, Kim SW, Kim EK, Kim T (2010) Contrast sensitivity measurement with 2 contrast sensitivity tests in normal eyes and eyes with cataract. J Cataract Refract Surg 36: 547-552.
14. Waring GO (2011) 4th. Correction of presbyopia with a small aperture corneal inlay. J Refract Surg 27: 842845.
15. Lin L, van de Pol C, Vilupuru S, Pospel JS (2016) Contrast Sensitivity in Patients with Emmetropic Presbyopia before and after Small-Aperture Inlay Implantation. J Refract Surg 32: 386-393.
16. Chua BE, Mitchell P, Cumming RG (2004) Effects of cataract type and location on visual function: the Blue Mountains Eye Study. Eye (Lond) 18: 765-772.
17. Pesudovs K, Hazel CA, Doran RM, Elliott DB (2004) The usefulness of Vistech and FACT contrast sensitivity charts for cataract and refractive surgery outcomes research. Br J Ophthalmol 88: 11-16.
18. Larsson E, Rydberg A, Holmström G (2006) Contrast sensitivity in 10 year old preterm and full term children: a population based study. Br J Ophthalmol 90: 87-90.
19. Whitman J, Dougherty PJ, Parkhurst GD, Olkowski J, Slade SG (2016) Treatment of Presbyopia in Emmetropes Using a Shape-Changing Corneal Inlay: One-Year Clinical Outcomes. Ophthalmology 123: 466-475.
20. Arden GB, Jacobson JJ (1978) A simple grating test for contrast sensitivity: preliminary results indicate value in screening for glaucoma. Invest Ophthalmol Vis Sci 17: 23-32.
21. Arba Mosquera S, Alió JL (2014) Presbyopic correction on the cornea. Eye Vis (Lond) 13: 1-5.
22. Whang WJ, Yoo YS, Joo CK, Yoon G (2017) Changes in Keratometric Values and Corneal High Order Aberrations After Hydrogel Inlay Implantation. Am J Ophthalmol 173: 98-105.

23. Steinert RF, Schwiegerling J, Lang A, Roy A, Holliday K (2015) Range of refractive independence and mechanism of action of a corneal shape-changing hydrogel inlay: results and theory. J Cataract Refract Surg 41: 1568-1579.

24. Kim E, Bakaraju RC, Ehrmann K (2017) Power Profiles of Commercial Multifocal Soft Contact Lenses. Optom Vis Sci 94: 183-196.

25. Ghaith AA, Daniel J, Stulting RD, Thompson KP, Lynn M (1998) Contrast sensitivity and glare disability after radial keratotomy and photorefractive keratectomy. Arch Ophthalmol 116: 12-18.

26. Dutt S, Steinert RF, Raizman MB, Puliafito CA (1994) One-year results of excimer laser photorefractive keratectomy for low to moderate myopia. Arch Ophthalmol 112: 1427-1436.

27. Mutyala S, McDonald MB, Scheinblum KA, Ostrick MD, Brint SF (2000) Contrast sensitivity evaluation after laser in situ keratomileusis. Ophthalmology 107: 1864-1867.

28. Vilupuru S, Lin L, Pepose JS (2015) Comparison of Contrast Sensitivity and Through Focus in Small-Aperture Inlay, Accommodating Intraocular Lens, or Multifocal Intraocular Lens Subjects. Am J Ophthalmol 160: 150-162.