**Long-term outcomes after LASIK using a hybrid bi-aspheric micro-monovision ablation profile for the surgical compensation of presbyopia: 6-year results.**

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Running head: Long-term outcomes of hybrid bi-aspheric micro-monovision profiles in presbyopia

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SYNOPSIS: The 6-years follow-up outcomes at far, intermediate and near distances confirm that presbyopic treatment using a hybrid bi-aspheric micro-monovision ablation profile is safe and efficacious. To increase satisfaction retreatments and reversal procedures shall be considered.

BACKGROUND/AIMS: To evaluate vision 6-years after hybrid bi-aspheric multifocal central presbyLASIK treatments.

Methods: Thirty-eight eyes of 19 patients consecutively treated with central presbyLASIK were assessed. The mean age of the patients was 51±3 years at the time of treatment with a mean spherical equivalent refraction of -0.57±1.98D and mean astigmatism of 0.58±0.57D. Monocular corrected distance visual acuity (CDVA), corrected near visual acuity (CNVA) and distance corrected near visual acuity (DCNVA) of non-dominant eyes; binocular uncorrected distance visual acuity (UDVA), uncorrected intermediate visual acuity (UIVA), distance corrected intermediate visual acuity (DCIVA) and uncorrected near visual acuity (UNVA) were assessed pre- and post-operatively. Subjective quality of vision and near vision was assessed using the 10-item, Rasch-scaled, Quality of Vision (QoV) and Near Activity Visual Questionnaires (NAVQ) respectively.

RESULTS: At six years post-operatively, mean binocular UDVA was 20/18±4; mean binocular UNVA and UIVA were 0.11±0.13logRAD and -0.08±0.08logRAD, respectively. Spherical equivalent showed a slow hyperopic drift of +0.1D per year with refractive astigmatism stable from 6 weeks postoperatively. Defocus curves show an improvement of 0.4 Snellen lines at best focus from year 1 to year 6 follow-up, reaching preoperative levels. Compared to the preoperative status, the corneal and ocular spherical aberrations (at a 6 mm diameter) decreased and were stable from 3 months follow-up. Questionnaires revealed a postoperative unaided QoV Score comparable to the preoperative corrected QoV Score, together with an improved postoperative unaided NAVQ Score compared to preoperatively.

CONCLUSIONS: Presbyopic treatment using a hybrid bi-aspheric micro-monovision ablation profile is safe and efficacious even after 6-years postoperatively. The post-operative outcomes indicate improvements in binocular vision at far, intermediate and near distances. An 8% retreatment rate should be considered to increase satisfaction levels, including a 3% reversal rate.

## Introduction

Presbyopia occurs when the physiological age-related reduction in the eyes focusing range reaches a point, when optimally corrected for distance vision, that the clarity of vision at near is insufficient to satisfy an individual's requirements.[1]
The etiology of the condition is predominantly attributed to a loss of elasticity of the crystalline lens, accompanied by a change in the ciliary muscle strength and lens curvature.[2] Corneal inlays and intraocular lenses have been used as a treatment for presbyopia.[3] Monovision techniques[4] usually involve correcting the dominant eye for distance as opposed to crossed monovision[5] where the dominant eye is corrected for near vision.

Multifocal ablations are designed to achieve a pseudo-accommodative cornea in the form of either a peripheral near zone (concentric ring for near vision)[6] or a central near zone (central disc for near vision).[7] PresbyLASIK is one such technique based on traditional laser-assisted in situ keratomileusis (LASIK) to correct the visual defect for distance while simultaneously reducing the near spectacle dependency in patients with presbyopia.[8] PresbyLASIK is considered a promising technology, but is less established when compared to traditional monovision strategies.[9] The goal of presbyopia refractive surgery is to provide patients with improved near vision without decreasing their distance vision. Previous approaches have failed for at least one of three reasons: the improvement in near vision was insufficient, the decrease in distance vision was not tolerated, or there was a lack of intermediate visual performance. A hybrid method combining micro-monovision and multifocal ablation could potentially achieve full range of vision.

Long term follow-ups after Presbyopic corrections are scarce in the literature, although they are essential to understand the effects and implications of increasing presbyopia with age as a negative impact on outcomes for presbyopia surgery. Further to that, so far it remains unknown whether the induced aberrations in multifocal/hyperprolate/aspheric ablations remain stable in the cornea in the long term.

In this work, an already established cohort of patients treated with a hybrid bi-aspheric micro-monovision technique[10] are followed-up for 6 years and the outcomes are retrospectively analyzed.

## METHODS

### *PATIENTS*

This cohort study was based on a consecutive case series of patients treated by a single surgeon (MHAL), with a hybrid bi-aspheric micro-monovision technique to correct presbyopia, at Bergman Oogzorg / VisionClinics, Utrecht, the Netherlands.[10] Signed informed consent was obtained from each patient, for both the treatment and use of their de-identified clinical data for publication. The Independent Review Board Nijmegen (IRBN) evaluated the study and stated that the investigation in this form is not subject to Medical Research Involving Human Subjects Act (WMO). Of the original cohort, 38 eyes (19 patients) completed the 6-year follow-up and were included for analyses. A summary of the preoperative demographics is presented in Table 1. The details of the cohort have been reported previously in detail.[10]

Table 1. Preoperative Demographics.

| | Mean | StdDev | min | MAX |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Age (years) | 51 | 3 | 45 | 55 |
| SEQ (D) | -1.01 | 2.56 | -6.75 | +2.00 |
| Cylinder (D) | 0.55 | 0.50 | 0 | 2.25 |
| Avg. K-Readings (D) | 42.8 | 1.5 | 39.5 | 45.4 |
| CDVA | 20/16 | 3 | 20/20 | 20/13 |
| Add (D) | 1.76 | 0.36 | 1.00 | 2.50 |
| Colvard Pupillometry (mm) | 5.8 | 0.8 | 4.0 | 7.5 |
| Planned OZ (mm) | 6.6 | 0.3 | 6.0 | 7.0 |

*POSTOPERATIVE EVALUATION*

Patients were reviewed at 66±1 months postoperatively (range 63 to 68 months [6 years]). The clinical follow-up at 1-year postoperatively has been reported previously.[10] The results presented in this work expand the clinical follow-up to 6 years, and compares them to the previous follow-up visits. The follow-up rates are presented in table 2. The 6-year (6Y) follow-up visit included measurements of monocular and binocular Uncorrected Distance Visual Acuity (UDVA), Uncorrected Near Visual Acuity (UNVA), Uncorrected Intermediate Visual Acuity (UIVA), manifest refraction, Corrected Distance Visual Acuity (CDVA), Distance Corrected Near Visual Acuity (DCNVA), Distance Corrected Intermediate Visual Acuity (DCIVA) and defocus curves. The response to the Quality of Vision and Near Activity Visual Questionnaires, topography and aberrometry, were also recorded. A full ophthalmologic examination was performed on all the patients. CDVA and UDVA were evaluated using the Early Treatment Diabetic Retinopathy Study (ETDRS) charts. Near and intermediate acuity were assessed both unaided and distance corrected (UNVA, DCNVA, UIVA and DCIVA), with the Dutch version of the Radner Reading Charts at 40cm and 80cm, respectively. All tests were conducted monocularly and binocularly.

Table 2. Follow-up rates.

| | Preoperative | 6-week | 3-month | 6-month | 1-year | 6-year |
|---|---|---|---|---|---|---|
| Patients (n) | 32 | 30 | 30 | 27 | 28 | 19 |
| Eyes (n) | 64 | 60 | 60 | 54 | 56 | 38 |
| Follow-up rate (%) | 100% | 94% | 94% | 84% | 88% | 59% |

The corrected visual acuity was always assessed with a phoropter. Binocular defocus curves were measured (with both eyes corrected for distance, i.e. eliminating the effect of the micro-monovision component) with induced lens blur from +1.5D to -4.0D in 0.5D randomized spherical steps, using distance ETDRS charts with the letters randomized between presentations and magnification effects being accounted for.[11]

Corneal and ocular aberrometry was performed with the OPD-Scan II (Nidek, Gamagori, Japan) over a 6mm diameter. Root mean square (RMS) higher order aberrations, Strehl ratio and corneal asphericity were extracted.

Subjective, patient reported outcomes were assessed using two questionnaires: the Quality of Vision questionnaire and the Near Activity Visual Questionnaire. The Quality of Vision questionnaire was developed by McAlinden et al.[12] to assess symptoms such as glare, halos, starbursts etc. with the use of simulation photographs. Symptoms are scored based on scales of symptom frequency, severity and bothersomeness. The questionnaire is valid for use with spectacle wearers, contact lens wearers, patients who have undergone laser refractive surgery, intraocular refractive surgery, or having eye disease including cataract.[13,14,15] The Near Activity Visual Questionnaire was used to assess patient satisfaction with near functional vision.[16] The questionnaire has been validated for use with spectacles, contact lenses and intraocular refractive surgery. Patients were instructed to answer the questionnaires to account their subjective impression in corrected conditions preoperatively and unaided conditions postoperatively.

*STATISTICAL ANALYSIS*

Data were assessed for normality using the Shapiro-Wilk test. Analysis of variance and t-tests were performed on normally distributed data and Friedman tests and *post-hoc* Wilcoxon signed-ranks tests when the data was not normally distributed. Distance visual acuity was measured in logMAR but converted to equivalent Snellen fractions for reporting comparability. Similarly, near visual acuity was evaluated in logRAD but converted to Jaeger scale for reporting comparability.

## RESULTS

*Standard graphs for Reporting Astigmatism Outcomes of Refractive Surgery*

At 6Y binocularly, 53% of the patients reached an UDVA of 20/16 or better (Fig 1A), for 95% of the patients UDVA remained within one line of preoperative CDVA (Fig 1B), no patient lost lines of CDVA (although 16% of the NE lost 2 lines of CDVA) (Fig 1C). At 6Y binocularly, 68% of the patients reached an UNVA of J2 or better (Fig 1D), for 47% of the patients UNVA remained within one line of preoperative CNVA (Fig 1E), no patient lost 2 lines of CNVA (although 21% of the DE and 11% of the NE lost 2 lines of CDVA) (Fig 1F).

At 6Y, the scattergram showed some 10% undercorrection in SEQ with 1D separation between DE and NE (Fig 1G), 74% of DE were within 0.5D from emmetropia and 58% of NE were within 0.5D from -0.9D target (Fig 1H), 89% and 74% of the eyes were within 0.5D of refractive astigmatism for DE and NE, respectively.

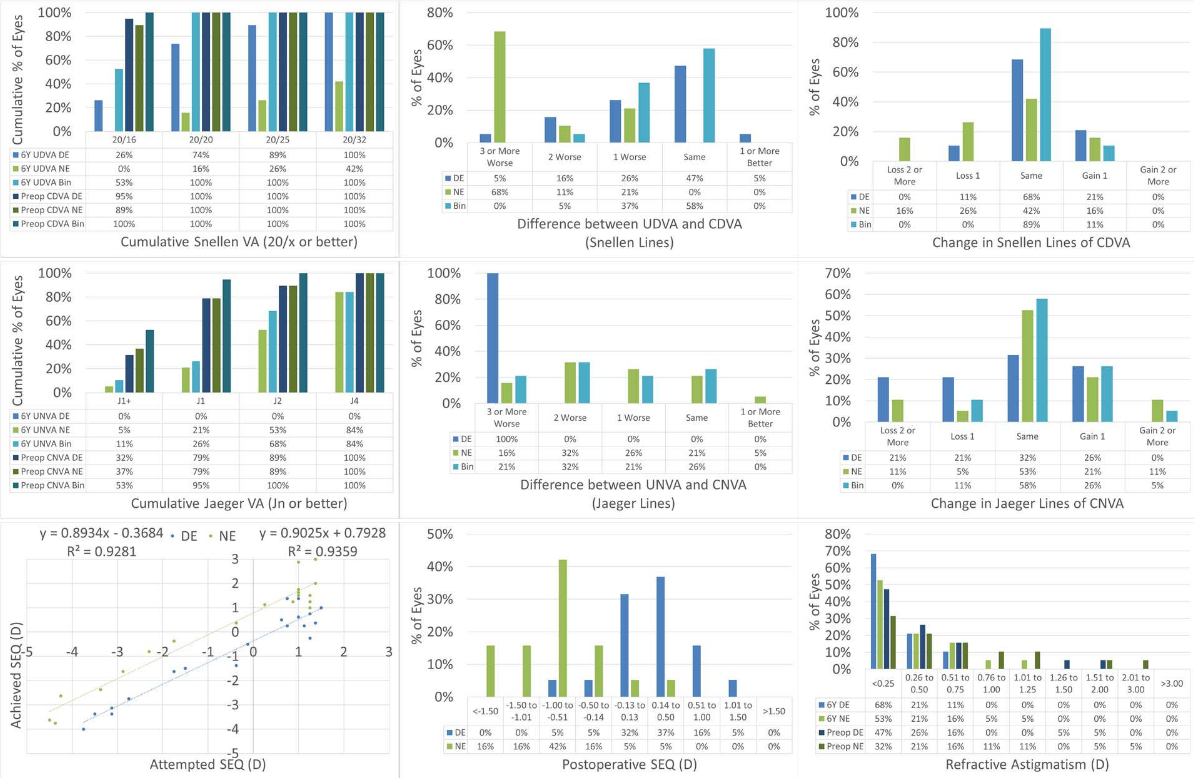


Fig. 1. Standard graphs for Reporting Astigmatism Outcomes of Refractive Surgery

*EFFICACY*

At 6Y, the mean monocular UDVA was 20/20±5 letters DE, 20/43±12 letters for NE, and 20/18±4 letters binocularly (Fig 2A). At 6Y, the mean UIVA was J3.2 for DE, J1.0 for NE, and J1.0 binocularly (Fig 2B). At 6Y, the mean UNVA was J8.5 for DE; J2.1 for NE; and J1.7 binocularly (Fig 2C).

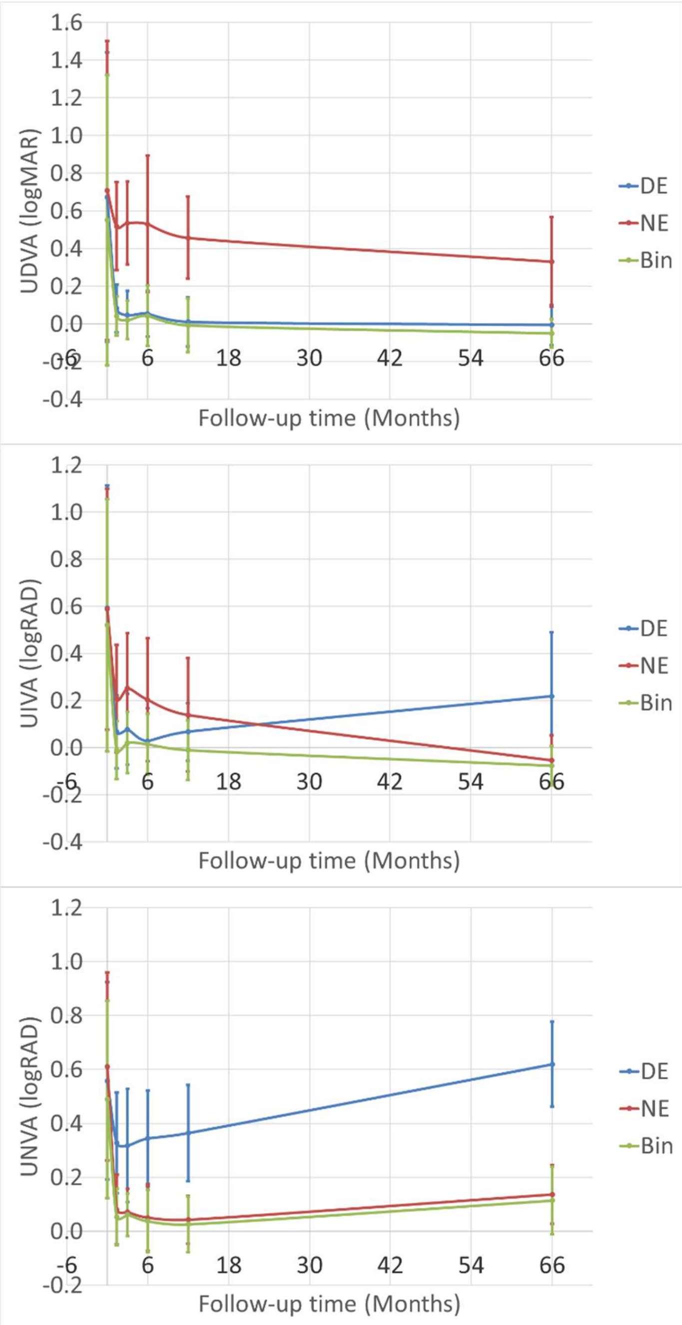



Fig. 2. *EFFICACY:* Mean uncorrected visual acuity up to 6-years follow up after treating with Hybrid bi-aspheric micro-monovision ablation profile for presbyopic corneal treatments. Top) UDVA Middle) UIVA Bottom) UNVA.

*ACCURACY*

Good refractive separation was observed between the DE and NE, for spherical equivalent and astigmatic error (figure 3). Spherical equivalent showed a +0.1D per year increase (hyperopic drift) (p=0.002) for DE and NE (Fig 3A). Refractive astigmatism was stable from 6W postoperatively (p=0.1) for DE and NE (Fig 3B).

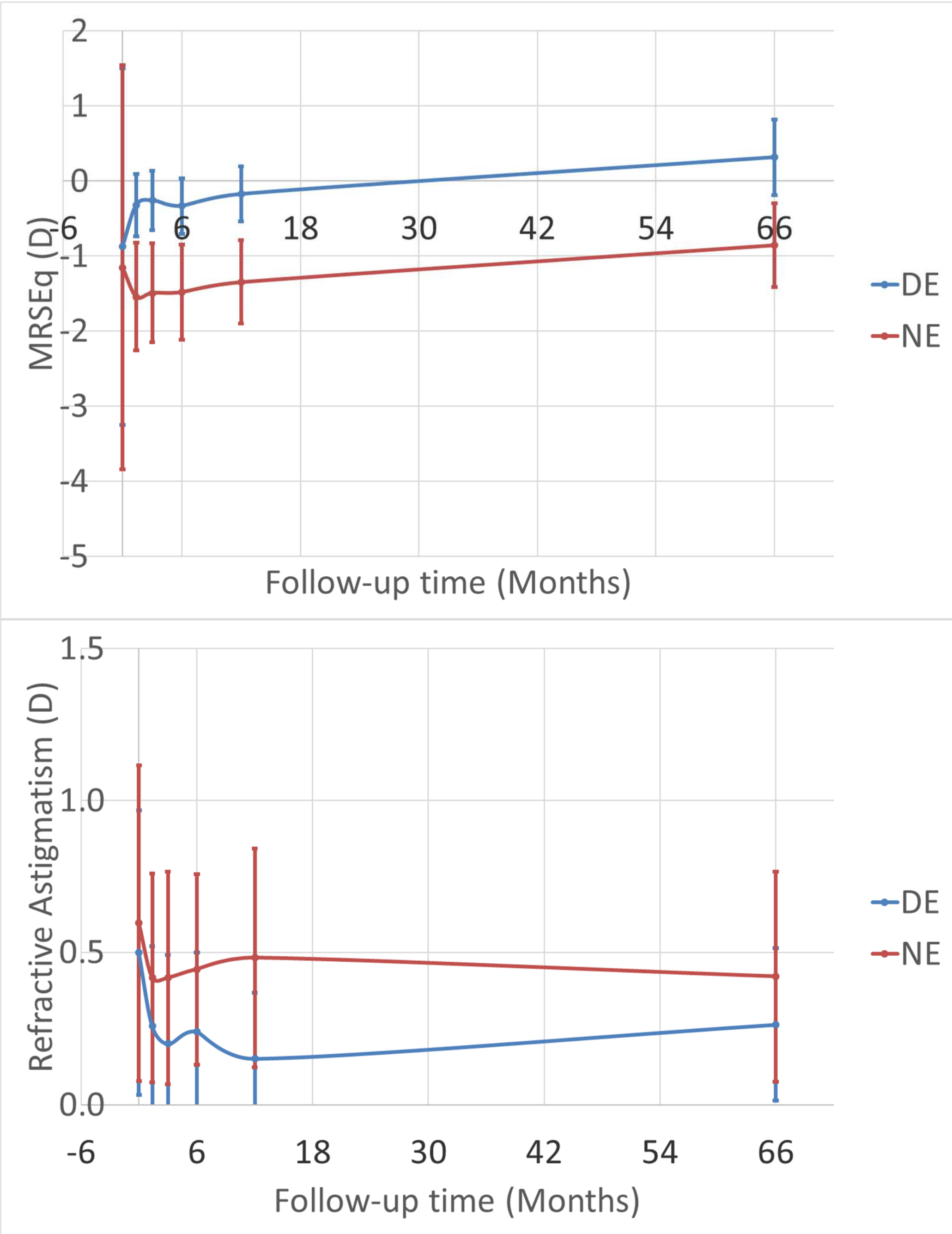



Fig. 3. *ACCURACY:* Mean manifest refraction assessed preoperatively, and up to 6 years follow up after treating with Hybrid bi-aspheric micro-monovision ablation profile for presbyopic corneal treatments. Top) MRSE Bottom) Refractive astigmatism.

*SAFETY*
At 6Y, mean CDVA was 20/15±3 letters for DE; 20/19±5 letters for NE; and 20/14±3 letters binocularly (Fig 4A). At 6Y, the mean CIVA was J1.0 for DE; J1.0 for NE; and J1.0 binocularly (Fig 4B). At 6Y, the mean CNVA was J2.2 for DE; J1.5 for NE; and J1.0 binocularly (Fig 4C).

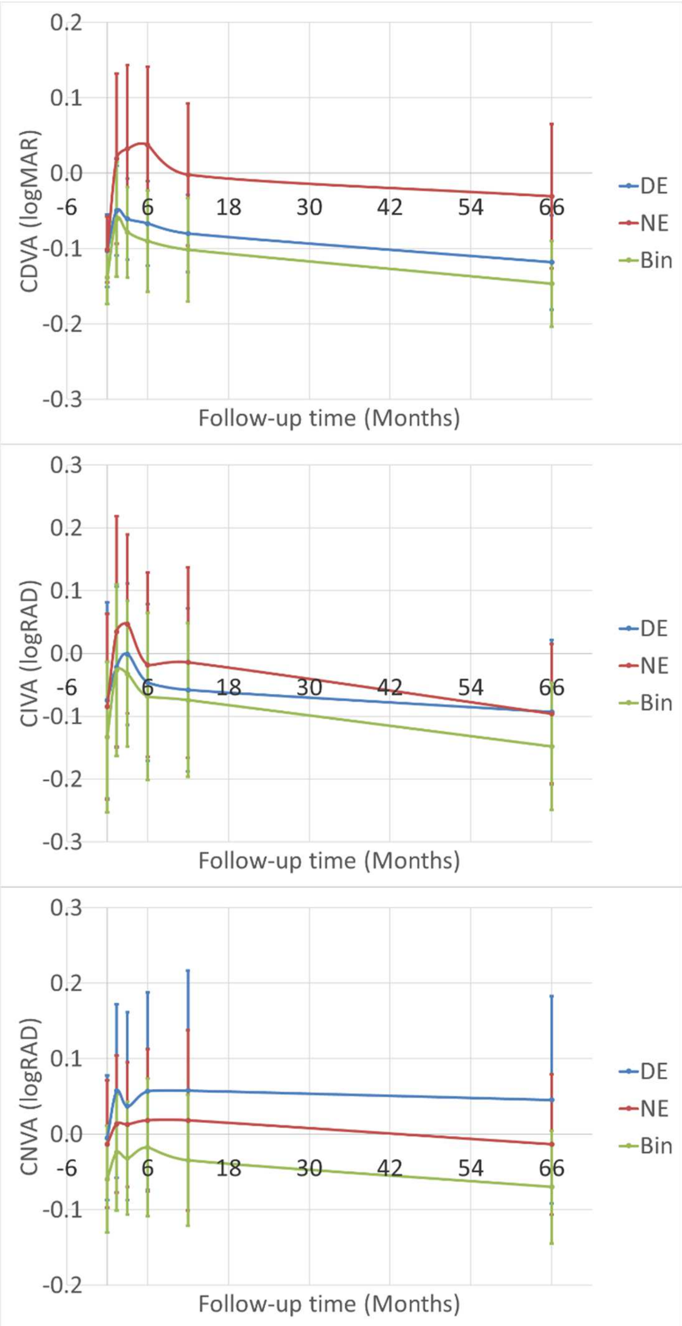



Fig. 4. *SAFETY:* Mean corrected visual acuity up to 6-years follow up after treating with Hybrid bi-aspheric micro-monovision ablation profile for presbyopic corneal treatments. Top) CDVA Middle) CIVA Bottom) CNVA.

*PSEUDOACCOMMODATION*
At 6Y, the mean DCIVA was J2.5 for DE; J1.8 for NE; and J1.1 binocularly (Fig 5A).  At 6Y, the mean DCNVA was J8.5 for DE; J5.4 for NE; and J4.7 binocularly (Fig 5B).

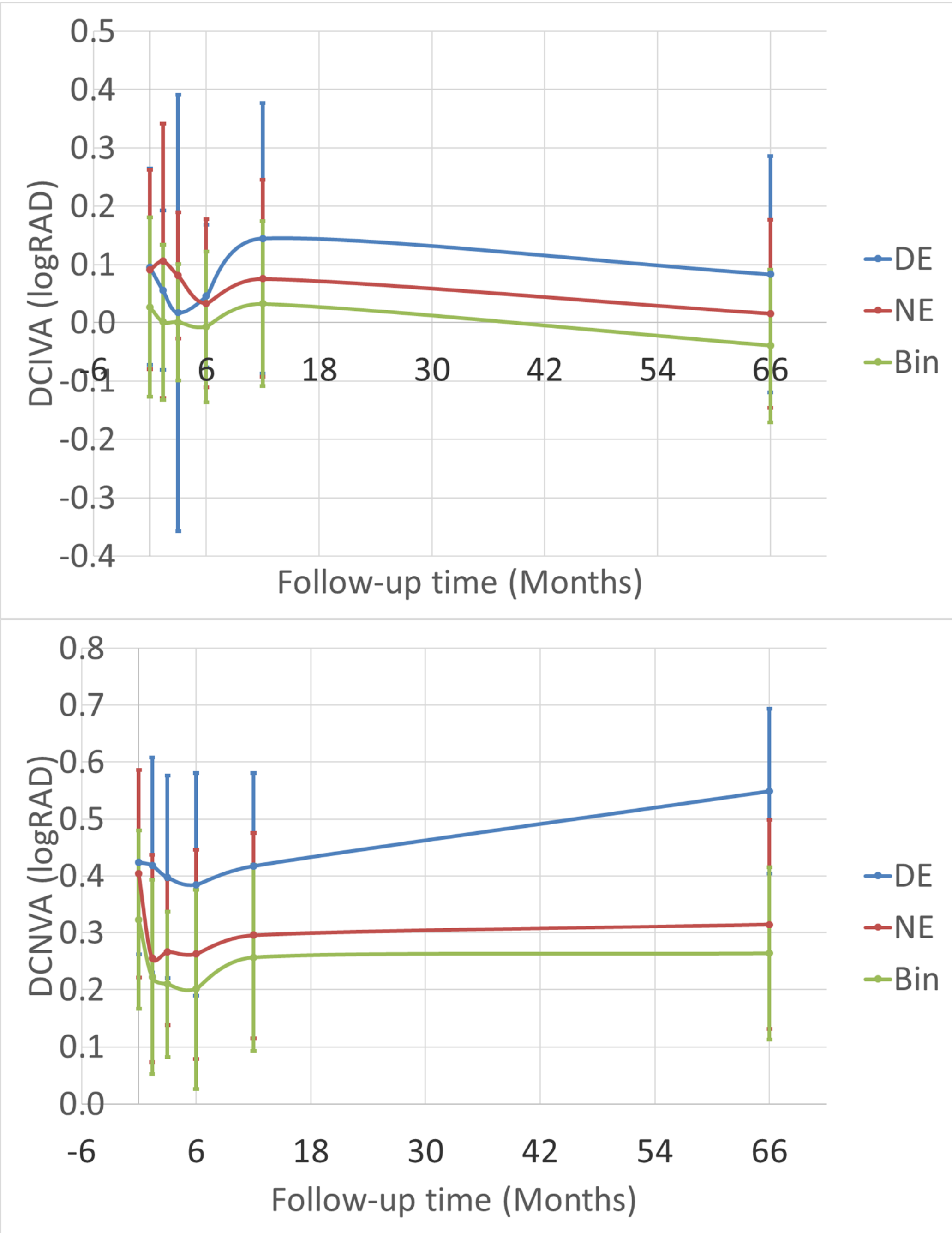



Fig. 5. *PSEUDOACCOMMODATION:* Mean distance corrected visual acuity up to 6-years follow up after treating with Hybrid bi-aspheric micro-monovision ablation profile for presbyopic corneal treatments. Top) DCIVA Bottom) DCNVA.

*DEFOCUS CURVES*

Binocular defocus curves (preoperatively and at 1 and 6 years follow-up) are presented in figure 6. The difference in defocus curves shows an improvement of 0.4 Snellen lines at best focus from 1Y to 6Y follow-up (p=0.008), reaching preoperative levels (p=0.5).

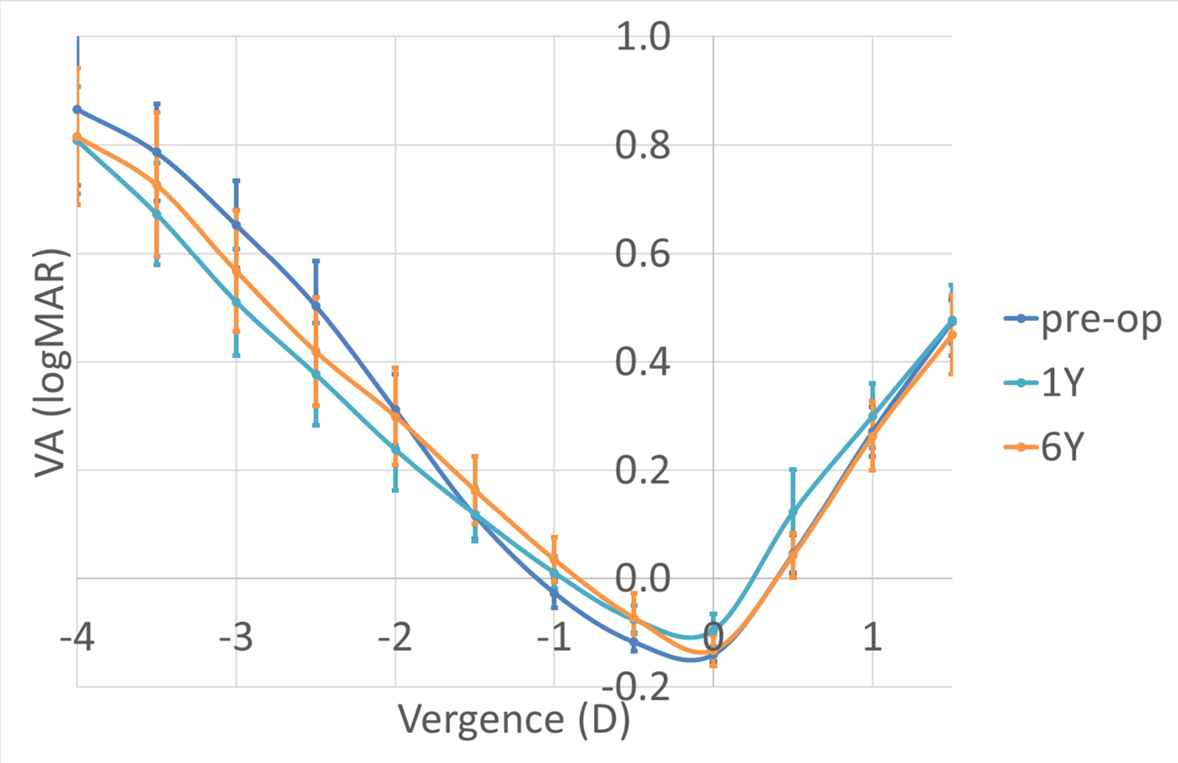



Fig. 6. *DEFOCUS CURVES:* Binocular defocus curves from uncorrected vision asymmetrically to longer (+1.5D) and shorter vergences (-4.0D), assessed preoperatively and at one and six years follow up after treating with Hybrid bi-aspheric micro-monovision ablation profile for presbyopic corneal treatments. The error bars represent the upper and lower 95% confidence limits of the mean of measurements, preoperatively.

*ABERRATIONS*

Asphericity was more prolate after surgery indicating central myopia (within a 3mm diameter, p=0.0003 for OPD-Scan II but not for Pentacam, p=0.4). Throughout the follow-up, asphericity became less prolate (0.03 units per year, p=0.01 for OPD-Scan II but not for Pentacam, p=0.1) (Fig 7A). Compared to the preoperative status, the corneal and ocular spherical aberrations (at ~5.4 mm diameter, Fig 7B) decreased (p=0.0005) and were stable from 3M follow-up (p=0.1) (Fig 7C), with an increase in RMS higher order aberrations (at a 6 mm diameter) (p=0.05) stable from 3M follow-up (p=0.1) (Fig 7D).

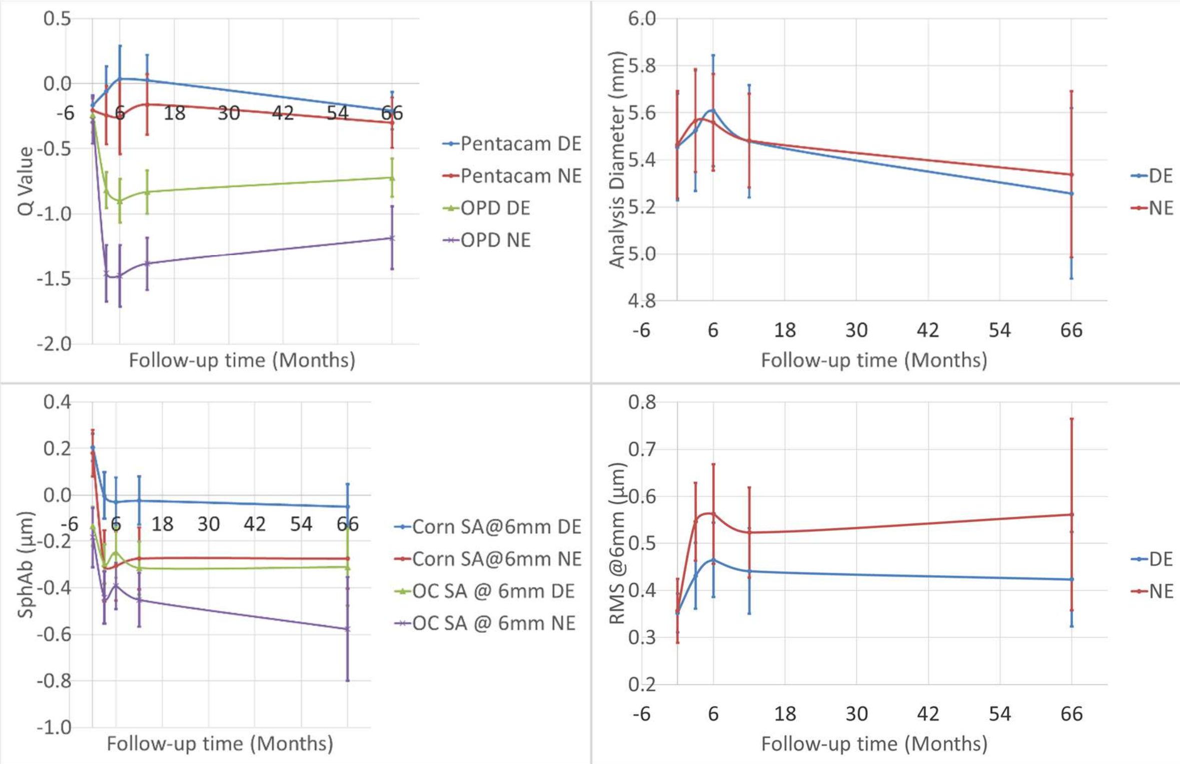
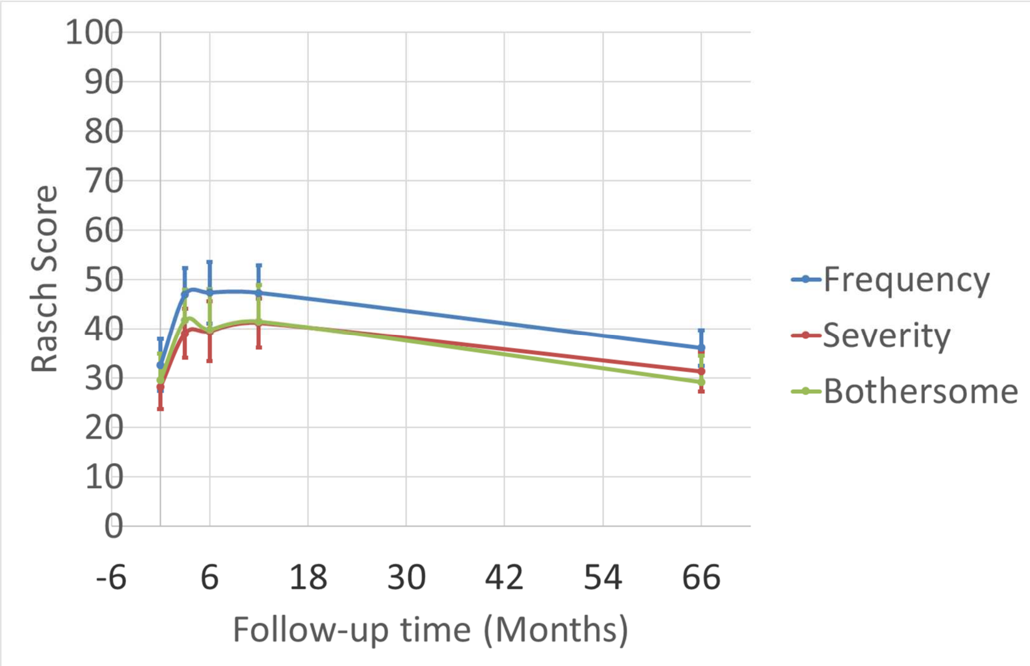



Fig. 7. *ABERRATIONS:* Corneal asphericity (Q value) at 3mm diameter, Root mean square (RMS) of higher order aberrations (at 6mm diameter), corneal and ocular spherical aberrations (Corn SA and OC SA respectively, at 6mm diameter) preoperatively, and up to six years follow up after treating with Hybrid bi-aspheric micro-monovision ablation profile for presbyopic corneal treatments. Top Left) Corneal asphericity Top Right) Analysis diameter for ocular aberrations Bottom Left) Spherical aberration Bottom Right) RMS HOA.

*SUBJECTIVE RATING*

Compared to the corrected preoperative scores, the Quality of Vision at 6Y was comparable to preoperative for all questionnaire items (p=0.1), but improved from 1Y scores mainly with a reduction in reported haloes (p=0.01) and blurred vision (p=0.03) (Table 3). Composite Rasch-scaled scores are displayed in Fig. 8 (Top). Scores continue to improve up to 6Y, returning to preoperative levels.

Compared to the preoperatively, at 6 Y follow up, The Near Activity Visual Questionnaire scores improved from little to high satisfaction level for all items (p=0.002), however, the scores for reading small print, medicine and food packaging, bank statements, writing letters, and conducting near work worsened from 1Y postoperatively to 6Y follow up (p=0.04) (Table 4). Overall scores are displayed in Fig. 8 (Bottom). Scores worsened between 1Y and 6Y, but symptoms remained well below the preoperative levels.



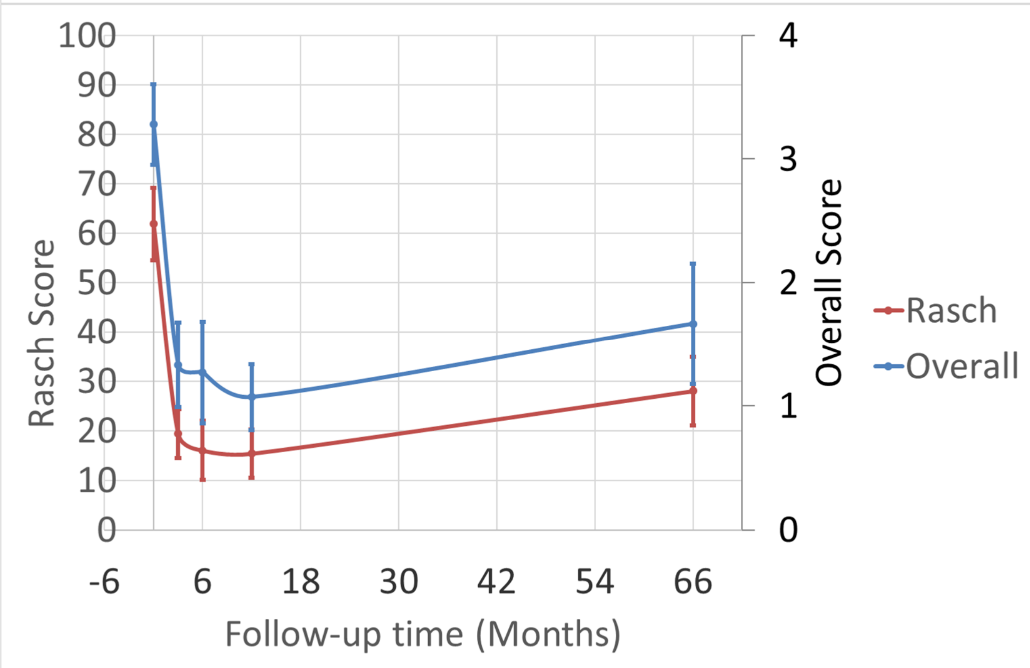




Fig. 8. *SUBJECTIVE RATING:* Patient Reported Outcomes assessed preoperatively, and up to 6 years follow up after treating with Hybrid bi-aspheric micro-monovision ablation profile for presbyopic corneal treatments. Top) QoV Questionnaire Bottom) NAVQ Questionnaire.

Table 3. QoV Questionnaire.

| QoV | Item | Frequency | | | | | Severity | | | | | Bothersome | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Preop | 1Y | 6Y | p Preop vs 6Y | p 1Y vs 6Y | Preop | 1Y | 6Y | p Preop vs 6Y | p 1Y vs 6Y | Preop | 1Y | 6Y | p Preop vs 6Y | p 1Y vs 6Y |
| **1** | Glare | 0.5±0.7 | 0.7±0.8 | 0.5±0.6 | 0.1 | 0.3 | 0.5±0.7 | 0.9±0.9 | 0.7±0.9 | 0.4 | 0.4 | 0.5±0.7 | 0.7±0.8 | 0.6±0.7 | 0.4 | 0.4 |
| **2** | Haloes | 0.3±0.4 | 1.0±0.7 | 0.3±0.5 | 0.4 | **0.005** | 0.3±0.5 | 1.1±0.9 | 0.4±0.7 | 0.5 | **0.01** | 0.3±0.4 | 0.9±1.0 | 0.3±0.4 | 0.4 | **0.004** |
| **3** | Starburst | 0.5±0.7 | 0.6±0.7 | 0.4±0.6 | 0.3 | 0.5 | 0.5±0.7 | 0.6±0.7 | 0.4±0.6 | 0.2 | 0.3 | 0.4±0.5 | 0.4±0.9 | 0.2±0.4 | 0.1 | 0.4 |
| **4** | Hazy Vision | 0.2±0.4 | 0.4±0.6 | 0.1±0.3 | 0.1 | 0.1 | 0.2±0.4 | 0.4±0.7 | 0.2±0.4 | 0.2 | 0.2 | 0.2±0.4 | 0.4±0.7 | 0.1±0.3 | 0.1 | 0.1 |
| **5** | Blurred Vision | 0.6±0.7 | 1.3±1.0 | 0.6±0.5 | 0.4 | 0.1 | 0.6±0.7 | 1.4±1.1 | 0.6±0.5 | 0.4 | 0.08 | 0.5±0.7 | 1.3±1.1 | 0.4±0.5 | 0.2 | **0.03** |
| **6** | Distortion | 0.1±0.2 | 0.1±0.3 | 0.1±0.2 | 0.2 | 0.2 | 0.1±0.2 | 0.1±0.3 | 0.1±0.2 | 0.2 | 0.2 | 0.1±0.2 | 0.1±0.3 | 0.1±0.2 | 0.2 | 0.2 |
| **7** | Multiple Images | 0.1±0.2 | 0.5±0.8 | 0.1±0.2 | 0.5 | **0.05** | 0.1±0.2 | 0.5±0.8 | 0.1±0.2 | 0.5 | **0.05** | 0.1±0.2 | 0.5±0.8 | 0.1±0.2 | 0.5 | **0.05** |
| **8** | Fluctuations | 0.5±0.6 | 0.9±0.7 | 0.6±0.6 | 0.4 | 0.4 | 0.6±0.8 | 1.0±0.8 | 0.6±0.6 | 0.2 | 0.2 | 0.6±0.8 | 0.9±0.8 | 0.5±0.6 | 0.1 | 0.2 |
| **9** | Focusing Difficulties | 0.9±0.6 | 1.3±0.7 | 1.0±0.0 | 0.2 | 0.3 | 0.9±0.6 | 1.2±0.7 | 1.0±0.3 | 0.2 | 0.2 | 0.9±0.6 | 1.1±0.9 | 0.9±0.4 | 0.1 | 0.4 |
| **10** | Depth Perception | 0.4±0.5 | 0.5±0.6 | 0.5±0.6 | 0.4 | 0.4 | 0.3±0.5 | 0.5±0.6 | 0.5±0.7 | 0.4 | 0.3 | 0.4±0.6 | 0.5±0.6 | 0.5±0.6 | 0.4 | 0.4 |
| | Rasch Score | 33±5 | 47±6 | 36±4 | 0.3 | 0.1 | 28±5 | 41±5 | 31±4 | 0.3 | **0.05** | 30±5 | 42±7 | 29±5 | 0.1 | 0.1 |

Table 4. NAVQ Questionnaire.

| NAVQ | Item | Preop | 1Y | 6Y | p Preop vs 6Y | p 1Y vs 6Y |
|---|---|---|---|---|---|---|
| **1** | Reading small print, such as newspaper articles, items on a menu, telephone directories? | 1.9±1.0 | 0.3±0.5 | 0.7±0.8 | **0.0003** | **0.01** |
| **2** | Reading labels/instructions/ingredients/prices, such as on medicine bottles, food packaging? | 2.2±1.0 | 0.4±0.5 | 1.1±0.9 | **0.002** | **0.002** |
| **3** | Reading your post/mail, such as electric bills, greeting cards, bank statements, letters from friends and family? | 1.9±1.1 | 0.1±0.3 | 0.4±0.6 | **0.0000009** | **0.03** |
| **4** | Writing and reading your own writing, such as greeting cards, notes, letters, filling in forms, checks, signing your name? | 1.6±1.0 | 0.0±0.0 | 0.2±0.4 | **0.0000002** | **0.02** |
| **5** | Seeing the display and keyboard on a computer or calculator? | 1.8±0.9 | 0.3±0.5 | 0.4±0.6 | **0.00008** | 0.09 |
| **6** | Seeing the display and keyboard on a mobile or fixed telephone? | 2.0±1.0 | 0.2±0.4 | 0.6±0.7 | **0.00009** | 0.06 |
| **7** | Seeing objects close to you and engaging in your hobbies, such as | 1.6±0.9 | 0.0±0.2 | 0.2±0.4 | **0.000000005** | 0.08 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | playing card games, gardening, seeing photographs? | | | | | |
| **8** | Seeing objects close to you in poor or dim light? | 1.8±0.9 | 0.6±0.6 | 0.8±0.8 | **0.00006** | 0.08 |
| **9** | Maintaining focus for prolonged near work? | 1.5±0.9 | 0.4±0.6 | 0.6±0.7 | **0.0001** | 0.3 |
| **10** | Conducting near work without spectacles? | 1.8±1.1 | 0.2±0.4 | 0.6±0.9 | **0.0002** | **0.04** |
| **11** | Overall Score | 3.3±0.3 | 1.1±0.3 | 1.7±0.5 | **0.0002** | **0.05** |
| | Rasch Score | 62±7 | 15±5 | 28±7 | **0.000003** | **0.01** |

*RETREATMENTS*

Secondary treatment was performed in 3 eyes (3 patients: 8% from the 38 eyes, but 16% of the patients) to improve distance outcomes. The secondary treatments were performed using a non-wavefront guided aspheric treatment to alter the distance refraction to the desired value. One of them (3% from the 38 eyes, but 5% of the patients) was combined with a partial presby reversal treatment to reduce the effects of the primary treatment, due to the patient's perceived intolerance (mainly loss of CDVA) to the induced multifocality. The details about the reversal of this technique and corresponding aberrations and topography changes have been published elsewhere.[17] All retreatments were performed between 6-months and 1-year after the initial treatment. No further retreatments were performed after 1Y postop, and no retreated eyes required a further retreatment.

## DISCUSSION

This case series analyzed the long term longitudinal changes up to 6Y follow-up of the efficacy and safety of presbyopic treatment using a hybrid bi-aspheric micro-monovision ablation profile. This technique aims to combine the benefits of multifocal ablations and micro-monovision with enhanced depth of focus and a wider range of intermediate vision. The analysis revealed very stable long-term results after the treatment. The binocular vision was expected to improve overall, with NE imparting an improvement in NAVQ scores and the DE imparting an improvement in QoV scores. Most of the outcome measures showed significant improvement compared to the preoperative status. The improvement in visual acuities was significant. In addition, analyzing the NAVQ responses revealed an improvement in all the topics from little (pre-operative) to high (post-operative) satisfaction. Although, it would be interesting to know the profile of the defocus curves monocularly for the presbyopic eyes; this was not part of the study protocol. However, the defocus curves with both eyes corrected for distance, i.e. eliminating the effect of the micro-monovision component, revealed an improvement of half a Snellen line at the best focus for distance compared to 1Y follow-up, reaching preoperative levels, but an overall loss compared to 1Y at near vergences. Monocularly, it would be expected that the defocus curves would be shallower, with refractive separation between the dominant and non-dominant eye. Defocus curves were assessed with trial lenses additive to the distance refraction while observing the ETDRS distance charts. This means that the naturally occurring pupil miosis (enhancing depth of focus) has been eliminated from the measurements, and actual reading and intermediate acuities may actually be better than those obtained in the defocus curves.

As often found in long-term follow-up studies, the number of patients attending the different follow-ups was not constant, the analyses performed was both based on a paired comparison (i.e. only the subset patients attending all follow-ups) as well as unpaired comparisons (i.e. comparing the mean and standard errors for the different follow-ups). Both analyses revealed the same trends. The main concern, however, remains in the relatively high loss to follow-up of 41% from preoperative, or 32% from 1-year follow-up baseline. The potential impact of this loss to follow-up is difficult to be assessed. Clearly, this reduced follow-up rate decreases the statistical power of the analyses, i.e. the probability of making a type II error (wrongly failing to reject the null hypothesis) increases.

UDVA was stable for DE (from 6W postoperatively) and binocularly (from 6M postoperatively) and continued to improve for NE through the years. Whereas for UIVA there was a worsening effect with time for DE, with an improvement for NE and binocular through the years observed. For UNVA, there was a global loss of effectiveness through the years. This corresponds well with the progression of MRSE with time moving from -0.17±0.37D at 1Y to +0.32±0.51D at 6Y for DE, and from -1.35±0.56D at 1Y to -0.86±0.56D at 6Y for NE. Refractive astigmatism was stable from 6W follow-up. Also the additional help of true accommodation will decrease over time.

A good separation in the refractive outcome was observed between the DE and NE, for spherical equivalent corresponding to the planned micro-monovision. DE drove binocular UDVA, and NE binocular UNVA. For UIVA, DE and NE crossed over at around 2Y postop but binocular UIVA remained stable. This cross-over was due to the slow drift in refraction observed for both DE and NE. Until 1Y follow-up, DE (slightly myopic and with moderate depth of focus) drove binocular UIVA (NE was more myopic with larger depth of focus), whereas at 6Y DE (slightly hyperopic and with moderate depth of focus) could no longer drive binocular UIVA, but NE (less myopic than at 1Y with larger depth of focus) covered better the intermediate region.

CDVA continued to improve during the 6Y follow-up reaching preoperative levels, whereas CIVA and CNVA reached preoperative levels at 6M follow-up and remained stable thereafter. Corrected VA was normal for DE and NE at all distances and follow-up times. DE drove binocular (C)DVA and (C)IVA (likely due to the hybrid approach, inducing half of the spherical aberration (SphAb) in DE, i.e. inducing less detrimental effects in distance and intermediate visions), and NE binocular (C)NVA.

Pseudoaccommodation, measured as IVA and NVA with distance correction, reached at least preoperative levels and remained stable from 6W postop, except for DCNVA in DE (at 6Y worse than preoperative, and decreased 0.2 lines per year). NE drove binocular DCIVA and DCNVA (likely due to the hybrid approach, inducing twice as much SphAb in NE, i.e. inducing higher gains in intermediate and near visions).

Asphericity was more prolate when measured with the OPD-Scan II than the values measured with the Pentacam. Postoperative asphericities were more prolate than preoperatively (indicating central myopia), with NE showing systematically more negative asphericities at all postoperative times, and a slight trend of losing hyperprolateness with time only measured by the OPD-Scan II (but not with the Pentacam, and also not confirmed by the SphAb).

Aberrations were induced across a 6mm corneal diameter, but ocular aberrations could only be measured through the pupil so that the actual values of analysis diameter were in the range of 5.4±0.2mm (stable throughout time). SphAb was more negative when measured with ocular aberrations than for corneal aberrations. Postoperative SphAb was more negative than preoperative (indicating central myopia), with NE showing systematically more negative values at all postoperative times (both for corneal and ocular SphAb), remaining (apparently) stable from 3M follow-up. The RMS higher order aberrations increased, with NE showing systematically higher inductions HOA at all postoperative follow-ups. Both the induction of SphAb (corneal or ocular, for DE or NE), as well as the postoperative ocular SphAb for NE were within -0.6µm. This level has been reported previously as the maximum compromise between the gain in near visual acuity versus the loss in distance visual acuity,[18] although newer assessments have suggested that with a 0.2µm induction, there is a just noticeable impact in perceived image quality.[19]

Binocular defocus curve at 6Y of follow-up seems to lie between the preoperative and 1Y postoperative defocus curves. Actually, it seems that there was a (not significant) loss of VA for shorter vergences compared to 1Y follow-up, despite the fact that SphAb (and HOA) was largely stable from 3M follow-up. This may indicate that for the long term, the micro-monovision component is more relevant in influencing the near visual performance of the patient than the induction of HOAs. Defocus curves contradict this: wider curves indicate pseudoaccommodation which must be a HOA effect. So decrease in near vision must be due to decrease in true accommodation.

QoV scores at 6Y were comparable to preoperative scores for all questionnaire items, and the previously reported haloes and blurred vision symptoms at 1Y resolved at 6Y. NAVQ scores assessing patient satisfaction with near functional vision improved for all items from preoperative, but the scores for reading small print, medicine and food packaging, bank statements, writing letters, and conducting near work worsened from 1Y postoperative (confirming the UNVA and defocus curve findings). There may be potential adjustments in the surgical goals or some other approach to remedy this complication. Surgeons may decide to increase the monovision effect (-0.9D in this work) to -1.25D or -1.5D to further strengthen NVA; alternative options could be to increase the depth of focus (+2.2D for NE in this work) to +2.5D or +2.75D (at the expense of a longer adaptation time for the recovery of UDVA). Both alternatives could be equally combined with near vision training.

Leydolt et al.[20] showed that near vision training made patients more independent of reading glasses. This was made by comparing a “motivated” group (instructed not to use reading glasses for at least three months) to a “control” group. On questioning the patients with a questionnaire, which was also done in an observer-masked fashion, it was found that the motivated group reported significantly better scores for near vision tasks without glasses. Additionally, the motivated group had a proportion of 40% (8patients) that never used glasses at the one year interview compared with none in the control group. Authors concluded that either impeding the use of reading glasses in the first months after surgery or motivation enhances near visual performance and results in a higher degree of spectacle independence. Therefore, studies that examine presbyopia treating strategies, such as accommodating IOLs, corneal presbyopic ablations, or multifocal IOLs, should not underestimate this ‘placebo’ effect of patient motivation that is present all the time. Whether this effect holds for longer terms (6 years in our cohort) remains unclear. But this may be reinforced with training strategies.[4]

All retreatments performed between 6-months and 1-year follow-ups after the initial treatment were reported previously.[10] One late retreatment was bilaterally performed after 6Y postop (hyperopic PRK in both eyes of 1 patient, NE was emmetropic, DE was hyperopic), but no retreated eyes required a second retreatment.

Many clinical studies have evaluated various surgical techniques to treat presbyopia; however the current developments throughout the corneal presbyopic correction spectrum indicate a converging trend towards hybrid techniques. These hybrid modifications include: Supracor™ (TECHNOLAS Perfect Vision GmbH),[21] PresbyMAX (reduced multifocality in the distance eye combined with full multifocality and monovision in the near eye),[10] Intracor (full correction in the distance eye combined with multifocality and monovision in the near eye),[22] KAMRA™ (AcuFocus, Inc.) (full correction in the distance eye combined with pinhole based extended depth-of-focus and monovision in the near eye),[23] Presbyond™ (Carl Zeiss Meditec AG) (laser blended vision (moderate multifocality in both eyes combined with monovision in the near eye)),[24] and refractive corneal inlays (e.g. Raindrop™ from ReVision Optics, USA; now withdrawn from the market).[25]

Methods depending only on the depth of focus might face difficulty to create more than 1.5D of range of focus, providing spectacle independence. In contrast, models combining µ-monovision with depth of focus may provide a higher near vision independence. Since, presbyopia increases with age, a wide range of near vision shall be an asset in such cases. In addition, the difference in the depth of focus between the near and far eye provides the patient with a wider binocular range of focus for an enhanced intermediate vision.

Corneal topography and aberrometery revealed an induction of negative SphAb in corneal and ocular spherical aberrations, associated with an increase in the RMS higher order aberrations. Furthermore, QoV responses revealed a recovery to preoperative (using correction glasses) levels for all items, including improvement in terms of haloes and blurred vision post-operatively compared to the patient responses at 1Y follow-up. The presented clinical outcomes are based on 6 years of clinical follow-up, which is considered long-term in refractive surgery. However, presbyopia increases with age. Therefore, even longer follow-ups could shed light on the durability of performance during further degradation of accommodation.

Other techniques reported long-term outcomes, but all shorter than 6Y. This includes intrastromal femtosecond laser presbyopia (3-years, showing a refractive progression of 0.13D per year),[22] intracorneal pinhole inlays (5-years),[23,26] or conductive keratoplasty (3-years, showing a refractive progression of 0.13D per year),[27]. From our cohort, as well as previous reports for other techniques, it seems that 0.13D per year is a reasonable estimate of the presbyopic progression at the considered ages (in our case ~51 year old at the time of treatment). Further, it seems that this presbyopic progression is not truly a corneal regression, but lenticular changes (corneal curvature did not change postoperatively in our cohort, as well as with conductive keratoplasty[27]).

The depth of focus acts as a useful marker, however, some studies consider acuity at a typical near vision distance as a more suitable metric that is closely related to patient expectations and concerns.[28] Our analysis and results indicate significant success in presbyopic treatments using the hybrid bi-aspheric micro-monovision ablation profiles. Presbyopic treatment using a hybrid bi-aspheric micro-monovision ablation profile is safe and efficacious. The post-operative outcomes indicate improvements in binocular vision at far, intermediate and near distances with improved contrast sensitivity. An 8% retreatment rate should be considered to increase satisfaction levels, with a 3% reversal rate.

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