Title: Optimising measurement of subjective amplitude of accommodation with defocus curves

Running Head: Measurement of accommodation with defocus curves

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Abstract

PURPOSE: Defocus curves are a popular method of evaluating subjective amplitude of accommodation (AoA) of presbyopia correction techniques including multifocal and 'accommodating' intraocular lenses. This study determined whether letter sequences and/or lens presentation order ought to be randomised when measuring defocus curves and also assessed the most appropriate criterion for calculating subjective AoA from defocus curves.

SETTING: Optometry Clinic, School of Life & Health Sciences, Aston University, Birmingham, UK.

METHODS: Defocus curves (from +3.00DS to -3.00DS in 0.50DS steps) for six possible combinations of randomised or non-randomised letter sequences and/or lens presentation order, were measured in a random order on twenty presbyopic subjects. Subjective AoA was calculated from the defocus curves by curve fitting using various published criteria and each was correlated to subjective push-up AoA. Objective AoA was measured to enable comparison of blur tolerance to pupil size.

RESULTS: Randomisation of lens presentation order and/or letter sequences, or lack of, did not affect the measured defocus curves (ANOVA, $p>0.05$). The range of defocus that maintains highest achievable visual acuity (VA) (allowing for variability of repeated measurement) was better correlated to ($r=0.84$) and agreed best with (± 0.50D) subjective push-up AoA than any of the other relative or absolute acuity criteria used in previous studies.

CONCLUSION: Non-randomised letters and lens presentation on their own did not affect subjective AoA measured by defocus curves, although their combination should be avoided.

Quantification of subjective AoA from defocus curves ought to be standardised to the range of defocus that maintains highest achievable VA.

Defocus curves are a popular method of evaluating the subjective range of clear vision in presbyopic correction techniques such as ‘accommodating’ and multifocal intraocular lenses (IOLs). The alternative more physical approach of actually measuring visual acuity (VA) at different distances from the eye can often be impractical. Optical alteration of the focal demand to view a distant object by placing lenses in front of the eye and then measuring the VA with each particular lens, using a letter chart with a regular progression of letter sizes (such as those based on logMAR),[1] has been shown to be a repeatable and reliable method of measuring the amplitude of accommodation (AoA).[2,3] However, this approach has also been shown to over-estimate the AoA in comparison to the more physical method,[4] possibly due to minification effects of negative lenses, but primarily due to an increase in depth of focus (DoF) through inevitable pupil miosis from the stimulation of the near triad.[5]

Memory effects can also influence the outcomes of defocus curve measurements if appropriate methodology of presenting letter sequences on acuity charts and the order of lens presentation are not used, as has been shown in pre-presbyopes.[6] In particular, letters may have been visible and then memorised at an earlier viewing of the chart in the presentation sequence. However, most studies that have used defocus curves to evaluate presbyopic correction techniques (Tables 1 and 2) have failed to acknowledge the methodology used or have used potentially inaccurate methodology that may have lead to over- or under-estimations of the AoA.

The evaluation of AoA from defocus curves also varies considerably with the criteria used to define ‘clear vision’.[32, 33] Criteria can either be *relative*, referring to a range of object vergences that is associated with the best level of VA (line A, Figure 1), or *absolute*, referring to a range of object vergences through which VA is considered ‘adequate’ (line B, Figure 1).[34] Furthermore, these criteria have also been applied to positive as well as negative lens stimulated defocus (lines C and D for relative and absolute criteria respectively, Figure 1), despite the former portion of the curve not relating to active eye focus provided the eye is refracted to maximal plus. This general lack of consistency (Tables 3 and 4), results in difficulty in comparing findings between studies.

Given the appropriateness of carrying out randomisation in clinical research to minimise bias from learning effects and adaptation in observed results,[41] the purpose of this study was to investigate the effect of non-randomisation of letter sequences and/or lens presentation order in measuring defocus curves and to determine the most appropriate criterion to then calculate the subjective AoA.

Methods

Informed consent was obtained from all participants following explanation of the nature and possible consequences of the study, and ethical approval was obtained from the Ethical Committee of Aston University. Twenty presbyopic subjects (average age 54.3±4.7 years, range 46 to 63 years) were first screened to exclude any ocular disease and then refracted using a phoropter. The principal of maximum plus without a reduction in VA at 6 metres was used to ensure the best-corrected VA was achieved (mean –0.10±0.08 logMAR, range –0.20 to 0.06 logMAR) and to eliminate latent hyperopia. No subject had an accommodative abnormality or astigmatism greater than 0.75DC.

Six defocus curves, each corresponding to the different combinations of randomised or non-randomised letter sequences and/or randomised or non-randomised (positive or negative) lens progression were measured in random order on one eye only of each subject for a defocus range of +3.00DS to -3.00DS (0.50DS steps). Lenses were presented in the same phoropter and all VAs were measured with a computerised Logarithm of the Minimum Angle of Resolution (LogMAR) chart (David Thomas Chart 2000, IOO marketing, London, UK) at 6 metres; the chart is based on the optimised principals of Bailey and Lovie.[1] Between each lens presentation, the eye was occluded so that the subject was not aware of which lens had been inserted and whether the letters on the chart had been changed or not. Although natural variability in repeated VA measures is likely to occur, it has been reported to be small in adults (±0.036 logMAR).[42]

Subjects were only prompted once for each VA measure, to ensure consistency of encouragement, by using only the phrase "*can you read any more letters on the line below?*" once when the subject stopped reading the letters on the chart. All measurements for all subjects were taken under the same conditions, in the same consulting room and under consistent illumination (500 lux), according to the required standards for VA testing.[43]

The defocus curve obtained by the most appropriate method, as determined from this first part of this study, was then analysed for each of the 20 individual subjects to evaluate the subjective AoA for the various criteria utilised by previous studies (identified in Tables 3 and 4). The subjective AoA was compared for each subject to (a) subjective push-up AoA, measured with a RAF rule (Clement Clarke International Ltd., Harlow, UK),[44] (b) objective range of focus as assessed by the maximum negative shift in objective refraction measured with a Shin-Nippon SRW-500 autorefractor (Ajinomoto Trading Inc., Japan) as the subject monocularly viewed a target within a Badal system between 0.0D and 5.0D (1.0D steps) of accommodative demand, with their best correction, and (c) the subject's pupil size (average of 3 readings) measured with a millimetre scale from a 10 times magnified image with the subject viewing a distant target.

Statistical Analysis

All defocus curve acuities were corrected for spectacle magnification. All defocus curves for each individual combination in turn were analysed by a single factor Analysis of Variance (ANOVA) to ensure that none of the subjects were statistically significantly different to other subjects. A two-factor ANOVA was then used to determine whether there was an overall statistically significant difference between the mean defocus curves obtained from each of the six combinations. A pair-wise comparison of each combination to each and every other combination in turn was conducted using a two-factor ANOVA, to determine if any single combination yielded a statistically significantly different defocus curve to any other combination. A Bonferroni adjustment for multiple comparisons was made (significant $p<0.0033$ for 15 pair-wise comparisons) to minimise the risk of a Type 1 statistical error.[45]

The subjective AoA calculated from the defocus curves by curve-fitting were compared to subjective push-up AoA by calculating Two-way Random Effects Intra-class Correlation Coefficients (ICC) and Bland-Altman limits of agreement[46] for each of the various criteria. Blur thresholds were then calculated as the difference between the subjective AoA (for each defocus curve criterion and push-up test) and the objective range of focus, and these were correlated (Pearson's Product Moment Correlations, PPMC) to pupil size.

Results

There was no significant difference in the mean defocus curves for each of the six methodologies (two-factor repeated measures ANOVA: $F=1.34$, $p=0.24$). Compared to the presumed optimal methodology of randomised letter sequences between each presentation and randomised lens presentation order, the other methods generally resulted in *lower* visual acuities (Figure 2). Error bars are not shown to allow for greater clarification; standard deviation between subjects at each level of defocus was ±0.15 logMAR (range 0.08 to 0.23 logMAR).

Due to the lack of statistical significance, subjective AoA was evaluated for each of the subjects from the defocus curve measured by combination 6; through maximal randomisation this combination represents best clinical practice. All of the best fit regression curves fitted the measured defocus curves to a high accuracy ($r>0.99$ on all occasions). The relationship between defocus curve AoA and push-up AoA for each of the criteria investigated are shown in Figure 3 and in Figure 4 for negative defocus only. Corresponding means, standard deviations, PPMC coefficients, significance values, ICCs and Bland-Altman limits of agreement are shown for all criteria in Table 5. Mean push-up AoA was 1.35 ± 0.47D (range 0.66 to 2.50D).

Table 5 reveals that the 'Best VA' criterion had the strongest correlation ($r=0.84$; $p<0.001$) and smallest Bland-Altman limits of agreement (±0.50DS) to push-up AoA. Two other criteria, 'Best VA with negative defocus only' and 'Best VA + 0.1 logMAR', produced similar but poorer limits of agreement and statistical significance. Although the latter provided the highest concordance, no criterion produced concordance above 75%. Correlations of blur thresholds (for each of the defocus curve criteria and for push-up AoA) with pupil size are shown in Table 6. Mean pupil size of all subjects under normal test conditions (500 lux) was 3.67 ± 0.38mm (range 3.2 to 4.5mm) and the mean objective AoA was 0.39 ± 0.40D (range 0.00 to 1.19D). All of the relative defocus curve criteria yielded the expected weak correlation with pupil size, which were comparable to the subjective push-up method ($r=0.02$).

Discussion

Defocus curves are a popular method of assessing the amplitude of accommodation (AoA) as part of the evaluation of presbyopic correction techniques such as 'accommodating' IOLs and multifocal IOLs. However, there is little consistency in the methodology employed for the measurement of defocus curves, which can potentially lead to inaccurate quantification of the AoA. No study has previously investigated the need for randomisation of letter sequences on acuity charts and/or lens presentation order in the measurement of defocus curves in presbyopes, nor has the most appropriate criteria for evaluation of AoA from defocus curves been determined.

Statistical analysis revealed no significant difference between the six possible combinations of presenting letter sequences on acuity charts and the order of lenses when measuring defocus curves. Further analysis failed to identify any statistically significant difference between any pairs of individual combinations. Intuitively, one would consider the defocus curve measurement in which both the letter sequences and the lens presentation order are not randomised (combinations 1 and 2) to be prone to memory effects. In these combinations, the presentation of further defocus *after* the apex (best VA) has been reached could result in the subject repeatedly reading the line corresponding to their highest achievable VA, if this is committed to memory, regardless of whether they are actually able to read it or not. This effect, noted in prepresbyopes,[6] did not occur, perhaps due to higher honesty or poorer short-term memory. However, it is apparent that given the possibility for *individual* evaluations to be over-estimated in this manner, the combination of non-randomised letter sequences and presentation of lenses from negative to positive defocus is best avoided. In particular the desire to restore the AoA with new presbyopic correction techniques, such as 'accommodating' IOLs, to a considerable amount of the pre-presbyopic level means that such presbyopic subjects could be prone to greater memory effects similar to those seen in pre-presbyopic subjects.[6]

Subjective assessments of AoA incorporate a patient's blur tolerance (DoF).[44] This blur tolerance is dependent on pupil size, since DoF is known to decrease with increasing pupil size.[47] However, spherical aberrations increase with increasing pupil size, which can counteract this effect. Although all but the absolute criteria in this study yielded measurements of subjective AoA that were weakly correlated to pupil size (r = -0.19 to r = -0.01), only one criterion was identified as providing clinically acceptable limits of agreement for AoA compared to the push-up test; *the range of defocus (both positive and negative) for which the best level of VA can be maintained*. This criterion provides, in clinical terms, a definition that is intuitive to the measure of 'range of clear vision' since only the best VA, including an allowance for natural variability in repeated VA measures of approximately ±0.04 logMAR,[42, 48] can be considered as 'clear vision'. All other criteria include some element of visual function that is well above the acuity threshold (i.e. assessment against letter sizes that are larger than the best VA), which can be considered as falsely improving the range through an artificial blur tolerance. Indeed this is demonstrated by the stronger correlations of blur thresholds with pupil size, derived from the absolute defocus curve criteria (Table 6).

It is likely that the lower values of AoA obtained from defocus curves using this criterion, compared to subjective push-up AoA, is due to differences in the target used. Under this criterion defocus curves use a fixed target size throughout the measurement whereas the push-up test is subject to variation in target size due to an increase in angular subtense as the text is brought closer to the subject. Indeed blur tolerance is estimated to range only between 0.1-0.2D[49] but varies with refractive error[50, 51] and target size.[52] Additionally, the push-up test may be more prone than defocus curve measurements to proximal effects that lead to pupil miosis and therefore an increased DoF.

A standardised criterion, best VA plus 0.04 logMAR to allow for the variance in repeated measures of VA, should be used for the quantification of subjective AoA from defocus curves. A linear progression chart must be used, such as one based on logMAR, and the measured acuities corrected for magnification effects. Indeed this criterion means that the measurement can be implemented in a short space of time since measurements need only be made until VA has been reduced beyond this level as opposed to a full range of negative and positive lenses. Deterioration in acuity with positive defocus confirms the correct end point in refraction and allows curve fitting. Curve fitting can be performed in most graphical packages with the resulting accurate equations ($r>0.99$) used to calculate the subjective AoA. Just determining the interval of the defocus levels for which the criteria were met, or extending this by linear fitting of the defocus levels to where the acuity dropped below the criteria, resulted in a lower correlation and poorer limits of agreement with the push-up AoA.

The findings of this study have potential implications on the research reviewed in Tables 1 to 4. For example, it appears that Heatley et al.[11] for the 1CU accommodating IOL and

Weghaupt et al.[22, 24] for the Array multifocal IOL may have over-estimated the AoA of by measuring defocus curves without apparently randomising letter sequences and by presenting lenses in a sequential order. Errors in the quantification of AoA from defocus curves may also have been made due to the criteria used. The criterion suggested by this study as being the most appropriate has only been used in a few studies, whilst the majority have used a criterion that extends beyond the resolution limit. As a result, these studies are likely to have over-estimated the true range of clear vision due to artificially set visual requirement. For example, Sauder et al.[12] quantified the AoA of the 1CU 'accommodating' IOL 6 months after implantation as 1.01±0.40D, using a relative criterion of 'best VA', whilst Küchle et al.[9] quantified the AoA of the same 'accommodating' IOL after the same period of time as 1.85±0.43D, using an absolute criterion of '0.40 logMAR' (20/50 Snellen VA). Naturally differences in study design may be accountable for some difference in the measured amplitudes, but the varying criteria is likely to be the substantial cause.

Conclusion

The methodology of implementing a defocus curve measurement should be standardised by randomising at least one or both the letter sequences on acuity charts and/or the order in which lenses are presented. Furthermore, quantification of the AoA from defocus curves ought to include only the range of defocus for which the level of best VA can be maintained, as assessed by curve fitting, with an allowance made to account for natural variation in repeated VA measures.

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References

1. Bailey IL, Lovie JE. New design principles for visual acuity letter charts. Am J Optom Physiol Opt 1976; 53:740-745
2. Langenbucher A, Huber S, Nguyen NX, et al. Measurement of accommodation after implantation of an accommodating posterior chamber intraocular lens. J Cataract Refract Surg 2003; 29:677-685
3. Langenbucher A, Seitz B, Huber S, et al. Theoretical and measured pseudophakic accommodation after implantation of a new accommodative posterior chamber intraocular lens. Arch Ophthalmol 2003; 121:1722-1727
4. Pieh S, Kellner C, Hanselmayer G, et al. Comparison of visual acuities at different distances and defocus curves. J Cataract Refract Surg 2002; 28:1964-1967
5. Myers GA, Stark L. Topology of the near response triad. Ophthalmic Physiol Opt 1990; 10:175-181
6. Gupta N, Naroo SA, Wolffsohn JS. Is randomisation necessary for measuring defocus curves in pre-presbyopes? Cont Lens Anterior Eye 2007; 30:119-124
7. Legeais JM, Werner L, Werner L, et al. Pseudoaccommodation: BioComFold versus a foldable silicone intraocular lens. J Cataract Refract Surg 1999; 25:262-267
8. Langenbucher A, Huber S, Nguyen NX, et al. Cardinal points and image-object magnification with an accommodative lens implant (1 CU). Ophthalmic Physiol Opt 2003; 23:61-70
9. Kuchle M, Seitz B, Langenbucher A, et al. Comparison of 6-month results of implantation of the 1CU accommodative intraocular lens with conventional intraocular lenses. Ophthalmology 2004; 111:318-324
10. Marchini G, Pedrotti E, Sartori P, Tosi R. Ultrasound biomicroscopic changes during accommodation in eyes with accommodating intraocular lenses: pilot study and hypothesis for the mechanism of accommodation. J Cataract Refract Surg 2004; 30:2476-2482
11. Heatley CJ, Spalton DJ, Hancox J, et al. Fellow eye comparison between the 1CU accommodative intraocular lens and the Acrysof MA30 monofocal intraocular lens. Am J Ophthalmol 2005; 140:207-213
12. Sauder G, Degenring RF, Kamppeter B, Hugger P. Potential of the 1 CU accommodative intraocular lens. Br J Ophthalmol 2005; 89:1289-1292
13. Hancox J, Spalton D, Heatley C, et al. Objective measurement of intraocular lens movement and dioptric change with a focus shift accommodating intraocular lens. J Cataract Refract Surg 2006; 32:1098-1103

14. Macsai MS, Padnick-Silver L, Fontes BM. Visual outcomes after accommodating intraocular lens implantation. J Cataract Refract Surg 2006; 32:628-633
15. McLeod SD. Optical principles, biomechanics, and initial clinical performance of a dual-optic accommodating intraocular lens (an American Ophthalmological Society thesis). Trans Am Ophthalmol Soc 2006; 104:437-452
16. Ossma IL, Galvis A, Vargas LG, et al. Synchrony dual-optic accommodating intraocular lens. Part 2: pilot clinical evaluation. J Cataract Refract Surg 2007; 33:47-52
17. Marchini G, Mora P, Pedrotti E, et al. Functional Assessment of Two Different Accommodative Intraocular Lenses Compared with a Monofocal Intraocular Lens. Ophthalmology 2007. In press
18. Post CT, Jr. Comparison of depth of focus and low-contrast acuities for monofocal versus multifocal intraocular lens patients at 1 year. Ophthalmology 1992; 99:1658-1664
19. Steinert RF, Post CT, Jr., Brint SF, Fritch CD, et al. A prospective, randomized, double-masked comparison of a zonal-progressive multifocal intraocular lens and a monofocal intraocular lens. Ophthalmology 1992; 99:853-861
20. Knorz MC, Claessens D, Schaefer RC, et al. Evaluation of contrast acuity and defocus curve in bifocal and monofocal intraocular lenses. J Cataract Refract Surg 1993; 19:513-523
21. Auffarth GU, Hunold W, Wesendahl TA, Mehdorn E. Depth of focus and functional results in patients with multifocal intraocular lenses: a long-term follow-up. J Cataract Refract Surg 1993; 19:685-689
22. Weghaupt H, Pieh S, Skorpik C. Visual properties of the foldable Array multifocal intraocular lens. J Cataract Refract Surg 1996; 22 Suppl 2:1313-1317
23. Walkow T, Liekfeld A, Anders N, et al. A prospective evaluation of a diffractive versus a refractive designed multifocal intraocular lens. Ophthalmology 1997; 104:1380-1386
24. Weghaupt H, Pieh S, Skorpik C. Comparison of pseudoaccommodation and visual quality between a diffractive and refractive multifocal intraocular lens. J Cataract Refract Surg 1998; 24:663-665
25. Arens B, Freudenthaler N, Quentin CD. Binocular function after bilateral implantation of monofocal and refractive multifocal intraocular lenses. J Cataract Refract Surg 1999; 25:399-404
26. Jacobi FK, Kammann J, Jacobi KW, et al. Bilateral implantation of asymmetrical diffractive multifocal intraocular lenses. Arch Ophthalmol 1999; 117:17-23

27. Walkow L, Klemen UM. Patient satisfaction after implantation of diffractive designed multifocal intraocular lenses in dependence on objective parameters. Graefes Arch Clin Exp Ophthalmol 2001; 239:683-687
28. Kamlesh, Dadeya S, Kaushik S. Contrast sensitivity and depth of focus with aspheric multifocal versus conventional monofocal intraocular lens. Can J Ophthalmol 2001; 36:197-201
29. Leyland MD, Langan L, Goolfee F, et al. Prospective randomised double-masked trial of bilateral multifocal, bifocal or monofocal intraocular lenses. Eye 2002; 16:481-490
30. Tsorbatzoglou A, Nemeth G, Math J, Berta A. Pseudophakic accommodation and pseudoaccommodation under physiological conditions measured with partial coherence interferometry. J Cataract Refract Surg 2006; 32:1345-1350
31. Toto L, Falconio G, Vecchiarino L, et al. Visual performance and biocompatibility of 2 multifocal diffractive IOLs Six-month comparative study. J Cataract Refract Surg 2007; 33:1419-1425
32. Ogle KN, Schwartz JT. Depth of focus of the human eye. J Opt Soc Am 1959; 49:273-280
33. Schwartz JT, Ogle KN. The depth of focus of the eye. Arch Ophthalmol 1959; 61:578-588
34. Tucker J, Charman WN. The depth-of-focus of the human eye for Snellen letters. Am J Optom Physiol Opt 1975; 52:3-21
35. Rosenfield M, Cohen AS. Repeatability of clinical measurements of the amplitude of accommodation. Ophthalmic Physiol Opt 1996; 16:247-249
36. Altan-Yaycioglu R, Gozum N, Gucukoglu A. Pseudo-accommodation with intraocular lenses implanted in the bag. J Refract Surg 2002; 18:271-275
37. Wold JE, Hu A, Chen S, Glasser A. Subjective and objective measurement of human accommodative amplitude. J Cataract Refract Surg 2003; 29:1878-1888
38. Ostrin LA, Glasser A. Accommodation measurements in a prepresbyopic and presbyopic population. J Cataract Refract Surg 2004; 30:1435-1444
39. Trager MJ, Vagefi RM, McLeod SD. A Mathematical Model for Estimating Degree of Accommodation by Defocus Curves Invest Ophthalmol Vis Sci 2005; 46:B691
40. Muftuoglu O, Hosal BM, Karel F, Zilelioglu G. Drug-induced intraocular lens movement and near visual acuity after AcrySof intraocular lens implantation. J Cataract Refract Surg 2005; 31:1298-1305
41. Altman DG, Bland JM. Statistics notes. Treatment allocation in controlled trials: why randomise? BMJ 1999; 318:1209
42. Raasch TW, Bailey IL, Bullimore MA. Repeatability of visual acuity measurement. Optom Vis Sci 1998; 75:342-348

43. Pandit JC. Testing acuity of vision in general practice: reaching recommended standard. BMJ 1994; 309:1408
44. Goss DA. Clinical accommodation testing. Curr Opin Ophthalmol 1992; 3:78-82
45. Bland JM, Altman DG. Multiple significance tests: the Bonferroni method. BMJ 1995; 310:170
46. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1:307-310
47. Charman WN, Whitefoot H. Pupil Diameter and the Depth of Field of the Human Eye as Measured by Laser Speckle. Optica Acta 1977; 24:1211-1216
48. Lovie-Kitchin JE, Brown B. Repeatability and intercorrelations of standard vision tests as a function of age. Optom Vis Sci 2000; 77:412-420
49. Jacobs RJ, Smith G, Chan CD. Effect of defocus on blur thresholds and on thresholds of perceived change in blur: comparison of source and observer methods. Optom Vis Sci 1989; 66:545-553
50. Rosenfield M, Abraham-Cohen JA. Blur sensitivity in myopes. Optom Vis Sci 1999; 76:303-307
51. Vasudevan B, Ciuffreda KJ, Wang B. Objective blur thresholds in free space for different refractive groups. Curr Eye Res 2006; 31:111-118
52. Atchison DA, Capper EJ, McCabe KL. Critical subjective measurement of amplitude of accommodation. Optom Vis Sci 1994; 71:699-706

Figure Legends

Figure 1. Defocus curve criteria can be relative (A) or absolute (B) and may include positive lens induced defocus (C and D)

Figure 2. Comparison of mean VA at each level of defocus between combination 6 and each of combinations 1 to 5

Figure 3. Relationship between push-up AoA and defocus curve AoA

Figure 4. Relationship between push-up AoA and defocus curve AoA (negative defocus only)

Author(s)	Letter Chart	Lens Sequence & Range
Legeais et al.[7]	Monoyer's Scale (Decimal) (NO DETAILS OF RANDOMISATION)	Increase in negative and then positive lens power from best correction in 0.50DS steps (Non-randomised)
Langenbucher et al.[2, 3, 8]	Snellen (Non-randomised)	+0.50DS to -3.00DS in 0.50DS steps (Non-randomised)
Küchle et al.[9]	Snellen (Non-randomised)	Increase in negative lens power from best correction in 0.50DS steps (Non-randomised)
Marchini et al.[10]	Snellen (NO DETAILS OF RANDOMISATION)	Increase in negative lens power from best correction in 0.25DS steps (Non-randomised)
Heatley et al.[11]	LogMAR (Non-randomised)	-2.50DS to +2.00DS in 0.50DS steps (Non-randomised)
Sauder et al.[12]	Snellen (Non-randomised)	+3.00DS to -3.00DS in 0.50DS steps (Non-randomised)
Hancox et al.[13]	No details given	Only negative spheres presented (NO DETAILS OF RANDOMISATION)
Macsai et al.[14]	Prince Rule Card (Non-randomised)	Increase in positive/negative lens power in 0.25DS steps (Non-randomised)
McLeod[15]	LogMAR (Non-randomised)	Increase in positive/negative lens power from best correction in 0.50DS steps (Non-randomised)
Ossma et al.[16]	LogMAR (Non-randomised)	Increase in positive/negative lens power from best correction in 0.50DS steps (Non-randomised)
Marchini et al.[17]	LogMAR (Non-randomised)	Increase in negative lens power from best correction in 0.25DS steps (Non-randomised)

Table 1. Summary of defocus curve methodology used in accommodating IOL studies to evaluate AoA

Author(s)	Letter Chart	Lens Sequence & Range
Post[18]	Snellen Chart (Non-randomised)	+6.00DS to -6.00DS in 0.50DS steps (Non-randomised)
Steinert et al.[19]	Snellen (NO DETAILS OF RANDOMISATION)	+6.00DS to -6.00DS in 1.00DS steps (+6.00DS to +1.00DS), 0.50DS steps (+1.00DS to -2.00DS) and 0.25DS steps (-2.00DS to -6.00DS) (NO DETAILS OF RANDOMISATION)
Knorz et al.[20]	Snellen (NO DETAILS OF RANDOMISATION)	+1.00DS to -5.00DS in 0.50DS steps (NO DETAILS OF RANDOMISATION)
Auffarth et al.[21]	Decimal (NO DETAILS OF CHART TYPE OR RANDOMISATION)	±1.00D to ±5.00D (no details of steps) (NO DETAILS OF RANDOMISATION)
Weghaupt et al.[22]	Snellen (NO DETAILS OF RANDOMISATION)	-6.00DS to +3.00DS in 0.50DS increments (Non-randomised)
Walkow et al.[23]	Snellen (NO DETAILS OF RANDOMISATION)	+5.00Ds to -5.00DS in 1.00DS steps (+5.00DS to +2.00DS) and 0.50 steps (+2.00DS to -5.00DS) (NO DETAILS OF RANDOMISATION)
Weghaupt et al.[24]	Snellen (NO DETAILS OF RANDOMISATION)	-6.00DS to +3.00DS In 0.50DS steps (Non-randomised)
Arens et al.[25]	Decimal (NO DETAILS OF RANDOMISATION)	+3.00DS to -5.00DS in 1.00DS steps (NO DETAILS OF RANDOMISATION)
Jacobi et al.[26]	Snellen (NO DETAILS OF RANDOMISATION)	-5.00DS to +3.00DS in 0.50DS increments (NO DETAILS OF RANDOMISATION)
Walkow & Klemen[27]	Snellen (Randomised charts)	+5.00DS to -5.00DS in 0.50DS steps (Non-randomised)
Kamlesh et al.[28]	Snellen (NO DETAILS OF RANDOMISATION)	Increase in positive/negative lens power in 0.50DS steps (Non-randomised)
Leyland et al.[29]	LogMAR (NO DETAILS OF RANDOMISATION)	+3.00DS to -5.00DS In 1.00DS steps (NO DETAILS OF RANDOMISATION)
Tsorbatzoglou et al.[30]	LogMAR (Non-randomised)	Increase in negative lens power from best correction in 0.25DS steps (Non-randomised)
Toto et al.[31]	LogMAR (NO DETAILS OF RANDOMISATION)	+2.00DS to -5.00DS In 0.50DS steps (Non-randomised)

Table 2. Summary of defocus curve methodology used in multifocal IOL studies

<table>
<tr><th>Depth of Focus Criterion</th><th>Studies Using Criterion</th><th>Measured Depth of Focus</th></tr>
<tr><td rowspan="9">Best VA</td><td>Rosenfield & Cohen[35]</td><td>Pre-presbyopic subjects = 9.10±0.73D</td></tr>
<tr><td>Altan-Yaycioglu et al.[36]</td><td>Monofocal IOL = 1.11±0.39D</td></tr>
<tr><td>Wold[37]</td><td>Pre-presbyopic subjects = 7.02±2.00D</td></tr>
<tr><td>Ostrin & Glasser[38]</td><td>Various age ranges:
31-35 year olds = 4.40±1.61D
36-40 year olds = 3.13±1.00D
41-45 year olds = 1.45±0.45D
46-50 year olds = 1.24±0.58D
51-55 year olds = 0.83±0.26D</td></tr>
<tr><td>Marchini et al.[10]</td><td>Accommodating IOL = 1.08±0.54D</td></tr>
<tr><td>Macsai et al.[14]</td><td>Accommodating IOL:
Monocular = 1.74±0.48D
Bbinocular = 1.96±0.50D</td></tr>
<tr><td>Marchini et al.[17]</td><td>Accommodating IOLs = 0.96±0.44D to 1.40±0.66D</td></tr>
<tr><td rowspan="2">Sauder et al.[12]*</td><td rowspan="2">Accommodating IOL = 1.01±0.40D</td></tr>
<tr></tr>
<tr><td>Best VA + 0.10 LogMAR</td></tr>
<tr><td>Best VA + 0.20 LogMAR</td><td>McLeod[15] & Ossma et al.[16]</td><td>Single Vision IOL = 1.65±0.58D (range 1.00D to 2.50D)
Dual Optic Accommodating IOL = 3.22±0.88D (range 1.00 to 5.00D)</td></tr>
<tr><td>Best VA + 0.30 LogMAR</td><td>Trager et al.[39]</td><td>Pseudophakic patients = 1.04D
Phakic patients = 0.09D to 2.62D</td></tr>
</table>

Table 3. Summary of relative defocus curve criteria used by various studies. All studies refer to presbyopes unless stated otherwise. Standard deviations are only stated if they were given in original publications. **This study evaluated AoA of an accommodating IOL using five techniques, one of which was by defocus curve with a criterion for AoA of ' best VA', whilst a second method and criterion of 'best VA + 0.10 logMAR' was also used. Individual evaluations for each method are not stated but only the mean and range of all methods is given.*

Depth of Focus Criterion	Studies Using Criterion	Measured Depth of Focus
Snellen 20/28 (0.15 LogMAR)	Legeias et al.[7]	Accommodating IOL = 2.10±0.58D
Snellen 20/40 (0.30 LogMAR)	Post[18]	Single Vision IOL = 1.80D Multifocal IOL = 3.80D
	Knorz et al.[20]	Single Vision IOL = 2.50D for a 3.2 mm pupil Bifocal IOL = 2.50D to 4.50D Diffractive IOL = 4.50D Varifocal IOL = 3.00D
	Weghaupt et al.[24]	Diffractive IOL = 5.00D Multifocal IOL = 4.50D
	Arens et al.[25]	Multifocal IOL = 4.00D Monofocal IOL = 2.00D
	Kamlesh et al.[28]	Multifocal IOL = 3.10D Monofocal IOL = 1.65D
	Heatley et al.[11]	Accommodating IOL = 1.73±0.56D
	Hancox et al.[13]	Accommodating IOL = 1.09±0.58D
	Toto et al.[31]	Aspheric diffractive multifocal IOL = 4.50D Adopised diffractive IOL = 4.00D
Snellen 20/50 (0.40 LogMAR)	Steinert et al.[19]	Multifocal IOL = 4.75D Monofocal IOL = 2.75D
	Langenbucher et al.[2, 3]	Accommodating IOL: 1 month = 1.46±0.53D 6 months = 1.46±0.53D
	Langenbucher et al.[8]	Accommodating IOL = 1.66±0.48D
	Küchle et al.[9]	Accommodating IOL = 1.85±0.43D
	Muftuoglu et al.[40]	Monofocal IOL = 1.14±0.24D
	Tsorbatzoglou et al.[30]	Monofocal IOL Type 1 = 0.82±0.18D Monofocal IOL Type 2 = 1.00±0.35D Multifocal IOL = Not quantified

Table 4. Summary of absolute defocus curve criteria used by various studies. All studies refer to presbyopes unless stated otherwise. Standard deviations are only stated if they were given in original publications

Defocus Curve Criterion		Mean Defocus Curve AoA	Comparison with Push-up AoA		
Type	**Definition**		**Correlation**	**Concordance**	**Limits of Agreement (D)**
Absolute	0.30 LogMAR (Snellen 20/40)	2.58±0.49	0.18 p=0.46	0.03	±1.21
	0.40 LogMAR (Snellen 20/50)	3.11±0.67	0.08 p=0.75	0.02	±1.54
	0.30 LogMAR (Snellen 20/40) *Negative defocus only*	1.34±0.32	-0.03 p=0.89	-0.03	±1.12
	0.40 LogMAR (Snellen 20/50) *Negative defocus only*	1.65±0.48	-0.04 p=0.86	-0.04	±1.34
Relative	Best VA	0.82±0.40	0.84 *p<0.001*	0.47	±0.50
	Best VA + 0.10 LogMAR	1.34±0.43	0.62 *p=0.0033*	0.63	±0.76
	Best VA + 0.20 LogMAR	1.83±0.50	0.57 p=0.01	0.38	±0.89
	Best VA + 0.30 LogMAR	2.24±0.54	0.49 p=0.03	0.19	±1.00
	Best VA + 0.40 LogMAR	2.75±0.77	0.32 p=0.18	0.11	±1.49
	Best VA *Negative defocus only*	0.56±0.46	0.66 *p<0.002*	0.20	±0.75
	Best VA + 0.10 LogMAR *Negative defocus only*	0.84±0.47	0.53 p=0.02	0.30	±0.88
	Best VA + 0.20 LogMAR *Negative defocus only*	1.07±0.51	0.54 p=0.01	0.44	±0.92

Defocus Curve Criterion		Mean Defocus Curve AoA	Comparison with Push-up AoA		
Type	Definition		Correlation	Concordance	Limits of Agreement (D)
	Best VA + 0.30 LogMAR *Negative defocus only*	1.28±0.51	0.51 p=0.02	0.51	±0.95
	Best VA + 0.40 LogMAR *Negative defocus only*	1.59±0.68	0.39 p=0.09	0.38	±1.24

Table 5. Statistical analysis of subjective AoA determined from defocus curves, compared to subjective AoA as determined by the push-up test, for various criteria, by Pearson's Product-Moment Correction (PPMC) coefficient & significance, two-way random effects intraclass correlation coefficient and Bland-Altman Limits of Agreement. Significant results are highlighted in italic.

Criterion Type	Criterion	Mean Blur Threshold ±SD (D)	Correlation (to pupil size)
Subjective Push-up Test		0.97±0.28	0.02
Absolute	0.30 LogMAR	2.19±0.51	-0.29
	0.40 LogMAR	2.73±0.66	-0.24
	0.30 LogMAR *Negative defocus only*	0.96±0.45	-0.31
	0.40 LogMAR **Negative defocus only**	1.26±0.56	-0.20
Relative	Best VA	0.44±0.30	-0.19
	Best VA + 0.10 LogMAR	0.96±0.35	-0.12
	Best VA + 0.20 LogMAR	1.44±0.41	-0.03

Criterion Type	Criterion	Mean Blur Threshold ±SD (D)	Correlation (to pupil size)
	Best VA + 0.30 LogMAR	1.86±0.47	-0.03
	Best VA + 0.40 LogMAR	2.37±0.70	-0.01
	Best VA *Negative defocus only*	0.17±0.37	-0.14
	Best VA + 0.10 LogMAR *Negative defocus only*	0.45±0.41	-0.16
	Best VA + 0.20 LogMAR *Negative defocus only*	0.54±0.38	-0.13
	Best VA + 0.30 LogMAR *Negative defocus only*	0.90±0.47	-0.13
	Best VA + 0.40 LogMAR *Negative defocus only*	1.20±0.62	-0.07

Table 6. Pearson's Product Moment Correlations of blur threshold to increasing pupil size for each defocus curve criterion and subjective push-up AoA.