Journal of the British Contact Lens Association, Vol. 17, No. 2, pp 51–57, 1994
Printed in Great Britain

CONCENTRIC-DESIGN RIGID BIFOCAL LENSES, PART III: PREDICTING VISION FROM OPTICAL MEASUREMENT

Russell L. Woods*, John E. Saunders†§ and Michael J.A. Port@

(Received 31st May 1993; in revised form 12th September 1993)

Abstract* — While the main purpose of previous optical investigations of contact lenses has been to elucidate the effect of differences in design, there have been no previous reports of measurements of both optical performance and visual performance of the same contact lenses. In this study optical and visual results were compared and models developed to predict visual performance from the optical performance measurements of rigid concentric-design bifocal contact lenses. Optical performance was measured using an EROS solid state modulation transfer function (MTF) system with apertures of 2 to 6mm and contact lens decentration of 0 to 2mm. Visual performance was measured with a monitor-based contrast sensitivity system, Pelli-Robson charts and high and low contrast visual acuity charts. Polymethylmethacrylate (PMMA) bifocal contact lenses were made on a back-surface design in both centre-distance and centre-near designs. Central optic zone diameters varied from 1.8 to 3.4mm, while the peripheral optic zone diameter was fixed at 7.5mm. Multiple regression analysis models were empirically derived to include the measured pupil diameter, decentration and central optic zone diameter. Best predictions (adjusted multiple correlation, R^2: range 0.46–0.80) of visual performance were found with the MTF measurements made with a 4mm aperture. The average measured pupil diameter of the five presbyopic subjects was 2.8mm. These models indicated that the MTF was a useful measure of changes in lens design and that, given the correct conditions of measurement, good predictions of visual performance could be made. Hence, changes in the MTF of bifocal contact lenses are a useful indicator of changes in vision.

KEY WORDS: Bifocal lenses, optical performance, modulation transfer function, visual performance, contrast sensitivity, mathematic models

Introduction

Poor visual performance is a major cause of failure with bifocal contact lenses.[1–3] Hence, during the development of new bifocal contact lenses the assessment of the effect of changes in optical design upon vision is of paramount importance. The assessment of visual performance is almost invariably time-consuming, typically involving a number of subjects and examiners. It would be desirable to reduce or eliminate the requirement for visual testing during the development stage of new bifocal contact lens designs. Optical performance measurement has been demonstrated to offer a relatively quick method of assessing changes in optical design.[4] If the changes in optical performance can be related to changes in visual performance then optical performance measurement may be used to predict visual performance.

This study describes the development of equations to predict visual results from optical measurements of bifocal contact lenses for which both the optical[4] and the visual[5] performance have previously been reported. Such equations may be used to reduce the lengthy process of visual testing. This would, of course, not remove the need finally to test a new bifocal contact lens upon experimental subjects, but may reduce the requirement for testing with intermediate or developmental bifocal contact lenses. To our knowledge there have been no similar reports.

Optical Performance

The modulation transfer function (MTF)[6] is the most comprehensive measure of optical performance in current use. The MTF is a measure of the ability of an optical system (e.g. a contact lens) to transmit optical information. The modulation transfer (ratio of the contrast of the image to the contrast of the object) is plotted against the spatial frequency of the sinusoidal grating object. Grey and Sheridan[7] demonstrated that there was very little difference between the MTF of various single vision contact lenses, and hence that there was little benefit in measuring them. However, large differences in the optical performance of bifocal contact lenses have been noted.[4,8] Lens design (centre-near or centre-distance), back central optic zone diameter (COZD), aperture (pupil) diameter and decentration have been demonstrated to influence the MTF.[4,8,9] The changes in the MTF have been demonstrated to be related to the changes in visual performance which result from various bifocal contact lens parameter changes.[5]

Visual Performance

Visual acuity (VA) is a measure of the resolution limit of the visual system and is sensitive to reductions in image quality (e.g. defocus). Contrast sensitivity (CS), a measure of the ability to detect contrast objects (typically sinusoidal gratings of different spatial frequencies) is considered a more subtle and more comprehensive test of visual performance than VA Bifocal contact

---

**PhD, BOptom, MBCO, FAAO, Centre for Eye Research, Queensland University of Technology, Locked Bag No. 2, Red Hill, QLD 4059, Australia.*
†PhD.
‡MSc, DCLP, FBCO, FAAO.
§Department of Optometry and Visual Science, City University, London EC1V 7DD, UK.

lenses reduce both VA and CS.[5,10–12] While the relevance of changes in CS to success with bifocal contact lenses has not been clearly demonstrated, performance at low spatial frequencies has been related to patient mobility.[13] Lens design, back COZD, pupil diameter and lens decentration have been demonstrated to influence VA and CS.[5,11]

The similarities between the changes in optical performance and visual performance with changes in lens parameters suggest that optical performance measurements may be used to predict visual performance.

Methods

Optical Performance

Optical performance was assessed as the MTF. The MTF was measured using an solid state EROS MTF analyser as described previously.[4,9] The MTF of all contact lenses was measured with apertures of 6, 5, 4, 3.5, 3, and 2mm diameter placed 3mm after the contact lens and with the contact lens centred to the axis of the optical system. In addition, a range of contact lenses was decentred over apertures of 5, 4, 3.5 and 3mm by 2, 1.5, 1.25, 1.0, 0.75, 0.5, and 0.25mm. Further details of the optical performance of the decentred lenses have been published elsewhere[9]. Repeatability of MTF measurement of bifocal contact lenses was worse than a previous report[7] and the manufacturer's specifications by a factor of approximately 10.[9]

Visual Performance

visual performance was assessed by means of (a) CS at 2, 4, 8 and 16 c.p.d. measured with a monitor-based system; (b) Pelli-Robson threshold contrast charts[14] used at 4 metres; and (c) high and low contrast Bailey-Lovie[15] VA charts.5 Mean luminance of the CS monitor was 50 cd/m2 and the mean maximum (white) luminance of the two charts was 250 cd/m^2. Repeatability of the visual performance measurement with bifocal contact lenses was worse than previously reported with 'normal' subjects by a factor of approximately 2.[16]

Subjects

Five presbyopic subjects with ages from 57 to 65 years wore a bifocal contact lens in one eye for visual assessment. An ocular anaesthetic was also used when requested to reduce the effects of excessive lacrimation. The best refractive correction (including any astigmatic component) for the relevant viewing distance and bifocal contact lens was worn in a trial frame. Contact lenses were worn for no longer than 45 minutes in a session. Each subject wore at least 10 different bifocal contact lens designs on at least two occasions.

Experimental Bifocal Contact Lenses

The contact lenses, made by Piigton VisionCare with a high precision lathe, were polymethylmethacrylate (PMMA) back-surface concentric-design bifocal contact lenses with a back COZD of 3.4, 3.0, 2.6, 2.2, or 1.8mm. The back peripheral optic zone diameter (POZD) was fixed at 7.5mm. Contact lenses were available in both a centre-distance (CD) and a centre-near (CN) format with a near addition of 2.00D *in vivo*. The back surface junction between the central optic zone (COZ) and the peripheral optic zone (POZ) was distinct and less than 5μm in width, with no blending for either lens design (CD or CN). All contact lenses were a tricurve (C3) design with an effective back optic zone diameter (BOZD) of 7.5mm and a calculated axial edge lii of 0.15mm at the total diameter of 9.5mm.

When worn by the subjects the bifocal contact lenses were fitted slightly steep to enhance centration and care was taken to ensure that there were no bubbles under the contact lens. The bifocal contact lenses were made for this study and have never been available on a commercial basis.

Pupil Diameter

Pupil diameter was determined, whilst the subject viewed a blank white field at a range of luminances from 0.001 to 320 4cd/m^2, with an infrared pupillometer which has a potential accuracy of 0.01.[17] Repeated measures indicated that the absolute pupil diameter varied on retest by as much as 0.5mm. Each subject was measured with the range of screen luminances on at least two occasions. A polynomial regression analysis was performed in order to determine a line of best fit so that the pupil diameter at the two test (CS and chart) luminances could be interpolated.

Contact Lens Decentration

Optical performance. To test the effect on the MTF of decentration of the contact lens over the aperture the bifocal contact lens was moved in relation to the aperture, which remained centred on the optical bench. The required decentration of the contact lens (and wet cell) was controlled using engineering thickness gauges with a tolerance of ±0.05mm.

Visual performance. An estimate of the average fit and decentration of the COZ in relation to the pupil was determined for each bifocal contact lens on each subject with a slit-lamp biomicroscope fitted with a graticule eyepiece. The decentration in relation to the pupil centre could then be determined (test-retest 95% confidence ±0.1mm). Pupil coverage by the COZ was then determined for each of the two test luminances using the interpolated pupil diameters.

Multiple Regression Analysis Procedures

Multiple regression analysis (MRA) is a statistical technique which investigates the influence of several independent variables upon the (dependent) variable of interest. It is an extension of the more common linear regression which investigates the influence of a single independent variable (x) upon the (dependent) variable of interest (y) and describes the relation in terms of a linear equation ($y = a + bx$) Similarly MRA describes the relation with an equation which involves several independent variables ($x_1, x_2, \ldots x_n$) in terms of a linear equation ($y = a + b_1x_1 + b_2x_2 + \ldots + b_nx_n$). The strength of the relation described by the MRA equation can be summarised as the multiple correlation (Hz). In addition, it is possible to determine the relative influence of the different independent variables. The equation derived from MRA can be considered as a model of the relation between independent and dependent variables.

MRA was used to model a single dependent variable (e.g. VA) in terms of both (manipulated) independent variables (e.g. lens design, COZD) and covariates (e.g. pupil diameter). This allowed an assessment of the influence of the variables and any interaction terms, but more importantly the development of predictive models. To facilitate the selection of appropriate models a two-stage procedure was adopted. Initially, all terms were forced into the equation in a standard MRA procedure, then a stepwise MRA procedure was used to remove those terms which were statistically redundant. MRA could have led to overoptimistic estimates of predictive power where the independent variables were highly correlated and where the number of terms included in the final equation was large in relation to the sample size.[18,19] Problems due to multicollinearity (excessive correlation between the independent variables) were reduced by restricting the tolerance and the use of the stepwise procedure.[18] A range of models was investigated for each analysis, and each model presented below was considered to be the most appropriate and most useful. All models were examined for a range of possible errors with standard procedures and, in particular, the model was devised to obtain an even spread of residuals. The reported multiple correlation (R^2), adjusted for the number of terms and sample size,[19] is referred to below as the adjusted R^2.

Results

Empirical models of visual performance in terms of the measured optical performance were derived using MRA as indicated above.

Preliminary Investigation

To reduce the possibility of incorrect results from the MRA a number of aspects of the data were examined. If the terms which are used in the MRA are highly correlated there is a risk of an incorrect result. The correlation, for all MTF measurements with bifocal contact lenses (n = 1802), between the MTF at each of the 16 spatial frequencies was very high (range: R^2 = 0.996 between adjacent spatial frequencies, to R^2 = 0.680 between the most distant spatial frequencies). Principal component analysis[20] indicated only a single factor describing the modulation transfer measured at each of the 16 spatial frequencies (i.e. no spatial frequency-related components were present). The high correlations between the measured modulation transfers at the different spatial frequencies increased the risk of overoptimistic estimation of the predictive power of any derived models. Further analysis indicated that there were only weak and inconsistent relations between the optical performance and the visual performance at any particular spatial frequency. It might have been expected that each visual performance measure would be more highly correlated with the modulation transfer measured at a similar spatial frequency. For example, the modulation transfer at 4 c.p.d. did not correlate with CS at 4 c.p.d. better than any other visual performance measure.

Numerous data reductions were investigated and the models presented here were derived with the number of terms in the subsequent MRA restricted to the measured modulation transfer at four spatial frequencies: 4, 12, 25 and 66 c.p.d. If too many terms were included there was a risk of an incorrect result. A stepwise MRA procedure as described was then used to develop equations, in terms of the modulation transfer at the four spatial frequencies, to describe each visual performance measure. No a *priori* assumptions were made about the spatial frequency content of the optical or visual performance measures. Terms which were judged to be statistically redundant were removed from the MRA equations by the stepwise procedure. A spatial frequency of 4 c.p.d. is close to the peak of the human contrast sensitivity function, 25 c.p.d. is approximately equivalent to a Snellen acuity of 6/7, while 66 c.p.d. is slightly above the human resolution limit of approximately 6/3.

Data Transformation

All visual performance measures were converted to a relative measure to remove the effects of different absolute visual performance levels by individual subjects, where:

$$\text{relative visual performance} = \log_{10}\left(\frac{\text{visual performance with bifocal contact lens}}{\text{visual performance without bifocal contact lens}}\right)$$

Two sets of equations modelling vision from optical performance are reported. Initially, a series of empirical MRA equations were derived using the measured MTF of centred bifocal contact lenses to predict the different visual performance measures. In a second analysis, using the measured MTF of decentred bifocal contact lenses and the measured on-eye decentration of the bifocal contact lens and the measured pupil diameter, a 'calculated' MTF for these conditions was used to predict visual performance.

Models Using Measured MTF of Bifocal Contact Lenses with Different Apertures

MTF measurements made with each bifocal contact lens centred over apertures of 2 to 6mm were averaged separately for each aperture stop and each spatial frequency (minimum 4 per set). The averaged, measured modulation transfers were then used in a stepwise MRA to predict the relative visual performance which had been averaged for all subjects. This is shown in ***Table 1*** for 3, 3.5, 4, and 5mm apertures.

The average measured pupil diameter of the five subjects was 3.1mm when viewing the CS test and 2.6mm when viewing the chart-based tests. A preliminary visual examination of the data indicated that the optical performance with bifocal contact lenses centred over the 4mm aperture stop most closely matched the changes in visual performance noted. As shown in

Table 1. *Prediction of visual performance with bifocal contact lenses. The adjusted multiple correlation (R^2) for the MRA which used the MTF measured with bifocal contact lenses (n = 36) centred over different apertures to predict the average visual perfrmance.*

Visual performance	Adjusted R^2 with aperture stop 3mm	3.5mm	4mm	5mm
CS at 2 c.p.d.	0.39	0.37*	0.47	0.37
CS at 4 c.p.d.	0.74	0.57	0.78	0.75
CS at 8 cp.d.	0.52	0.37	0.55	0.51
CS at 16 c.p.d.	0.45	0.33"	0.46	0.42
Pelli-Robson CS	0.61	0.54	0.80	0.79
Low contrast VA	0.64	0.72	0.76	0.80
High contrast VA	0.51	0.54	0.47	0.50

*$p < 0.0005$ (all others $p < 0.0001$)

Table 1, most visual performance measures were slightly better predicted using the MTF measured with the 4mm aperture.

As an example, the equations for the prediction of the relative visual performance from the MTF measured with a 4mm aperture were:

$$\text{CS at 2 c.p.d.} = -0.25 + 1.41\,M_{12} - 0.99M_{25} \qquad \text{(log units)} \quad (1)$$

$$\text{CS at 4 c.p.d.} = -0.23 + 1.40\,M_{12} - 0.77M_{25} \qquad \text{(log units)} \quad (2)$$

$$\text{CS at 8 c.p.d.} = -0.31 - 0.24M_4 + 1.50\,M_{12} - 0.62M_{25} \qquad \text{(log units)} \quad (3)$$

$$\text{CS at 16 c.p.d.} = -0.31 - 0.33M_4 + 1.68\,M_{12} - 0.67M_{25} \qquad \text{(log units)} \quad (4)$$

$$\text{Pelli-Robson CA} = -0.20 + 1.77M_{12} - 1.14M_{25} \qquad \text{(log units)} \quad (5)$$

$$\text{low contrast VA} = -1.57 + 10.14M_{12} - 5.43M_{25} \qquad \text{(10.logMAR)} \quad (6)$$

$$\text{high contrast VA} = -0.21 + 1.19M_{12} - 0.63M_{66} \qquad \text{(10.logMAR)} \quad (7)$$

where M_4, M_{12}, M_{25}, M_{66} were the measured modulation transfers at 4, 12, 25 and 66 c.p.d. respectively. The units are shown in brackets. These equations give the relative visual performance, i.e. the reduction in vision expected with a particular measured MTF.

The standardised regression coefficient (ß) attempts to indicate the importance of the different terms retained in an MRA equation. The larger the ß, the more important the term. As shown in *Table 2* for the 4mm aperture, the MRA equations provided limited support for the hypothesis that the lower spatial frequency visual performance measures (CS at 2 and 4 c.p.d.) would be best predicted by the modulation transfer measured at lower spatial frequencies, while the visual performance measures with a higher spatial frequency content (VA) would have been best predicted by the modulation transfer measured at higher spatial frequencies. Similar results were found for the other aperture sizes.

Table 2. *There was a weak relation between the modulation transfer at different spatial frequencies and the spatial frequency content of the visual performance measures. The standardised regression coefficients (ß) terms retained by the stepwise MRA are shown. There was a weak trend for the higher spatial frequency modulation transfer terms to be retained in the equations which described visual performance measures with a higher spatial frequency content (and vice versa). In this example, modulation transfer was measured with the bifocal contact lens over a 4mm aperture. Similar results were found with the other apertures.*

Visual perfrmance	Standardised regression coefficients (ß) MTF spatial frequency (c.p.d.) 4	12	25	66
CS at 2 c.p.d.		5.57	5.10	
CS at 4 c.p.d.		7.54	5.38	
CS at 8 cp.d.	1.86	3.32	2.33	
CS at 16 c.p.d.	2.18	3.12	2.14	
Pelli-Robson CS		10.5	8.85	
Low contrast VA		6.75	4.71	
High contrast VA		1.84		2.02

Models Using Calculated MTF of Decentred Bifocal Contact Lenses

The first model used the MTF measured with the bifocal contact lenses centred over the aperture. The average on-eye decentration was 1.2mm and pupil diameter varied considerably between subjects.[5] Decentration and pupil diameter have large effects on both the optical performance[4,9] and the visual performance,[5] of concentric-design bifocal contact lenses. Variations in the subject's pupil diameter and the on-eye decentration were expected to be factors that would influence the MTF which most usefully predicted the visual performance. Hence, in the second analysis, MRA was first used to develop equations which described the optical performance of the bifocal contact lenses measured under all conditions (centred and decentred) in terms of the COZD, optic giving the focus (COZ or POZ), aperture size and decentration. This equation was then used to calculate the MTF for the actual pupil diameter and decentration of each subject with each bifocal contact lens. The calculated modulation transfer at each of the four spatial frequencies was then subject to a stepwise MRA and models developed to predict visual performance.

As indicated by the adjusted R^2 values given in *Table* 3, the calculated MTF was less successful at predicting visual performance than the measured MTF of centred bifocal contact lenses *(Table 1).*

Discussion

In previous reports of the same bifocal contact lenses the general agreement between optical performance[4] and visual performance[5] results was high, indicating

Table 3. *Calculated modulation transfer was used to predict visual performance of bifocal contact lenses. The adjusted multiple correlation (R^2) for MRA equations which described visual perfrmance in terms of the modulation transfer calculated for the measured COZD, pupil diameter and decentration. (All equations p < 0.0001; n = 129.)*

Visual performance	Adjusted R^2
CS at 2 c.p.d.	0.36
CS at 4 c.p.d.	0.36
CS at 8 c.p.d.	0.27
CS at 16 c.p.d.	0.25
Pelli-Robson	0.59
Low contrast VA	0.56
High contrast VA	0.32

that the MTF could be a useful index of vision. As expected from these similarities it was possible to use the MTF to predict visual performance with adjusted R^2 values as high as 0.80. This suggests that such empirically derived models which describe visual performance (CS, Pelli-Robson, and VA) in terms of the measured optical performance (MTF) may be used to investigate the effects of changes in bifocal contact lens design. Hence the MTF is a useful tool for the optical designer who may wish to investigate the effects of changes in the optical design of bifocal contact lenses. Hopefully the wider use of this tool (MTF) in the development of bifocal contact lenses may lead to improvements in the optics of bifocal contact lenses and ultimately to optimised bifocal contact lens designs.

The only previous attempt to evaluate the optical and visual performance of the same bifocal contact lenses, was a preliminary investigation by Freeman and Mulen[21] of diffractive bifocal contact lenses. This was limited to reporting that the overall reduction in visual performance was less than predicted by the measured optical performance.

In our data there was a large amount of variability in the measurement of both the optical and the visual performance as indicated by the poor repeatability of measurement. As noted[9,16] the repeatability was much worse than previously reported and appeared to be related to the reduced image quality with bifocal contact lenses. This variance would be expected to reduce the ability to predict visual performance.

The empirical models relating optical and visual performance were based on the MTF data measured at four spatial frequencies. The four spatial frequencies were chosen after a preliminary examination of the correlations between visual performance and the modulation transfer measured at each of the original 16 spatial frequencies. As shown in ***Table*** 2, there was only a weak relation between the spatial frequency content of the visual performance measure and that of the MTF terms retained in the stepwise MRA. This was due to the high correlations between MTF data at the different spatial frequencies[9] and the correlations between the visual performance measures.[16] The changes in bifocal contact lens parameters were shown, in general, to have similar effects on all spatial frequencies of the measured MTF and on all visual performance measures. Hence, visual performance was correlated almost equally well with measured MTF data at all the spatial frequencies. The stepwise MRA procedure retained those spatial frequencies with the greatest ability to explain the variations in visual performance and, as noted, there was often very little difference between the different spatial frequencies. The use of the stepwise procedure and the restriction of the number of spatial frequencies (from 16 to 4) reduced the risk that overly optimistic estimates of predictive ability may have been obtained.[18]

Various averaging procedures and other constrictions of the data were investigated, and the MRA models given were judged to be the most useful. Two different approaches to the prediction of visual performance with bifocal contact lenses are reported. The first was based upon the actual measured MTF of centred bifocal contact lenses, while the second was based upon the calculated MTF derived from MTF measurements of decentred bifocal contact lenses.

Measured Optical Performance

As shown in ***Table 1,*** the measured optical performance of centred bifocal contact lenses provided a better prediction of visual performance than the more elaborate decentred model discussed above. The average pupil diameter was 2.8mm, and it might have been expected that measurements of optical performance with the 3mm aperture would have proved the best predictor of visual performance. Examination of the trends in the data suggested that the visual performance data may have been best predicted by optical performance with the 4mm aperture. As ***can*** be seen in ***Table 1*** the MTF measured with the 4mm aperture size was slightly better than the others (range 3 to 5mm) in the prediction of visual performance. This was not surprising as the variation in optical performance with COZD and vergence changed significantly with aperture.

Differences between the on-eye situation and the bifocal contact lens during MTF measurement may explain the better prediction of visual performance with an aperture larger than the measured pupil. In the optical apparatus used to measure the MTF, the aperture stop was 3mm behind the bifocal contact lens, and light leaving the bifocal contact lens, because of the Badal optometer arrangement, was parallel, being focused by a subsequent lens onto the detector array.[4] Conversely, when on-eye, the effective size of COZ at the pupil (aperture stop) would have been effectively reduced to approximately 0.85 of the measured diameter of the power of the cornea (Gullstrand-Emsley schematic eye)[22], whereas the COZD effective at the aperture stop on the optical bench would not have reduced. Hence, considering the area of the COZD and the aperture stop, a measured 2.8mm pupil would be represented by a 3.9mm aperture stop on the optical bench (2.8 x 0.85^{-2}).

MTF measurements with a 4mm aperture and equations (1) to (7) comprise the best estimate of vision available with the bifocal contact lenses available from this study. These equations need to be further evaluated for their more general application.

Calculated Optical Performance

Aperture size and lens decentration have been shown to influence the optical performance of bifocal contact lenses.499 As there were differences in the size of the pupil and bifocal contact lens decentration between subjects, it was expected that these factors would influence the visual performance in a predictable way. Thus, it was expected that visual performance would have been best predicted by optical performance which had been calculated from the measured COZD, pupil diameter and bifocal contact lens decentration. Unfortunately, the MRA model derived from the calculated optical performance was not as useful to predict visual performance as the measured optical performance (Tables *1* and 3). This may have been largely due to a compounding through the additional computations required of the relatively large variance (poor repeatability) of both the optical and the visual performance measurement. Other factors may also have influenced this model. The on-eye situation was not entirely analogous to the optical measurement, as the optic axis, visual axis and pupil centre of the eye are rarely concentric.23 In addition measurement of the MTF with the bifocal contact lens immersed in a wet cell will reduce the effects of aberrations which would normally occur at the air-lens interface when on-eye. The decentration measurement was an average, whereas the bifocal contact lens on-eye was constantly moving, altering the optical performance. The direction of decentration would be expected to influence measurement of visual performance, particularly CS, as decentration in the direction of the axis of the gratings (in this case vertical) would be expected to have only a minimal effect. Characteristics of lens movement have been shown to influence visual performance and may have been a further confounding factor in this computation.[24]

In the current study, variations in the optical quality of the eyes of the individual subjects[25,26] and variations in pupil location with changes in pupil diameter[23], which may have influenced visual performance, were not investigated. Future work investigating the performance of bifocal contact lenses could usefully involve measurement of the quality of the actual retinal image with the bifocal contact lens in situ, either objectively or subjectively. Physical measurement of the retinal image by any double-pass procedure[25] would be very difficult to compute, and subjective procedures[26,27] may be preferred. Further investigation of the effects of lens location and movement may also improve the understanding of the quality of visual performance with bifocal contact lenses.

The relation between the optical performance and certain visual performance measures has been demonstrated, with the result that reasonable models have been developed for the prediction of visual performance with rigid concentric-design bifocal contact lenses. These models (equations (1) to (7)) should be tested with another group of subjects to assess their durability. In addition, the functional relevance of the different visual performance measures used in the present study has not been demonstrated. For example, the relation between low spatial frequency CS or Pelli-Robson contrast thresholds and patient success with bifocal contact lenses has not been investigated.

Conclusions

The modulation transfer function (MTF) was demonstrated to provide a useful means of predicting the visual performance with concentric-design bifocal contact lenses. Equations were derived which may be used to predict vision with rigid concentric-design bifocal contact lenses. Further development of such models may allow their use in the design stage of bifocal contact lenses thereby reducing the requirement for laborious testing of preliminary designs. This may allow for the development of better bifocal contact lenses.

Acknowledgements

Sections of this information were presented at the 1993 British Contact Lens Association Conference in the presentation entitled ‘Bifocal Contact Lenses: Predicting Vision from Optical Measurement.’

Pilkington VisionCare provided a Research Scholarship to R.L.W. and produced the experimental bifocal contact lenses.

Address for Correspondence

Dr R.L. Woods, Centre for Eye Research, School of Optometry, Queensland University of Technology, Locked Bag No. 2, Red Hill, QLD 4059, Australia.

REFERENCES

[1] Back, A., Holden, B.A. and Hine. N. Correction of Dresbvoaia with contact lenses: comparative success rates with three systems. *Obtom.. Vision Sci..,* **66(8)** 518-525 (1989)

[2] Cburtney, R.C., Tarantino, N., Nelson, ‘N.E., Mackey, AM. and Komorowski, J. Clinical evaluation of the Hydron Echelon bifocal hydrophilic contact lens. Part 1: Success rates. *Contact Lens Spectrum*, **7(7)**, *29-38* (1991).

[3] Back, A, Grant, T., Hine, N. and Holden, B.A. Twelve-month success rates with a hydrogel diffractive bifocal contact lens. *Optom. Vision Sci..* **69(12)**, 941-947 (1992).

[4] Woods, R.L., Saunders, J.E. ‘and Port, M.J.A. Concentric-design rigid bifocal lenses, Part I Optical performance. *J. Br. Contact Lens Assoc.*, **16(1)**, 25-36 (1993).

[5] Woods, R.L., Port, M.J.A. and Saunders, J.E. Concentric-design rigid bifocal lenses, Part II. Visual performance. *J. Br. Contact Lens* Assoc., **16(2)**, 71-82 (1993).

[6] Hopkins, H.H. The application of frequency response techniques in optics. *Proc. Phys. Soc.*, **79**, 889–919 (1962).

[7] Grey, C.P. and Sheridan, M. The modulation transfer function of contact lenses. *J. Br. Contact Lens Assoc.*, 1 l(l), 9-17 (1988).

[8] Young, G., Grey, C.P. and Papas, E.B. Simultaneous vision bifocal lenses: A comparative assessment of the in *vitro* optical performance. *Optom. Vision Sci.*, **67(5)**, *339-345* (1990).

[9] Woods, RL., Saunders, J.E. and Port, M.J.A. Optical performance of decentered bifocal contact lenses. *Optom. Vision Sci.*, **70(3)**, 171-184 (1993).

[10] Erickson, P. and Robboy, M. Performance characteristics of a hydrophilic concentric bifocal contact lens. *Am. J. Optom. Physiol. Optics*, **62(10)**, 702-708 (1985).

[11] *Cox, LG. Power variation across the surfaces of soft contact lenses and its effect on* vision. PhD thesis, University of New South Wales, Sydney (1986).

[12] Jones, B. and Lowther, G.E. The effect of near zone size of a center-near zone hydrogel contact lens bifocal on visual acuity. *ht. Contact Lens Clin.*, **16(3)**, 87-93 (1989).

[13] Cunningham, P.J., Johnston, A.W. and Howell, E.R. Edge detection as a measure of functional visual performance of low vision patients. *Proc. ANZAAS Congress,* May 1980.

[14] Pelli, D.G., Robson, J.G. and Wilkins, A.J. The design of a new letter chart for measuring contrast sensitivity. *Clin. Vision Sci.*, **2(3)**, 187-199 (1988).

[15] Bailey, LL. and Lovie, J.E., New design principles for visual acuity letter charts. *Am. J. Optom. Physiol. Opt.*, **53(1 1)**, 740-745 (1976).

[16] Woods, R.L. Reliability of visual performance measurement under optical degradation. *Ophthalmol. Physiol. Opt.*, **13(2)**, 143-150 (1993).

[17] Barbur, J.L., Thomson, W.D. and Forsyth, P.M. A new system for the simultaneous measurement of pupil size and two dimensional eye movements. *Clin. Vision Sci.*, **2(2)**, 131-142 (1987).

[18] Tabachnick, B.G. and Fidell, L.S. Using *Multivariate statistics.* Harper & Row, New York (1983).

[19] Winer, B J. *Statistical Principles in Experimental Design,* 2nd edn. McGraw-Hill, New York (1971).

[20] Jolliffe, I.T. *Principal Component Analysis.* Springer-Verlag, New York (1986).

[21] Reported in Phillips, A.J. Results of a clinical trial of the “Diffrax” diffractive bifocal RGP lens. *Trans. Br. Contact Lens Assoc. Int. Contact Lens Cent. Conf.*, *89-94 (1988).*

[22] Bennett. *A.G.* and Rabbetts. RB. *Clinical Visual Optics.* Butterworths, ‘London (1984).

[23] Wilson, MA., Campbell, M.C.W. and Simonet, P. Change of pupil centration with change of illumination and pupil size. *Optom. Vis Sci.,* **69(2),** *129-136* (1992).

[24] Tomlinson, A. and Ridder, III, W.H. Effect of lens movement on vision with RGP contact lenses. *J. Br. Contact Lens Assoc.,* **15(1),** 25–29(1992).

[25] Walsh, G. and Charman, W.N. Measurement of the axial wavefront aberration of the human eye. *Ophthal. Physiol Opt.,* **5(1),** 2331 (1985).

[26] Campbell, M.C.W., Harrison, E.M. and Simonet, P. Psychophysical measurement of the blur on the retina due to optical aberrations of the eye. *Vision Res.,* **30(11),** 1587–1602 (1990).

[27] Howland, B. and Howland, H.C. A subjective method for the measurement of monochromatic aberrations of the eye. *J. Opt. Soc. Am.,* **67(11),** 1508–1518 (1977).