British Journal of Ophthalmology, 1991, 75, 359–366

Quality of vision through diffractive bifocal intraocular lenses

J L Jay, H S Chakrabarti, J D Morrison

Abstract

Two elderly women have each received a monofocal intraocular lens in one eye and a 3M diffractive bifocal intraocular lens in the other eye. Both eyes were shown to have equivalent retinal/neural function by measuring contrast sensitivity to laser interference fringes which bypassed refractive and other defects of the ocular media. The eyes with a bifocal intraocular lens displayed a much greater depth of focus, though at the expense of diminished contrast sensitivity compared with the normal values expected for that age. Simulation experiments suggested that the observed reduction in contrast sensitivity was not adequately explained by a simple reduction in retinal illumination of the in-focus image as might intuitively be expected from the bifocal separation of incident light to two simultaneous focal points. The simultaneous superimposition of the out-of-focus image on the in-focus image must also be considered, since this caused a significant reduction in contrast sensitivity when the retinal illumination was insufficiently above the photopic luminance threshold.

The replacement of a cataractous lens by an acrylic lens of single focal length is now very widely practised. The implanted lens restores contrast transmission over the relevant range of spatial frequencies[1] and enhances colour discrimination.[2] However, even in the absence of postoperative astigmatism the patient still requires a spectacle correction for either near or distance viewing, depending on the chosen power of the intraocular lens. Two zone concentric bifocal intraocular lenses are under clinical investigation, but they seem likely to depend critically on centration, and pupil size and position. To avoid this difficulty the theoretical basis for an intraocular lens with an enhanced depth of focus has been described.[3] This consists of an artificial lens with a refractive power determined by the curvature of the surface, plus an additional refractive power produced by diffraction. The theory and the limitations of this type of lens have recently been reviewed.[4,5]

The 3M Company has now introduced a diffractive bifocal intraocular lens in which an additional +2·5 DS (now increased to +3·5 DS) is conferred by a series of concentric diffraction rings ('microslopes rings') etched on the posterior surface of the lens.[6] A survey of 55 patients who received either the +2·5 DS or +3·5 DS bifocal lens showed that some patients noted that the increased depth of focus was only at the expense of image clarity.[7] Patients with an intraocular bifocal lens also showed a significant loss of contrast sensitivity compared with age-matched controls with an intraocular monofocal lens at the near distance,[8] though it must be said that both groups of patients had been selected on the basis of having 20/20 vision or better.

Recently one of us (JLJ) has had the opportunity to insert the 3M bifocal lens into one eye of two elderly women each of whom had previously received the conventional monofocal lens in the companion eye. We have set out to compare the performance of the bifocal and monofocal lenses in situ by measurement of contrast sensitivity. This involves the determination of the contrast threshold for the detection of a vertical grating pattern which has a sinusoidal variation in luminance across its horizontal extent. A schematic drawing of such a grating pattern is shown in Fig 1. Hence by repeating this test for a range of different spatial frequencies – that is, the number of cycles per degree of visual angle – a more complete assessment of visual function is obtained than is possible with the Snellen test, which gives only the point of highest acuity. It is also possible to determine how the visibility of a grating pattern of a particular spatial frequency might vary with, say, defocus, which is not possible with Snellen letters of fixed contrast. This technique was, thus, employed in our determination of depth of focus.

Patients and methods

PATIENTS

The two healthy elderly women underwent clinical assessment and surgery at the Tennent Institute of Ophthalmology. Both had previously had an extracapsular cataract extraction and insertion of a Pearce tripod monofocal posterior chamber lens of power appropriate to the corneal curvature and axial length of the patient's eye. The operation in the second eye was by extracapsular extraction followed by insertion of a 3M bifocal intraocular lens (3M Health Care, Morley Street, Loughborough LE11 1EP). The possible merits and deficiencies of this type of lens were carefully explained to each patient, who gave her consent to the operation. Both patients received the standard postoperative medication. In one patient, who had cloudiness of the posterior capsule of the monofocal eye, YAG laser capsulotomy was subsequently performed.

About three months after the second operation each patient was further examined ophthalmoscopically and was refracted for distance vision by both the Snellen test and retinoscopy. The subjective refraction for the reading distance was determined with the Faculty of Ophthalmologists' reading type. After an explanation of the experimental procedures involved, including their right to withdraw from the assessment at

Tennent Insitute of Ophthalmology, Western Infirmary, Glasgow, G11 6NT
J L Jay

Institute of Physiology, University of Glasgow, Glasgow G12 8QQ
H S Chakrabarti
J D Morrison

Correspondence to:
J D Morrison.

Accepted for publication
1 November 1990

any time, each patient then gave her consent to undergo the following visual assessments, which were undertaken at the Institute of Physiology.

PRELIMINARY PROCEDURES

The optimum refraction was confirmed with the Snellen test and astigmatism fan. The diameter of the pupil of each eye was measured at intervals throughout the tests by photography.

ASSESSMENT OF RETINAL/NEURAL FUNCTION

This was undertaken to confirm that the patient has normal retinal/neural function and was not, for example, amblyopic. The contrast threshold was measured with the patient's natural pupil in response to vertical laser interference fringes of wavelength 632 nm. These were generated by focusing two collimated and converging laser beams on to the posterior nodal point of the eye, so that the interference fringes falling on the retina were essentially unaffected by the ocular media.[1] The contrast sensitivity was obtained as the reciprocal of the mean of five to eight contrast threshold readings to stationary laser interference fringes at each of spatial frequencies 10, 20, and 30 cycles/degree. These were obtained with the ascending method, by which the contrast of the interference finges was increased by the experimenter, from a uniform field, until the interference fringes were just visible. We were concerned that one eye should not be at a disadvantage to the other owing to a difference in the effective illumination at the retina by, perhaps, different retinal sensitivities. So the intensity of the laser display was arranged to be an equal increment above photopic threshold for the left and right eyes by the following method. First, the intensity at which the uniform display was just detectable was determined by attenuation with calibrated neutral density filters after 5 minutes in darkness for each eye in turn. Then the intensity of the experimental display was arranged to be suprathreshold by the same increment for each of the left and right eyes.

ASSESSMENT OF OVERALL VISUAL PERFORMANCE

Contrast sensitivity was measured for vertical sinusoidal grating patterns generated on a Tektronix 606B monitor of screen luminance 5·3 cd/m^2 and peak wavelength 520 nm.[9] Since this target was refracted by the ocular media of the eye, the contrast sensitivity measurements represent the product of ocular transmission and retinal/neural contrast sensitivity. This assessment of spatial discrimination was undertaken for spatial frequencies in the range 5–25 c/deg at a viewing distance of 2·86 m at which the display subtended 2° arc. The patient viewing with the natural pupil was refracted for this distance. In addition, the display luminance was adjusted to be an equal increment above photopic threshold for left and right eyes, as described for the laser display.

ASSESSMENT OF DEPTH OF FOCUS

Contrast sensitivity was measured for a vertical sinusoidal grating pattern of 5 c/deg viewed at 1·0 m. At this spatial frequency the contrast threshold is relatively low, even in older subjects,[10] which results in there being a substantial range of suprathreshold contrasts. On the other hand, at higher spatial frequencies the contrast threshold becomes appreciably greater, especially in the elderly, and the range of suprathreshold contrast is curtailed. This would thus limit the power of defocusing lens which could usefully be studied, since the grating pattern would not be detectable even at modest defocus. The patient was accurately refracted after both pupils had been dilated to minimise the depth of focus, which would be significantly enhanced in senile miosis and which would be different if left and right pupil diameters were unequal.[11] This was achieved by instilling one drop of 1% cyclopentolate hydrochloride *BP* (Minims) repeated after 5 minutes. In the case of M, these had only a moderate effect, and three drops of 10% phenylephrine hydrochloride *BP* (Minims) were subsequently instilled. A constant display luminance was employed with each eye. Contrast thresholds were measured for the left and right eyes alternately, for optimal focus and then with defocusing lenses of −2·0 DS, −4·0 DS, −6·0 DS, −8·0 DS, +1·0 DS, −1·0 DS, and −5·0 DS, in that order, in addition to a final duplicate measurement at optimal focus.

EFFECTS OF LUMINANCE ON CONTRAST SENSITIVITY

To simulate the effects of reduced intensity of the in-focus image produced by the bifocal lens, contrast sensitivity at 5 c/deg was measured for the monofocal eye at various levels of display luminance. This was done with a dilated pupil in response to logarithmic attenuations of the display luminance of −0·3 (50%), −0·6 (75%), −0·9 (87·5%), and −1·2 (93·7%), when viewing through the appropriate calibrated neutral density filter, in addition to final repeat measurements at the unattenuated luminance.

SIMULATION EXPERIMENT

Two Tektronix 606B monitors were viewed, each at 1·43 m, at which the screens subtended 4° arc, through a 38 mm cube beam splitter shown as BS in Fig 1. At this distance the smallest number of cycles (12) was well above the minimum required before contrast sensitivity was limited by the number of cycles, and the largest number of cycles (100) was below the maximum above which contrast declined owing to the characteristics of the monitor. Each screen was enclosed within a rectangular aperture in green card which matched the colour of the display. The display luminances were balanced by the addition of an appropriate neutral density filter (NDF1) in the path of oscilloscope 1. The Z modulation of each monitor was driven from the same oscillator and the timebase from the same ramp generator, so that grating patterns were of the same spatial frequency, spatial phase, and contrast and were accordingly precisely superimposable. The relationship between grating contrast and Z modulation voltage determined psychophysically[12] was similar for the two

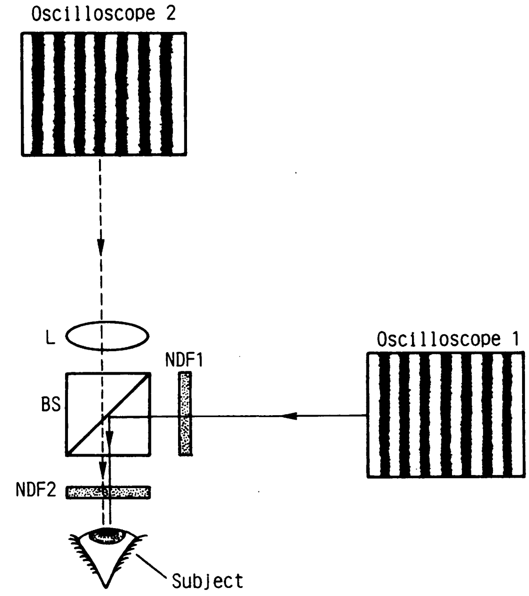

Figure 1 Apparatus for the production of two superimposed oscilloscope generated grating patterns which were viewed through the beam splitter BS. The beams were made equiluminant by the neutral density filter NDF1 (0·16 logarithmic unit), and defocus of oscilloscope 2 was effected by the trial lens L (+2·75 DS). Additional luminance decrements were produced by the neutral density filter NDF2.

monitors (namely, 0·253 and 0·265 contrast units per volt) except at relatively high voltages, where some divergence occurred: relatively few readings arose within this range and the contrast threshold was taken as the arithmetic mean of the two display contrasts. Coincidence of the two grating displays was tested by measurement of contrast sensitivity at 3, 5, 10, 15, 20, and 25 c/deg for viewing oscilloscope 1 alone and for viewing oscilloscopes 1 and 2 superimposed after the total luminance had been reduced by neutral density filter NDF2 to make it equal to oscilloscope 1 alone. These measurements proved to be identical (p>0·25), indicating accurate superimposition had been made. Whenever the displays had to be realigned, superimposition was always checked by this method for spatial frequencies 10 and 20 c/deg.

To simulate the condition in which the diffractive bifocal lens causes the simultaneous formation of an in-focus image and an out-of-focus image, oscilloscope 2 was defocused by a +2·75 DS trial lens positioned as near to the subject's eye as possible, which, owing to the presence of the beam splitter, was 100 mm from the estimated position of the posterior nodal point (L in Fig 1). The defocus at the posterior nodal point was calculated to be +3·79 DS.[13] To take account of the resultant magnification of the defocused image, oscilloscope 2 was moved further away from the beam splitter until its display outline, which though defocused was still discernible, was judged to equal that of oscilloscope 1. Further adjustments were made by viewing a square wave grating pattern of 5–6 cycles and high contrast after splitting the images so that oscilloscope 1 appeared in the upper half and oscilloscope 2 appeared in the lower half of the display. The lateral position of oscilloscope 2 was adjustable by a micrometer translation slide, the height by a scissors jack, and distance by mounting the assembly on a trolley, the movement of which was constrained by two parallel tables. The increase in magnification was compensated by moving oscilloscope 2 from 1·43 m to 1·82 m, which would have the effect of reducing the defocus caused by lens L by 0·15 DS. This gave a calculated net defocus of +3·64 DS, which is close to the diffractive power of the intraocular bifocal lens.

Table 1 Summary of visual test data

	Patient J		*Patient M*	
	Monofocal	*Bifocal*	*Monofocal*	*Bifocal*
Snellen acuity uncorrected	6/5	6/36	6/12 (−2)	6/12
Snellen acuity corrected	6/5	6/9	6/12*	6/9
Correction	nil	−0·25 DS −3·00 DC/30°	+0·75 DS +1·00 DC/120°	+1·25 DC/160°
Near acuity uncorrected	N.12	N.6	N.24 not resolved	N.6
Near acuity corrected	N.5	N.5	N.5	N.5
Correction	+2·5 DS	+1·0 DS	+3·5 DS	+1·0 DS
Natural pupil diameter	3·3 mm	4·5 mm	3·5 mm	3·5 mm
Dilated pupil	6·8 mm	6·1 mm	6·5 mm	6·0 mm

*6/9 after capsulotomy.

Contrast thresholds were first measured for 3, 5, 10, 15, 20 25 c/deg in response to the superimposed in-focus displays and, then, for the superimposed displays, but this time with that of oscilloscope 2 defocused as described above. The experiment was also repeated in the reverse order – that is, defocus followed by in-focus. But no differences were present when the experimental sequence was reversed. These measurements were undertaken for the two subjects H and D at the normal display luminance and with 0·9 logarithmic units attenuation to take account of the increased luminance thresholds of the elderly (see later). These experiments were also repeated on patient J when viewing with her monofocal eye.

To determine whether the defocused image contributed to the display contrast, contrast thresholds were measured for the superimposed displays with oscilloscope 2 defocused and with the defocused grating pattern substituted by a uniform background, which was effected by disconnecting the Z modulation of oscilloscope 2. The effects of a phase shift of the defocused image were also tested by displacement of the position of the defocused image by one half cycle, so that the defocused bright half cycle was superimposed on the in-focus dark half cycle of the in-focus grating display.

Results

The visual test data for J (age 77 yr) and M (age 71 yr) are summarised in Table 1.

Patient J had clear ocular media in both monofocal (right) and bifocal (left) eyes: the best Snellen acuity after optimal refraction was 6/5 in the monofocal eye and only 6/9 in the bifocal eye. Near acuity was equal in each eye at N5, though the monofocal eye required an additional +2·5 DS compared with only +1·0 DS in the bifocal eye. This patient told an impartial interviewer that she was delighted with the result of the second (bifocal) operation, which had restored her binocular vision. Hitherto she had experienced a lack of confidence in going out of doors and, for instance, avoided escalators. She felt that distance vision, as judged by reading the number and destination board of oncoming buses while wearing the prescribed spectacles, was better with the monofocal eye than the bifocal eye. She could read text well with each eye, though the resolution of the telephone directory was better with the monofocal eye, again while wearing the prescribed spectacles.

Patient M also had clear media in the bifocal (right) eye, though the monofocal (left) eye showed some haziness of the posterior capsule. Hence, the best Snellen acuity after opitmal refraction was better in the bifocal eye at 6/9 than in the monofcal eye at 6/12. After capsulotomy the Snellen acuity in the monofcal eye had improved to 6/9. Near acuity was N5 with each eye. The monofocal eye required an additional +3·5 DS, while the bifocal eye required only +1·0 DS. This patient was again delighted with the result of her second (bifocal) operation, for she had been bumping into furniture prior to the operation. With her spectacles she could read price tickets in shop windows equally well with either eye and was not aware of any difference in distance vision betwen the two eyes. She could read well unaided with her bifocal eye, though she required additional refraction in her monofocal eye. Otherwise there was again no apparent difference in performance between the two eyes. She wholeheartedly recommended the bifocal implant.

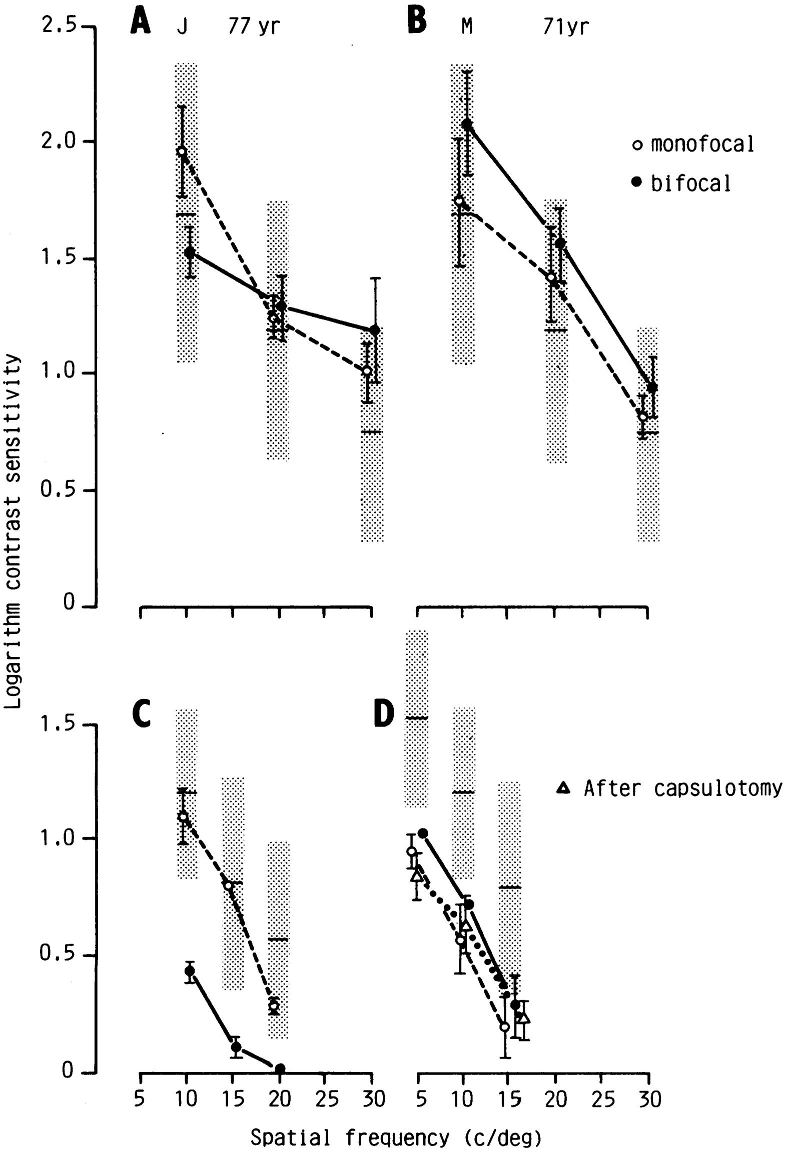

Figure 2 Contrast sensitivities to laser interference fringes (A and B) and oscilloscope-generated grating patterns (C and D) for viewing with the monofocal eye and bifocal eye. D also shows the results after capsulotomy. Note the different spatial frequency ranges in C and D. Each point is the mean with SD for 5-8 measurements. The stippled areas show the mean with 2 SD for 12 normal subjects ages 69–80 years obtained from Morrison and McGrath.[1]

Neither patient reported the presence of blurring or shadows at the reading distance, as had been noted previously by some patients.[7]

ASSESSMENT OF RETINAL/NEURAL FUNCTION (LASER INTERFEROMETER)

In these experiments the display luminance was arranged to be an equal increment above photopic threshold in left and right eyes to take account of any intereye difference, and viewing was with the natural pupil. The magnitude of neutral density filter required to attain threshold was slightly different for the monofocal and bifocal eyes (3·31 and 3·15 logarithmic units, respectively, for J; and 2·71 and 2·63 logarithmic units, respectively, for M). A correction was applied in the case of J but not M. The contrast sensitivities to the laser display were marginally higher in the bifocal eye at 20 and 30 c/deg than in the monofocal eye of J (Fig 2A), while it was higher in the bifocal eye at 10, 20, and 30 c/deg in M (Fig 2B). All the measured values were within the expected normal range obtained from previous data.[1] Thus the neural performance of the four eyes was judged equivalent.

ASSESSMENT OF OVERALL VISUAL FUNCTION (OSCILLOSCOPE DISPLAY)

Minor differences in photopic thresholds were again present between monofocal and bifocal eyes (3·00 and 2·70 logarithmic units, respectively, for J; and 2·63 and 2·49 logarithmic units, respectively, for M) and were compensated with the appropriate neutral density filter.

The contrast sensitivity measurements of J and M were compared with the expected normal range obtained from previous data.[1] Only those values for the monfocal eye of J fell within the normal range (Fig 2C). The contrast sensitivities for the bifocal eye of J, which were reduced by some 0·70 logarithmic unit at 10 and 15 c/deg compared with the monofocal eye, fell below the normal range. In M the contrast sensitivities, which were measured over 5-15 c/deg owing to her diminished resolution, were abnormally low for both monofocal and bifocal eyes. Comparisons between the two eyes showed no significant differences at the three spatial frequencies ($p>0{\cdot}062$). Following capsulotomy of the monofocal eye contrast sensitivity was found to be reduced slightly at 5 c/deg ($p=0{\cdot}017$) and unchanged at 10 and 15 c/deg ($p>0{\cdot}25$) (Fig 2D).

ASSESSMENT OF DEPTH OF FOCUS

Viewing in these experiments was with a dilated pupil which was within the range of 6·0–6·8 mm, when the depth of focus is negligible,[11] and for a constant display luminance for each eye. The contrast sensitivity at 5 c/deg for the monofocal

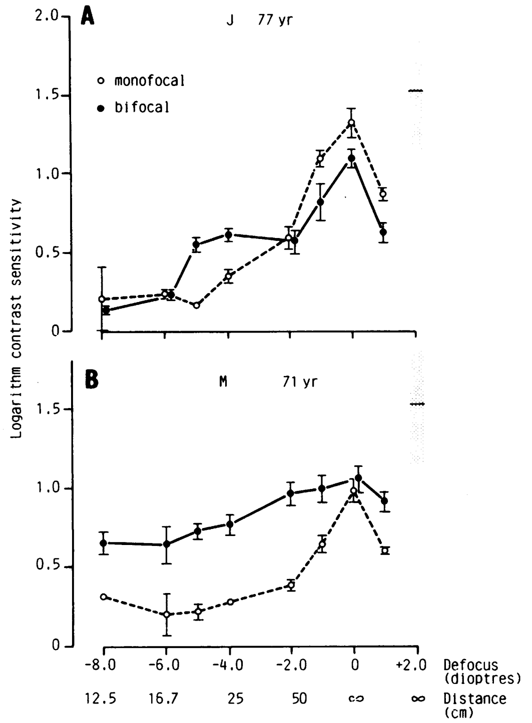

Figure 3 Contrast sensitivity at 5 c/deg for the monofocal eye and bifocal eye of the two patients (A and B) in response to viewing through trial lenses which simulated different viewing distances. Each point is the mean with SD for 5–8 measurements. The stippled zone shows the mean with 2 SD for 11 normal subjects ages 69–78 years obtained from McGrath and Morrison.[10]

eye of J fell within the expected normal range obtained from previous data,[10] while that of the monofocal eye of M and the two bifocal eyes fell below the normal range (Fig 3A, B). With increasing defocus the contrast sensitivity for both monofocal eyes declined, with a 0·30 logarithmic unit reduction occurring at ±1·0 DS.

The contrast sensitivities for the two bifocal eyes, however, were not affected as much by defocus. In J it was greater by 0·26 and 0·38 logarithmic units than for the monofocal eye at −4·0 DS and −5·0 DS, respectively, despite the fact that at optimum focus it was actually 0·23 logarithmic unit less than that of the monofocal eye (Fig 3A). At none of the defocuses did the contrast sensitivity lie within the expected normal range. This was also the case with M, though the reduction of contrast sensitivity for the bifocal eye with defocus was much less than with the monofocal eye (Fig 3B). At −5·0 DS the contrast sensitivity had fallen by 0·80 logarithmic unit for the monofocal eye and by 0·32 logarithmic unit for the bifocal eye. Thus in both patients the bifocal lens had conferred a considerable depth of focus which was not present with the monofocal lens.

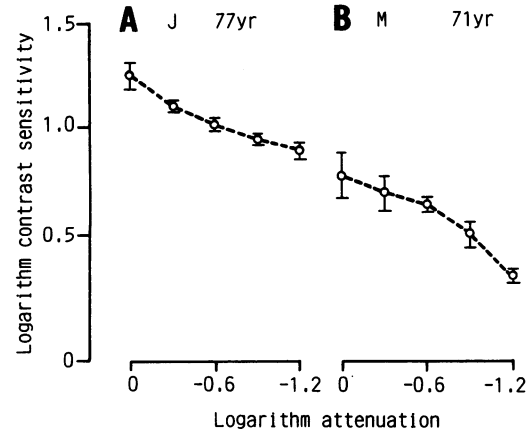

Figure 4 Contrast sensitivities at 5 c/deg for attenuation of the display luminance when viewing with the monofocal eye of the two patients (A and B). Each point is the mean with SD for 5–6 measurements.

EFFECTS OF LUMINANCE OF CONTRAST SENSITIVITY

On the assumption that the incident light is divided equally between the two focal points of the bifocal lens we tested the possibility that it was the reduction in retinal illumination as such of the in-focus image which caused the abnormally low contrast sensitivity at 5 c/deg. Contrast sensitivity was measured in the monofocal eye at 5 c/deg for progressive 0·3 logarithmic unit (50%) attenuations in display luminance. It declined monotonically with increasing attenuation in both patients (Fig 4). An attenuation in luminance of 50% resulted in a significant reduction in contrast sensitivity of 0·14 logarithmic unit in J ($p=0\cdot0001$, Fig 4A). While this would account in part for the 0·23 logarithmic unit difference between monofocal and bifocal eyes at 5 c/deg (Fig 3A), it would not be relevant to the difference present in Fig 2C. In M the reduction was only 0·07 logarithmic unit ($p=0\cdot22$, Fig 4B), which, when taken into account, is insufficient to explain the abnormally low contrast sensitivity in comparison with the expected normal range (Fig 3B). In young subjects the 0·3 logarithmic unit attenuation did not result in reduced contrast sensitivity, which is consistent with previous results.[1]

SUPERIMPOSION OF A DEFOCUSED IMAGE

At the normal display luminance, which was 3·53 logarithmic units above photopic threshold for subjects H and D, contrast sensitivities over the range 3–25 c/deg for the presence of the superimposed defocused display were indistinguishable from those for when the two displays were in-focus ($p>0\cdot25$, paired *t* test) (Fig 5A). The mean photopic luminance threshold for the bifocal eyes of J and M was, however, 2·60 logarithmic units. So, when the experiment was repeated with an additional attenuation of 0·9 logarithmic unit, a consistent fall in contrast sensitivity over 3–25 c/deg was recorded (Fig 5B). The reduction of 0·14 and 0·28 logarithmic unit (28% and 40%, respectively) for H and D, respectively, was statistically significant ($p<0\cdot01$). For an attenuation of 0·6 logarithmic unit contrast sensitivity was not reduced ($0\cdot05<p<0\cdot01$).

The contribution of the defocused image to the display contrast was assessed by substitution of a uniform background in place of the defocused display. This resulted in a further loss of 0·12 logarithmic unit (24%) ($p<0\cdot05$) (Fig 5C, open triangles). A similar reduction in contrast sensitivity also occurred when the defocused grating pattern was displaced laterally by one half cycle (Figure 5C, inverted solid triangles). The main reduction occurred at spatial fre-

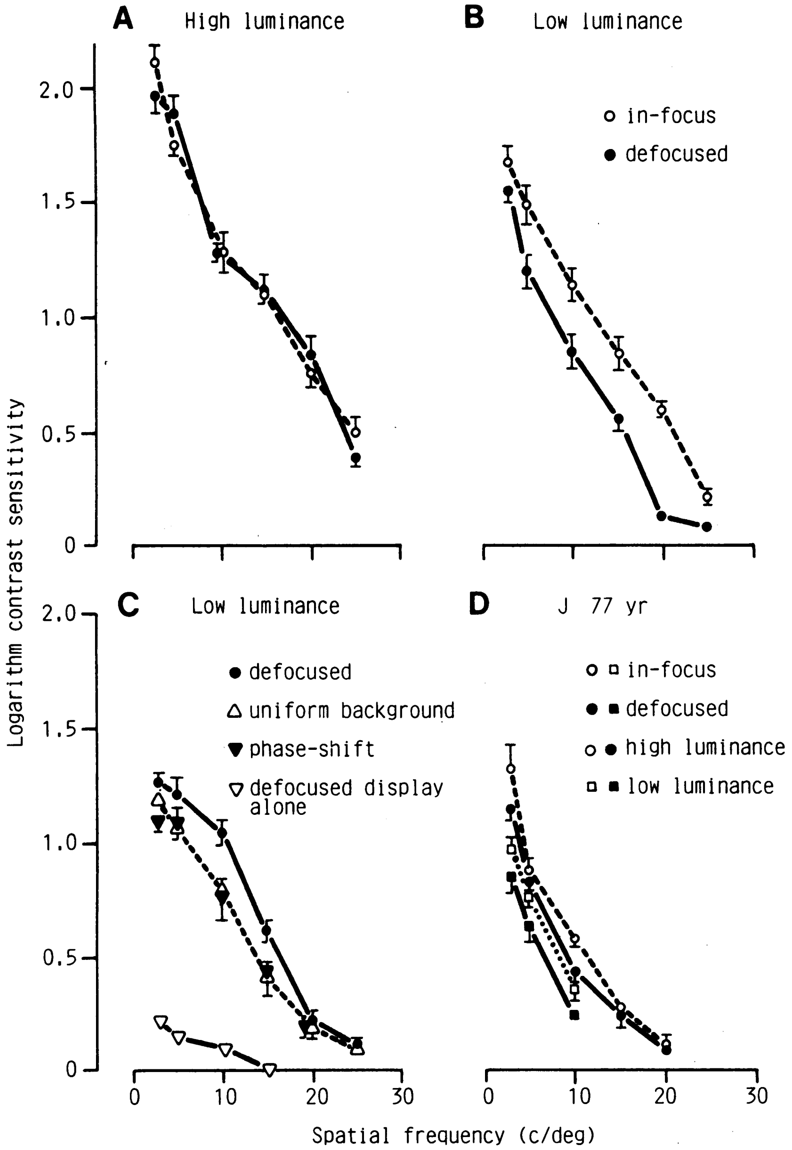

Figure 5 Effects of a superimposed defocused image on contrast sensitivity in a young subject at normal luminance (A) and at 0·9 logarithmic unit attenuation (B). Open circles denote the superimposed in-focus displays and solid symbols denote the superimposition of the defocused display of oscilloscope 2 on the in-focus display of oscilloscope 1. Substitution of the defocused display (solid circles) by a uniform background of the same overall luminance (open triangles) and by the counterphased defocused grating pattern (inverted solid triangles) are shown in C. Contrast sensitivities to the equiluminant defocused display alone are shown by inverted open triangles. In D the contrast sensitivities of patient J viewing with her monofocal eye are shown for the superimposed in-focus display (open circles and squares) and superimposed defocused display (solid circles and squares). These were measured for the normal display luminance (circles) and at 0·6 logarithmic unit attenuation (squares). J wore an additional +0·75 DS for optimal focus at the normal viewing distance of 1·43 m. Each point is the mean with SD for 5–6 measurements.

quencies of below 20 c/deg, which was interpreted as meaning that at 20 and 25 c/deg the display was defocused to such an extent that neither the in-phase nor out-of-phase grating patterns contributed to the detection of the in-focus display. This is consistent with the markedly depressed contrast sensitivities, especially those at higher spatial frequencies, which were off-scale, in response to the defocused display alone of the appropriate luminance (Fig 5C, inverted open triangles).

In the experiments with J viewing with her monofocal eye the normal display luminance, which was the same as that employed in Fig 2C, in which the monofocal eye showed a markedly superior performance to the bifocal eye was initially employed. This was 3·00 logarithmic units above the photopic threshold. In the presence of the superimposed defocused display, contrast sensitivity was reduced somewhat compared to when the two superimposed displays were in-focus (Fig 5D, open and solid circles). The reduction of 0·09 logarithmic unit (19%) was on the borderline of statistical significance ($0.05<p<0.1$). When the overall luminance was reduced by 0·6 logarithmic unit, by which the monofocal eye was placed on a par with the bifocal eyes in terms of effective rentinal illumination, a slightly larger reduction of 0·12 logarithmic unit (24%) which was statistically significant ($p<0.01$) was recorded (Fig 5D, open and solid squares). This was, however, still insufficient to account for the large decrement between bifocal and monofocal eyes shown in Fig 2C.

Discussion

In our two patients the diffractive bifocal intraocular lens's main purpose in conferring an additional depth of focus than with the monofocal lens was shown to have been fulfilled. However, this appeared to be at the expense of spatial resolution, which was markedly impaired. In terms of contrast sensitivity, in one patient, the performance of the bifocal lens in situ was on par with the monofocal eye, the performance of which was suspected to be suboptimal. In the other patient the bifocal eye was markedly inferior to the monofocal eye.

RETINAL/NEURAL FUNCTION

The retinal/neural contrast sensitivities of all four eyes fell within the expected normal range and indeed were broadly similar. This suggests that there was no adverse effect of the operation on retinal/neural function. Moreover, there did not appear to be a deleterious effect of the diffraction rings of the bifocal lens on the contrast of the laser interference fringes. This may be surmised to be due to the fact that the two laser beams incident to the eye are focused by the Maxwellian lens on to the posterior nodal point of the eye. Thus the beam diameter at the bifocal lens is relatively small in comparison with the spacing of the diffraction rings, the first of which may be expected to have a diameter of 1·07 mm for +3·5 DS.[4] In the case when a large collimated beam is incident to the diffraction rings, a circular diffraction pattern would be generated for each beam, and these themselves would mutually interfere. No such patterns were ever reported, and only the vertical interference fringe pattern was ever detected by the patients, even at high contrasts. Thus it becomes feasible to assess the deficit caused by the bifocal lens on the resolution of the oscilloscope-generated grating pattern by an estimation of the Snellen acuity expected from the laser interference fringe contrast sensitivities. On the basis of the data in Figure 2A and B a Snellen acuity of 6/6 or 6/5 would reasonably have been expected for the bifocal eyes instead of the recorded 6/9.[1]

OVERALL VISUAL FUNCTION

It would appear that a penalty has been paid in our two patients in terms of best distance acuity in order to gain depth of focus. This is most apparent in patient J, to whom the difference was readily discernible. In M the monofocal and bifocal eyes did show a similar level of performance, though in this patient we believe that this was attributable to the anomalous underperformance of the monofocal eye. In this respect it was noted that capsulotomy of the monofocal eye with the hazy posterior capsule did not result in improved vision (Fig 2D), which indicates that the capsule was unimportant in causing this anomaly. Other such anomalies have been encountered occasionally in a previous study.[1] No definite explanation can be given other than to remark that irregularities of the cornea and pathology of the retina might be excluded, since both would adversely affect the laser interference fringe contrast sensitivity.

The division of incident light between the two focal points by the bifocal lens, and hence, a reduction in luminance of each in-focus image, may reasonably be expected to have some effect on contrast sensitivity (Fig 4), though this would not account for the observed reduction in contrast sensitivities under the experimental condition where the effective luminance of left and right eyes had been made equal (Fig 2C, D). However, it must be said that by simply matching luminances for the monofocal and bifocal eyes the possibility of a reduced illumination of the in-focus image is not completely excluded. First, it does not follow that the two eyes should have equivalent photopic thresholds, especially in the elderly, where there may have been differential effects of aging; and, secondly, the in-focus image will have superimposed upon it the out-of-focus image. In the luminance matching procedure this would serve to cause an underestimation of the luminance of the in-focus image.

However, we believe that another explanation, other than a simple reduction in luminance, should be considered. We have demonstrated that the superimposition of the out-of-focus image on the in-focus image has a deleterious effect on contrast sensitivity when the display luminance is an insufficient amount above the photopic luminance threshold in both the control subjects and the patient J. In these experiments our estimate of an age related increase in photopic threshold of 0·9 logarithmic unit, based as it was on a limited number of eyes, is consistent with previous data.[14] Patient J actually had a somewhat lower than expected luminance threshold for her monofocal eye, but, once taken into account, contrast sensitivities were signficantly reduced in the presence of the superimposed defocused image. The reduction, however, was insufficient to explain the marked deficit recorded in Fig 2C, for which other explanations must be sought. It must be emphasised that the cause must be optical rather than neural, since retinal contrast sensitivities were normal (Fig 2A). One unknown factor which has yet to be evaluated theoretically[5] is the possibility of a phase shift by the diffractive optics. This would cause a further decrement in contrast sensitivity (Fig 5C), though again not to an extent that would completely explain the deficit shown in Figure 2C.

Several further complexities exist. The performance of the bifocal lens will depend critically on the accuracy of the position of the diffraction rings, since the interval between rings must decrease with eccentricity.[4] Thus the machining of the diffraction rings and centring of the lens would need to be precise to ensure constructive interference of the diffracted light rays; otherwise destructive interference would arise. Secondly, the characteristics of the diffractive lens are specific to a certain wavelength of light, since refraction is *directly* related to wavelength. In other words, the 41% transmission specified by the manufacturer is applicable to only one (unstated) wavelength. On the assumption that the specifications are for green light we may surmise that the performance obtained in response to our green oscilloscope display is in fact the best possible and would be poorer for other wavelengths.[5] Hence it would appear from the lower than expected contrast sensitivities for the two bifocal eyes (Fig 2C, D) that there are factors yet to be recognised in the explanation for these deficits. This would perhaps justify the mounting of a larger scale in-depth study of patients with a monofocal implant and diffractive bifocal implant in their respective eyes. Our more detailed experimental study thus complements the clinical study of Percival[7] and the photographic analysis of Zisser and Guyton.[15]

If the experiment in which a defocused image was superimposed on the in-focus image is a reasonable simulation of the effects of the diffractive bifocal lens, we could expect that no measureable impairment of visual performance would arise, provided the luminance was sufficiently high with respect to that individual's photopic threshold, irrespective of age. This disregards the possible contribution of the factors of a phase – shift, chromatic aberration and decentration, which have yet to be evaluated. However, with insufficient illumination a significant decrement in contrast sensitivity would be predicted, especially in older patients, whose luminance threshold is raised as part of the normal aging process.[14] This decrement would be predicted to be exacerbated for viewing within the scotopic range. Hence under conditions of low illumination the diffractive bifocal intraocular lens may not reasonably by expected to give the same quality of vision as the monofocal lens.

Some patients may, however, happily trade diminished contrast sensitivity in distance vision for a greater depth of focus. This may apply to elderly patients who have a more sedentary life style and for whom resolution of distant objects is relatively unimportant, and to younger patients who still have accommodation in one eye and who might thus prefer the bifocal intraocular lens in the companion eye. On the other hand the monofocal implant may be the choice of those for whom distance vision is of particular importance. This choice should be considered in terms of the prospective patient's photopic luminance threshold. Plainly it is impracticable to make determinations on a cataractous eye, though regard could profitably be given to the previously well established data across the lifespan.[14] Accordingly, the potential difference in performance

between the diffractive bifocal and monofocal lens should be explained fully to the patient.

We thank Dr W N Charman for discussion of the results and Dr B R Mackenna for his painstaking interviews of the patients. The cooperation and forbearance of our two elderly patients were very much appreciated.

HSC was in receipt of an SHHD research award.

1 Morrison JD, McGrath C. Assessment of the optical contributions to the age-related deterioration in vision. *Q J Exp Physiol* 1985; **70**: 249-69.

2 Jay JL, Gautam VB, Allan B. Colour perception in pseudophakia. *Br J Ophthalmol* 1982; **66**: 658-62.

3 Freeman MH. Improvements in or relating to artificial eye lenses. *UK Patent GB 2101764B*. London: Patent Office, 1984: 1-32.

4 Charman WN. Diffractive bifocal contact lenses. *Contax* 1986; May: 11-7.

5 Klein SA, Ho Z-Y. Multizone bifocal contact lens design. *SPIE* 1986; **679**: 25-35.

6 Simpson MJ. The diffractive multifocal intraocular lens. *Eur J Implant Ref Surg* 1989; **1**: 115-21.

7 Percival SPB. Prospective study of the new diffractive bifocal intraocular lens. *Eye* 1989; **3**: 571-5.

8 Olsen T, Corydon L. Contrast sensitivity in patients with a new type of multifocal intraocular lens. *J Cataract Refract Surg* 1990; **16**: 42-6.

9 Kay CD, Morrison JD. The effects of a single intramuscular injection of atropine sulphate on visual performance in man. *Hum Toxicol* 1987; **6**: 165-72.

10 McGrath C, Morrison JD. The effects of age on spatial frequency perception in human subjects. *Q J Exp Physiol* 1981; **66**: 253-61.

11 Campbell FW. The depth of field of the human eye. *Optica Acta* 1958; **4**: 157-64.

12 Campbell FW, Green DG. Optical and retinal factors affecting visual resolution. *J Physiol (Lond)* 1965; **181**: 576-93.

13 Duke-Elder S, Abrams D. *Ophthalmic optics and refraction. System of ophthalmology*. London: Kimpton, 1970; **5**: 74-6.

14 Weale RA. *Biography of the eye*. London: Lewis, 1982: 268.

15 Zisser HC, Guyton DL. Photographic simulation of image quality through bifocal intraocular lenses. *Am J Ophthalmol* 1989; **108**: 324-6.