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Multifocal Intraocular Lenses and Glare

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ABSTRACT

In a previous paper, we reported finding deficits in the contrast sensitivity functions of patients with diffractive multifocal intraocular lenses (IOL's). The results were consistent with optical measurements of the modulation transfer function (MTF) of the IOL. When this MTF is treated as a linear spatial frequency filter, it predicts the existence of a *glare effect*; contrast threshold for the recognition of target letters should be elevated by a bright, adjacent stimulus. We tested this prediction by measuring contrast thresholds for recognizing 0.2° Sloan letters on a background luminance of 11.2 cd/m². The letters were presented inside bright (300 cd/m²) annular rings with inner diameters ranging from 0.42 to 1.22°. Thresholds were measured for seven multifocal subjects, age-matched groups of monofocal subjects and phakic-control subjects, and a young group. Multifocal subjects exhibited a greater glare effect than monofocal subjects, and they in turn exhibited a greater effect than phakic-control subjects. The observed glare effect for multifocal subjects was about twice that expected from the spatial filtering property of the multifocal IOL.

Key Words: multifocal intraocular lens, glare, contrast sensitivity, MTF

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IOL implants have become a common treatment after cataract extraction. Multifocal IOL's, a new type of IOL, increase the depth of focus compared with monofocal IOL's. They simultaneously create images on the retina that are conjugate with two or more depth planes.

Our previous papers[1, 2] presented detailed data illustrating the visual tradeoff inherent in IOL's: increased depth of field vs. reduced contrast sensitivity. The increased depth of field was evident from our finding that multifocal patients corrected for distance had almost the same acuities and contrast sensitivities for near (40 cm) and far targets. But multifocal patients had contrast sensitivities that were lower by about a factor of 2 than well focused age-matched phakic controls and monofocal patients for sinewave gratings of intermediate and high spatial frequencies. Contrast sensitivities were also a factor of 2 lower for recognizing letters subtending 0.3 and 1.0°, a task requiring intermediate spatial frequencies. Consistent with the grating thresholds and the letter recognition results, our multifocal patients showed deficits in reading speed when the text had small characters or low contrast.

Many studies have emphasized the clinical importance of measuring disability glare (e.g., Hirsch et al.[3]) because glare can have a serious impact on everyday visual function. A *glare effect* occurs if the visibility of an object of interest is reduced when a bright stimulus is presented elsewhere in the visual field. Sources of disabling glare include bright sunlight and the headlights of oncoming cars at night. Glare effects experienced by people with normal (phakic) eyes are thought to be due in large part to retinal contrast reduction due to intraocular light scatter from the cornea, lens, and retina.[4] There are two reasons to ask if multifocal patients experience abnormal glare effects: (1) theory predicts a glare effect associated with the optical MTF of the

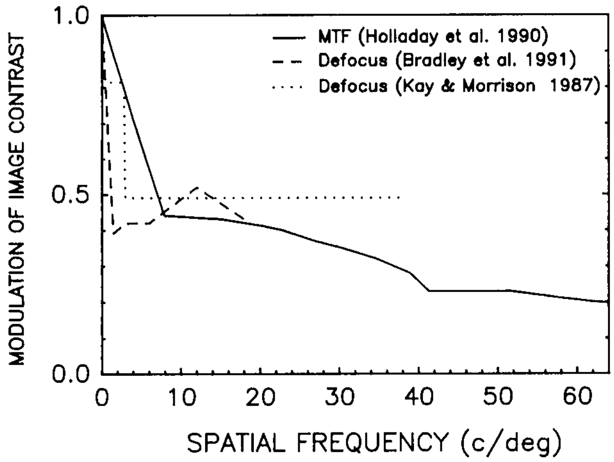

Figure 1. The MTF of the multifocal lens is shown, based on the measurements of Holladay et al.[2] We used Holladay's MTF as a radially symmetric 2-D spatial frequency filter. For comparison, we have included curves showing the contrast attenuation associated with +1 D defocus, based on the data of Kay and Morrison[5] and Bradley et al.[6] The defocus curves show the ratio of mean contrast sensitivities for +1 D defocus to in-focus contrast sensitivities, with 3-mm diameter pupils (Kay and Morrison) and with natural pupils (Bradley et al.).

lens and (2) empirical studies of patients with contact lenses and IOL's have sometimes revealed abnormal glare. In the following paragraphs, we elaborate on these two issues.

The MTF of the diffractive multifocal lens was measured by Holladay et al.[2] and is replotted in Fig. 1. This MTF has a low-pass form because the IOL attenuates the contrast of high spatial frequencies more than low frequencies.[1, 2] The lens can be viewed as a low-pass spatial frequency filter that introduces slight blurring into retinal images. When a localized bright stimulus with sharp luminance edges is present in the visual field, this blurring "smears" the edges of the corresponding retinal image, casting a significant veil of light across the adjacent retina. This veil would reduce the contrast of adjacent retinal images, near the glare image, especially those with low luminance.

For comparison, Fig. 1 also shows the contrast-attenuation effect of 1 D of blur, estimated from two studies of contrast sensitivities with and without defocus[5, 6] (see the figure caption for more details). The spatial filtering property of the multifocal MTF is qualitatively similar to that of 1 D defocus.

In our experiment, the glare stimulus was a bright ring of light surrounding a dark interior. For blur-free optics, the corresponding retinal image would also have a dark interior. However, low-pass filtering of the glare ring results in the spread of light into the interior. Fig. 2 shows one-dimensional luminance profiles of such a ring stimulus after low-pass filtering. Plots are shown for rings of three inner diameters. The unfiltered rings had a luminance of 300 cd/m^2. The filter function was constructed from the MTF of the diffractive multifocal IOL (see Fig. 1). In Fig. 2, the filtered rings have nonzero luminance at their centers—average values of 13.4, 3.4, and 1.6 cd/m^2 for the small, medium, and large rings, respectively.

In our experiment, we measured contrast thresholds for isolated letters presented at the center of glare rings. The letters were rendered as dark characters on a lighter (11.2 cd/m^2) background. How would the veiling light from the filtered rings affect contrast thresholds? Suppose that a subject's glare-free threshold is 10% Michelson contrast, corresponding to 9.16 cd/m^2 letters on an 11.2 cd/m^2 background. After adding 13.4 cd/m^2 of veiling light from a low-pass-filtered glare ring, the luminances become 22.56 (letters) and 24.6 cd/m^2 (background). The effective contrast is now 4.3%. To restore the letters to their threshold contrast of 10%, the luminance of the letters on the screen must be reduced from 9.16 to 6.73 cd/m^2. Letters of this luminance on an 11.2 cd/m^2 background have a screen contrast of 25%. In this example, the

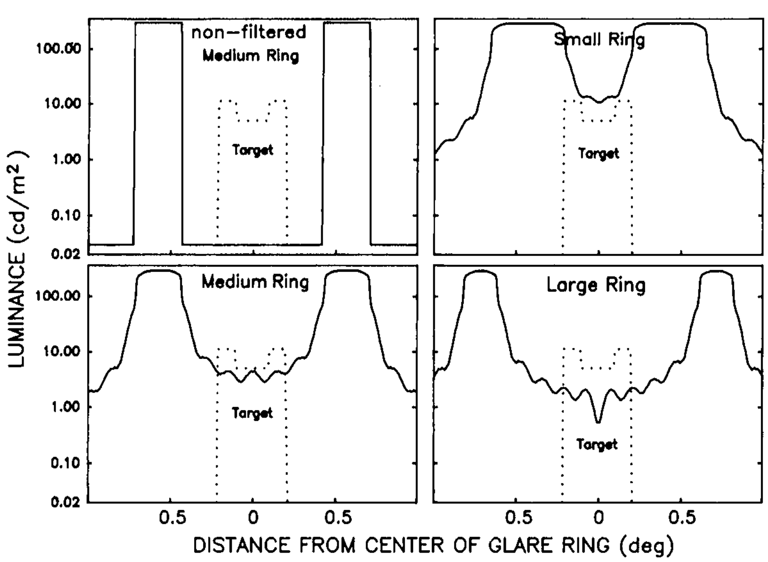

Figure 2. One-dimensional cross-sections of the radially symmetric luminance profiles are shown for an unfiltered glare ring and for glare rings of three different sizes after spatial frequency filtering. The filter function, taken from the MTF of the multifocal lens measured by Holladay et al.[2] is shown in Fig. 1. Luminance is plotted on a log scale. The dotted profile schematically shows the presence of a low-contrast target on a low-luminance background at the center of the glare ring. Effects of filtering on the target are not shown. Notice that the filtered glare rings have significant luminance at their centers, overlapping the target.

dilution of retinal contrast by the veiling light from the filtered ring elevated the subject's contrast threshold by 2½ times.

The theoretical model implicit in this example is one in which the multifocal-wearing subject is considered to be equivalent to a phakic control subject preceded by a low-pass spatial frequency filter characterized by the MTF of the multifocal IOL. This simple model works well in accounting for contrast sensitivity functions of multifocal wearers.[1] We can use the model, as outlined in the preceding example, to predict threshold elevation produced by our glare stimuli. The MTF of a monofocal IOL is essentially flat within the visible range, so a filtering analysis predicts no abnormal glare effects for monofocal wearers. Our theoretical purpose was to determine if multifocal wearers show glare effects of the predicted size.

Several studies have examined glare effects associated with contact lenses and monofocal IOL's. Hydrogel contact lenses were found to produce more disability glare than the spherical equivalent spectacles.[7] Wearers of bifocal contact lenses suffered more from glare than wearers of monovision contact lenses in a low-contrast acuity task.[8] There is evidence that patients with monofocal IOL's are more susceptible to glare than phakic controls.[9-11]

Two studies of multifocal wearers have reported no significant glare effects on acuity with the Brightness Acuity Test (BAT).[12, 13] Another study, using the Humphrey glare tester, showed that glare reduced acuity about equally for multifocal and monofocal wearers.[14] A study with the InnoMed TVA system reported that multifocal wearers exhibited greater contrast-threshold elevation due to glare than monofocal wearers.[15] The same study reported a significantly higher proportion of complaints of blurred vision, rings, halos, and glare in patients with multifocal IOL's.[15] Our second purpose was to address an empirical question. Are glare effects in multifocal wearers greater than those experienced by phakic control or monofocal wearers?

SUBJECTS AND METHODS

There were 7 subjects in each of 4 groups, the same 28 subjects discussed in our earlier paper.[1] Age was matched for the *multifocal*, *monofocal*, and *phakic-control* groups. The *young-control* subjects were college students. None showed evidence of other ocular abnormalities. The experiment was conducted at least 4 months after the implant surgery. The ocular health of the young group was determined from their self-report. Table 1 shows each subject's age, far-focus visual acuity with the Lighthouse Early Treatment Diabetic Retinopathy Study chart (ETDRS chart), and contrast sensitivity with the Pelli-Robson chart. Acuities and contrast sensitivities were obtained with natural pupils in a well illuminated room. The illuminance of the white portions of the test charts was approximately 100 cd/m^2.

TABLE 1. Subjects' acuities and contrast sensitivities,[a] far acuity is shown in logMAR units,[b] contrast sensitivity with the Pelli-Robson chart is in log units (P-R CS).[c]

	Age (yr)	Acuity	P-R CS
Young-Normal Group			
subject			
1	20	0.0	1.73
2	37	0.0	1.80
3	32	−0.1	1.65
4	33	0.0	1.80
5	20	0.0	1.80
6	22	−0.1	1.95
7	24	−0.1	1.80
Mean	26.9	−0.043	1.79
SD	7.0	0.053	0.09
Phakic-Control Group			
subject			
8	57	0.0	1.65
9	66	0.1	1.65
10	70	0.0	1.57
11	68	0.1	1.65
12	68	−0.1	1.65
13	64	0.1	1.80
14	70	0.1	1.43
Mean	66.1	0.043	1.63
SD	4.6	0.079	0.11
Monofocal IOL Group			
subject			
15	68	0.0	1.73
16	76	0.0	1.58
17	66	0.1	1.58
18	73	0.0	1.65
19	70	0.0	1.50
20	75	0.0	1.65
21	63	0.0	1.50
Mean	72.4	0.0	1.62
SD	3.4	0.0	0.09
Multifocal IOL Group			
subject			
22	62	0.0	1.50
23	65	0.0	1.50
24	68	0.1	1.65
25	79	0.1	1.50
26	64	0.0	1.50
27	61	0.0	1.80
28	69	0.0	1.43
Mean	67.7	0.03	1.56
SD	6.3	0.051	0.14

[a] Subjects 17, 21, and 22 are excluded from the calculation of means and SDs (see text).
[b] Far acuity was measured at 4 m distance.
[c] Contrast sensitivity was measured at 1 m distance.

Two monofocal wearers (subjects 17 and 21) and one multifocal wearer (subject 22) were found to have trace capsular haze. We excluded these three subjects from the subsequent data analysis. Our glare measurements on the remaining subjects represent findings for monofocal and multifocal wearers with good visual outcomes.

All of the remaining 25 subjects had acuities of 0.1 logMAR (Snellen 20/25) or better. The average logMAR acuities and Pelli-Robson contrast sensitivities for the four groups were: young (−0.04, 1.79); phakic control (0.04, 1.63); monofocal (0.0, 1.62); and multifocal (0.03, 1.56). The average acuity of the phakic group was consistent with that reported by Elliott and Hurst.[16] Mean contrast sensitivities for the young and phakic control groups were also consistent with those reported by previous studies.[6, 16, 17]

Multifocal wearers were implanted with 3M diffractive multifocal IOL's (model 815 LE). Monofocal wearers received 3M monofocal IOL's (model 15 LE) which were identical to the multifocal IOL in all respects except for the optical element. For the design characteristics of both implants refer to Akutsu et al.[1]

We measured contrast thresholds for recognizing single letters (10 Sloan optotypes) in the presence of glare rings (see Fig. 3). The letters were displayed as dark characters on a circular light background at the center of a video screen. The background field had a diameter of 0.4° and a luminance of 11.2 cd/m^2. The letters were 0.2° in size (about twice the acuity limit), viewed from 4.0 m. Letter contrast was reduced by increasing letter luminance toward the constant background luminance. Contrast was reduced 0.1 log units if the subject correctly identified six or more letters in a series of eight at a given contrast level. Contrast threshold is defined as the lowest contrast for which the subject met this criterion. We use the Michelson definition of contrast in this study: contrast is equal to $(L_{max} - L_{min})/(L_{max} + L_{min})$, where L_{max} and L_{min} are maximum and minimum stimulus luminances, respectively. The inner diameters of the bright glare rings were 0.42°, 0.86°, and 1.22° in visual angle. The ring luminance was 300 cd/m^2. In order to keep the corneal flux constant, the glare ring area was kept constant by adjusting thickness as follows: 0.44°, 0.28°, and 0.21° for the small, medium, and large rings, respectively. We verified photometrically that the illuminance at the position of the eye was approximately constant for the different glare rings.

During a series of trials, the glare ring was present continuously. A target letter remained on until the subject responded. It then disappeared and was immediately replaced by the next letter.

Measurements were monocular in a dark room. Subjects were given appropriate refractive correction. Thresholds for the four conditions (three ring diameters and no glare) were measured twice for each subject, in opposite orders. The order was randomized across subjects. The data points for individual subjects show means of the two thresholds.

Multifocal-threshold elevation in the presence of glare rings was compared with the predictions of a spatial frequency filtering model (see earlier text). According to this model, the multifocal wearer is equivalent to an age-matched phakic control subject preceded by a low-pass spatial frequency filter. The filter function is given by the MTF of the multifocal lens. We used the MTF measurements reported by Holladay et al.[2] (their Fig. 2). We used an HP 7470A digitizing plotter to sample the piecewise linear spatial frequency curves at 16 discrete frequencies from 0 to 64 cpd. The glare ring images were filtered with the HIPS image processing package.[18] Using linear interpolation, a radially symmetric multifocal MTF filtering function was computed for every coefficient in the 2-D FFT frequency grid. The glare ring images submitted to the FFT program spanned −2° to +2° with respect to the center of the image on a 512 by 512 pixel grid (i.e., 128 pixels/deg). The highest horizontal and vertical FFT spatial frequency was 64 cpd.

All the target letters fit in a 0.2 by 0.2° square. We computed the average luminance of the veiling light cast by a filtered glare ring in the circle circumscribing this square (i.e., a 0.28° diameter circle centered on the letters). As illustrated in Fig. 2, the filtered images contain spatial fine structure (ripples) within the veiling light. For purposes of our analysis, we ignored this fine structure and considered only the effects of mean veiling light level. It is possible that the spatial structure would increase the glare effect through masking, so we consider our estimates a lower bound on the glare expected from the filter model.

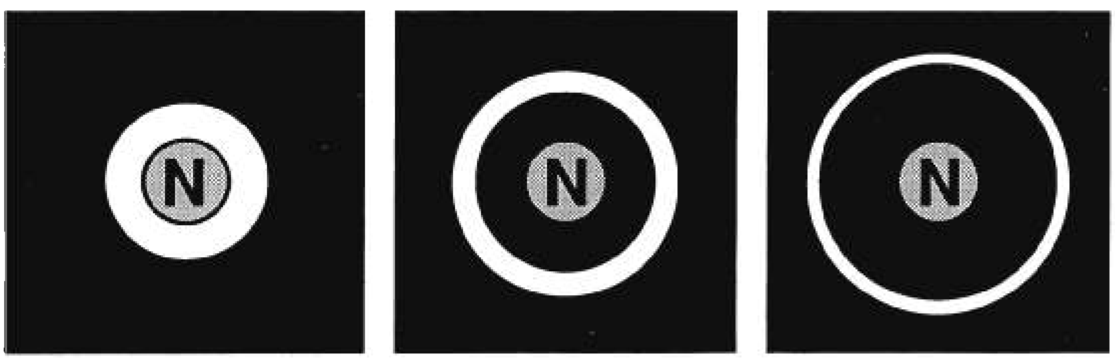

Figure 3. Schematic diagrams of the stimuli used in the experiment. A target letter subtended 0.2° and the background 0.4°. The inner diameters of the glare rings were 0.42°, 0.86°, and 1.22°. The luminance of the glare ring was 300 cd/m^2, and that of the background was 11.2 cd/m^2 (indicated by the half-tone). Contrast of the letters was reduced to determine the subject's threshold.

Our prediction of multifocal thresholds from corresponding age-matched phakic control thresholds involved two steps:

1. In the absence of glare rings, we expect the multifocal letter threshold to be about twice the phakic control threshold for the following reason: Previous research has shown that letter recognition can be based on spatial frequencies extending from about 1 to 2 cycles/letter.[19-21] For our 0.2° letters, this band corresponds to spatial frequencies of 5 to 10 cpd. In our previous paper,[1] multifocal contrast sensitivities were shown to be about a factor of 2 lower than phakic control sensitivities in the 5 to 10 cpd frequency range. The filter model therefore predicts a 2-fold reduction in multifocal contrast sensitivity for 0.2° letters.

2. When the glare ring is present, we expect even more loss in sensitivity due to the veiling light cast over the retinal image of the letter. The size of this effect can be found with the help of the following formulas: Let the maximum and minimum luminances in the absence of glare be L_{max} and L_{min}, and the veiling luminance associated with glare be L_0. The Michelson contrast in the absence of glare is:

$$C = (L_{max} - L_{min})/(L_{max} + L_{min}).$$

In the presence of glare, L_0 is added to both L_{max} and L_{min}. The added terms cancel in the numerator but add in the denominator to give the reduced contrast, Cg, in the presence of glare:

$$Cg = (L_{max} - L_{min})/(L_{max} + L_{min} + 2L_0).$$

In summary, we derived the predicted multifocal thresholds from the corresponding phakic-control thresholds by: (1) doubling the phakic-control threshold, based on results in our previous paper and (2) further increasing the threshold to compensate for the contrast loss due to the veiling light from the glare rings, as calculated above.

Because many of the multifocal wearers could not recognize letters at maximum contrast for the two smallest glare rings (see Results below), corresponding contrast thresholds were not available for data analysis. Accordingly, we conducted two separate statistical analyses: (1) analysis of variance for the data of the young, phakic-control and monofocal groups in all glare conditions and (2) analysis of variance for the data of all four groups for the large-ring and no-glare conditions. In both analyses, we used Duncan's Multiple Range test for the multiple comparisons of the means for each condition (group × glare condition).[22] Our criterion for statistical significance is $p = 0.05$ by Duncan's test.

RESULTS

Fig. 4 displays contrast thresholds for letter recognition as a function of the inner diameter of the glare ring. Mean values of the young-control group are shown by the solid line. Individual contrast thresholds are depicted by ▲ for the phakic-control subjects, ○ for the monofocal wearers, and ● for the multifocal wearers. Superimposed data points have been laterally offset so that they can be seen. Some of the multifocal wearers could not reach the criterion of six letters out of eight correct, even at the maximum letter contrast of 98%. These subjects are represented on the graph by a symbol above 1.0 contrast with a number showing how many fell in this category. Table 2 shows mean thresholds and 95% confidence intervals for the four groups.

When there was no glare ring, mean threshold

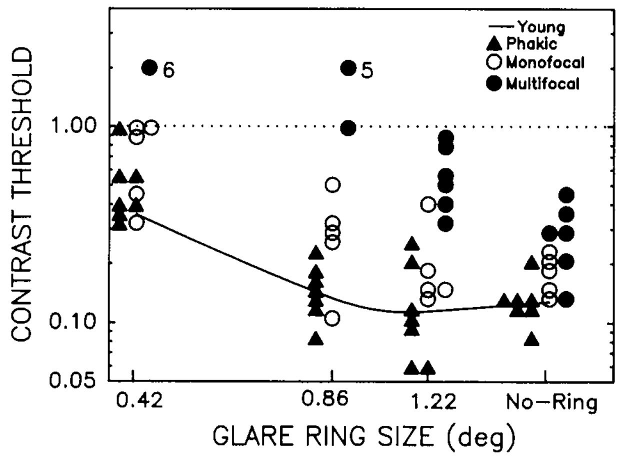

Figure 4. Contrast thresholds for letter recognition are shown as a function of the inner diameter of glare rings, and for the no-glare condition. The solid line shows average data for the young subjects. Individual data are shown for the phakic-control subjects (▲), monofocal wearers (○), and multifocal wearers (●). Superimposed data points have been laterally offset so that they can be seen. Some multifocal wearers could not reach the criterion for letter recognition (six or more of eight correct) at the highest letter contrast. These subjects are represented by ● above a contrast of 1.0 with the number of subjects indicated.

Table 2. Mean contrast thresholds and 95% confidence limits in 4 groups.[a]

Glare Ring Diameter	0.42°	0.86°	1.22°	No-Ring
Young-Normal Group				
Mean	0.354	0.133	0.114	0.128
upper limit	0.443	0.167	0.142	0.160
lower limit	0.283	0.106	0.091	0.102
Phakic-Control Group				
Mean	0.478	0.145	0.112	0.128
upper limit	0.598	0.181	0.140	0.160
lower limit	0.382	0.116	0.089	0.102
Monofocal IOL Group				
Mean	0.656	0.263	0.184	0.176
upper limit	0.821	0.328	0.230	0.220
lower limit	0.524	0.210	0.147	0.141
Multifocal IOL Group				
Mean	—[b]	—	0.541	0.267
upper limit	—	—	0.677	0.334
lower limit	—	—	0.432	0.213

[a] The means are geometric means. The pooled error variance from 4 groups in 4 conditions was used as an estimator of the common error variance.

[b] Indicates that the data were not available.

for the multifocal group was 2.1 times higher than the phakic-control group. This elevation is consistent with letter-recognition results reported in our previous paper[1] and with the filter model. The mean monofocal threshold was about 1.4 times higher than the phakic control mean in the absence of glare, but this difference was not statistically significant.

Contrast thresholds in the no-glare condition for phakic-control and young subjects are somewhat higher than values reported in the literature for letters of a comparable size. Much of the discrepancy is related to the low luminance level used for our targets (11.2 cd/m^2). Comparable measurements with three young subjects at 300 cd/m^2 yielded contrast thresholds ranging from 2.5 to 7%, close to values previously reported.[19, 23, 24]

The young and phakic-control groups showed no appreciable effect of glare except for the smallest glare ring (0.42° diameter). For the small ring, their thresholds were elevated by factors ranging from about three to four times. Mean monofocal thresholds were higher than phakic-control thresholds for all glare rings (Table 2) and the differences between the two groups were statistically significant for the intermediate and large glare rings. These results indicate that the monofocal wearers suffered an abnormal glare effect.

The multifocal wearers showed a greater effect of glare than the other groups. None of the multifocal wearers could pass the criterion (six letters of eight correct) at maximum contrast for the smallest glare ring (0.42° diameter). Only one passed the criterion at maximum contrast for the medium size ring (0.86°). (All the subjects in the other groups could do the task for all glare rings.) All the multifocal wearers could reach criterion for the largest glare ring (1.22°) but their mean threshold for this condition was about five times that of the phakic control subjects and three times that of the monofocal wearers. These differences were statistically significant.

Fig. 5 compares the glare effects predicted by the filter model with the multifocal subject data. For comparison, the means for the phakic control subjects and monofocal wearers are also plotted. The error bars represent 95% confidence intervals, computed from the pooled error variance of the data of the four groups in all glare and no-glare conditions. In agreement with the data, the model predicts that for the smallest glare ring, the multifocal wearers will be unable to reach criterion even for the maximum letter contrast. For the intermediate and large glare rings, the model underestimates the observed glare effects. The predicted threshold was 51% of the actual mean multifocal threshold for the large glare ring, and 43% for the intermediate glare ring. The 43% figure for the intermediate glare ring is an upper bound. It is based on the assumption that the observed multifocal threshold is 100% contrast (i.e., the maximum possible) in this case. Recall that only one of the multifocal subjects

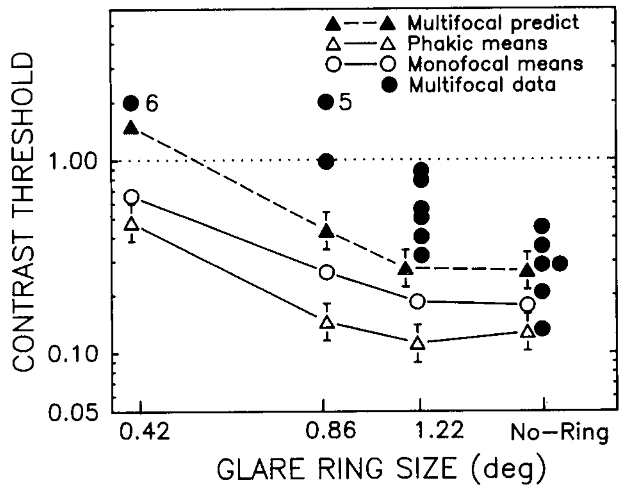

Figure 5. Predictions from the filter model are shown along with data from the multifocal wearers and average data and 95% confidence limits for the phakic-control subjects. Average data for the monofocal wearers are also shown (○). The multifocal data (●) are replotted from Fig. 4. Predictions from the filter model are shown by ▲ with 95% confidence intervals. These confidence intervals are estimated from the pooled error variance in the actual data. In agreement with the data, the model predicts a threshold exceeding the maximum possible contrast of 1.0 for the 0.42° glare ring.

achieved a measurable contrast threshold for this glare ring. The spatial-frequency filtering model predicted smaller glare effects than those actually experienced by the multifocal subjects.

Finally, we examined the correlations between glare effects and our measures of acuity and contrast sensitivity. For this analysis, we quantified the glare effect as the threshold elevation due to the largest glare ring (i.e., ratio of threshold with glare to threshold without glare). We used results with the largest glare ring because it was the only glare condition for which all subjects in all groups had measurable contrast thresholds. Analysis for the intermediate glare ring with 20 subjects showed very similar results. Fig. 6A shows glare effect vs. distance visual acuity for all the subjects. The correlation between glare and acuity was low ($r = 0.22$) and was not significant. Fig. 6B plots the glare effect vs. Pelli-Robson contrast sensitivity. When one case (marked by * in Fig. 6B) was excluded there was a statistically significant correlation ($r = -0.41$, $p < 0.05$) that accounted for 16.6% of the variance. We eliminated one data point (subject 24, marked by * in Fig. 6B) as an outlier, based on Cook's distance of 0.30 and outlier test ($t = 2.88$).[25] (When attention was restricted to IOL patients only—multifocal and monofocal—the correlation between glare effect and Pelli-Robson contrast sensitivity was only −0.28.) The results in Fig. 6 demonstrate that visual acuity and contrast sensitivity with the Pelli-Robson chart are not good predictors of glare disability. Similar results were obtained in

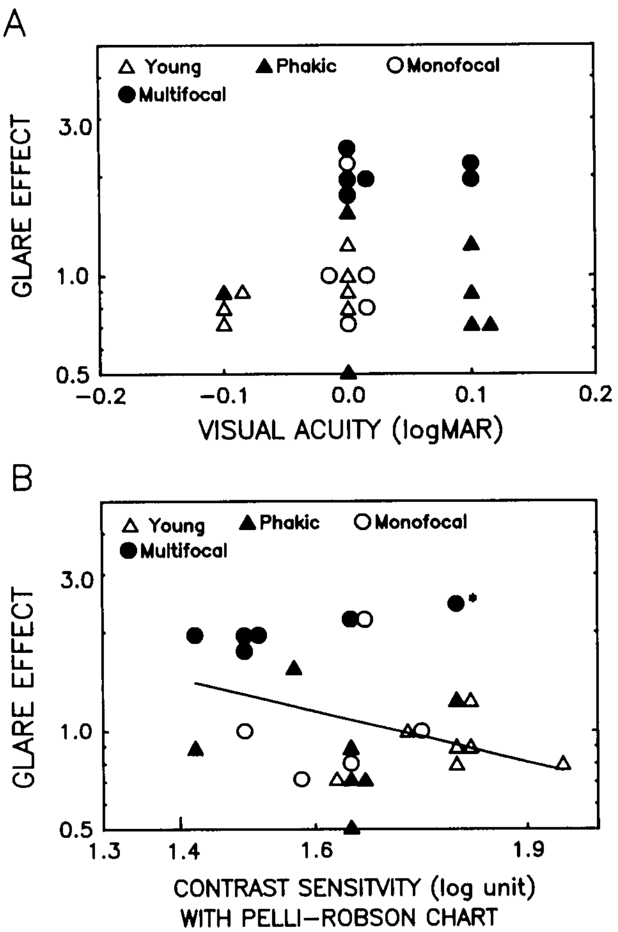

Figure 6. A: a scatter plot of the glare effect vs. visual acuity is shown for all 25 subjects. *Glare effect* is defined as the ratio of contrast threshold in the presence of the large glare ring to contrast threshold in the absence of glare. Superimposed data points have been laterally offset to be seen. There was no statistically significant correlation between glare effect and acuity. B: a similar scatter plot is shown for Pelli-Robson contrast sensitivity. The regression line is based on the data of 24 subjects and excludes the subject marked by *. There was a significant correlation between glare effect and Pelli-Robson contrast sensitivity ($r = -0.41$) which accounted for 16.6% of the variance.

studies with cataractous eyes and monofocal IOL's.[9, 16, 26]

DISCUSSION

We evaluated disability glare by measuring contrast-threshold elevation for letter recognition in the presence of surrounding bright rings. Our empirical results are summarized in three points:

1. Multifocal wearers exhibited an abnormal glare effect for all glare-ring sizes. This finding may explain subject reports of rings, halos, and glare.[15]

2. Monofocal wearers showed a greater effect of glare than age-matched phakic controls, but less than the multifocal wearers. Our observation of abnormal glare in monofocal wearers is consistent with previous findings.[9-11]

3. Age-matched phakic-control and young-control subjects showed very little effect of glare, with significant threshold elevation only for the smallest glare ring.

In the introductory text and the Subjects and Methods section, we described an optical spatial filter model for the spatial frequency and contrast effects of the multifocal IOL. The model treats the eye with a multifocal IOL as equivalent to a phakic control eye preceded by a spatial frequency filter. The filter is characterized by Holladay et al.'s optical measurements of the lens' MTF.[2] In our previous paper,[1] we showed how this model accounts for contrast sensitivity and reading deficits in multifocal subjects. In the present paper, we have shown that this model predicts about one-half of the glare effect experienced by the multifocal wearers.

We can identify two possible reasons why the model underestimates the observed glare effect. First, as explained in the Subjects and Methods section, the veiling light from the filtered glare rings contains some spatial fine structure which may have an additional masking effect. Second, there appears to be a source of glare inherent in IOL's that is not related to the spatial filtering properties of the multifocal IOL. This is likely because the monofocal wearers also showed an abnormal glare effect. Speculations by other authors on the sources of glare effects with monofocal IOL's relate to: bright glare reflections produced by the large difference in index of refraction between the aqueous and IOL,[9] translucent patches of iris due to loss of pigmentation during surgery,[9] decentration of IOL's,[10] or light scatter from capsular clouding or early Elschnig's pearls.[11]

We take the following view of the abnormal glare experienced by patients with multifocal IOL's. The effect has at least two components. One is unique to the multifocal IOL and can be characterized by the spatial filtering property of the lens. A second is common to monofocal and multifocal IOL's.

Can clinical measurements of acuity or contrast sensitivity identify IOL patients who will suffer from abnormal glare? The answer seems to be no. We found no significant correlation between acuity and glare effect (Fig. 6A). Pelli-Robson contrast sensitivities accounted for only 16.6% of the variance in glare effects (Fig. 6B). Sine-wave grating contrast sensitivity measurements are also insufficient to characterize glare effects. Monofocal wearers showed abnormal glare effects despite the fact that their contrast sensitivity functions were indistinguishable from those of the phakic controls.[1] The spatial filter model for multifocal wearers accounts for contrast sensitivity deficits in the absence of glare,[1] but only for a portion of the glare effect reported in this paper.

Our glare results are qualitatively consistent with those of Gimbel et al.,[15] described in the introductory text, but inconsistent with the lack of glare effect reported in studies with the BAT.[12, 13] The BAT may be less sensitive in identifying glare effects in multifocal subjects for two reasons. First, acuity measures, such as the BAT, are known to be less dependent on contrast reduction (caused by veiling light from the glare source) than is a contrast threshold measure such as ours.[15, 16, 24] Second, the BAT may induce a smaller pupil size than our glare stimulus, and there is evidence for reduced glare effects with smaller pupils in subjects with monofocal IOL's.[10]

What are the implications of the glare effects experienced by multifocal wearers for real-world visual function? Our results indicate that problems may occur for high-resolution visual tasks when very bright light sources are nearby. We briefly consider reading and driving situations in which glare problems might be found.

Under good conditions, readers do not need to contend with the kind of glare discussed here, because the page is evenly illuminated and light sources are located far away from the print. (Glare due to light from the white page plays a role in limiting reading performance in some forms of low vision.[27]) Under more adverse reading conditions, particularly with glossy magazine paper, specular reflections may be present. Across the specularities, the intensity can change by more than a factor of 10. Our results indicate that an intensity difference of this magnitude may cause glare problems for multifocal wearers. They might experience particular difficulty reading text very close to the bright areas.

The headlights of an oncoming car at night could act as a glare source, hindering a driver's ability to see an obstacle on the road ahead in his/her lane. Oncoming headlights can be very bright and greatly exceed the luminance of an object on the road (e.g., pedestrian, small animal, tire debris, etc.) lighted only by the driver's own headlights.[28] If the luminance difference is large enough (say, 30 times as in our experiments, or even more) and if the angular separation between headlight and object is small (about 1° or less), glare effects might be expected. For a driver watching the road straight ahead, light from very distant approaching cars is initially imaged near the fovea but moves into the periphery as the car gets closer. As an example, on a perfectly straight road with a lateral separation of 2 m between cars going in opposite directions, the headlights of an oncoming car will be displaced more than 1° from the driver's straight-ahead view when the car is nearer than 100 m. At greater distances, however, or perhaps on curves, approaching headlights may be within 1° of the driver's line of sight. Multifocal drivers may experience more severe glare than normal drivers, especially for high beams. Their particular difficulties would be expected to occur when the driving conditions are such that the oncoming light lies in a direction close to the driver's line of sight.

Even normal subjects experience glare disability when sufficiently bright lights are placed in close proximity to visual targets. Multifocal wearers, however, experience greater than normal glare effects. These effects should be taken into account in the clinical evaluation of the visual trade-offs associated with the multifocal IOL.

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