

Optical performance of multifocal intraocular lenses

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ABSTRACT

The optical performance of one monofocal and five multifocal lenses was evaluated in the laboratory and photographically. The laboratory testing included determination of the modulation transfer function (MTF), through focus response (TFR), resolution efficiency, and Strehl ratio of each lens. The photographic testing included photographs of the Regan high contrast acuity chart at ten feet with clearest focus and 18 additional photographs in which the image was defocused using minus trial lenses in 0.25 diopter increments. A color photograph of the Kodak color chart was also taken using each lens. All testing was conducted using a 3 mm artificial pupil under ideal implant conditions with no decentration or tilt. The laboratory and photographic results demonstrate that all the multifocal lenses had a two- to three-fold increase in the depth of field with at least a 50% lower contrast in the retinal image. The photographic testing revealed a one to two line better resolution limit with the monofocal lens, which corresponded to the 12% to 41% better MTF cut-off value with the monofocal lens by laboratory testing. The measured resolution efficiencies of all six lenses were comparable. The color photographs revealed color mixing of adjacent colors with the multifocal lenses, whereas the colors appeared unchanged from the original with the monofocal lens.

Key Words: modulation transfer function, monofocal intraocular lens, multifocal intraocular lens, resolution efficiency, through focus response

Implantation of a monofocal intraocular lens (IOL) following cataract extraction has become one of the most successful surgical procedures in medicine; over one million operations are performed each year. Over 90% of these patients achieve a best corrected visual acuity of 20/40 or better.¹ Although the monofocal lens exhibits approximately 1.5 diopters

(D) of pseudoaccommodation,^{2,3} this is not enough to provide adequate near vision in many patients without the aid of bifocal spectacles or reading glasses.

To overcome this deficiency in accommodation, clinicians have tried monovision (setting one eye for distance and the other for near)⁴ and planned myopic

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astigmatism.⁵ Even though these studies have demonstrated that approximately 70% of the patients do not need bifocal spectacles using these methods, a significant number still requires their use.

To increase pseudoaccommodation, and possibly eliminate the need for a bifocal in spectacles, a number of multifocal IOL designs have become available. We have evaluated the optical performance of five of these new designs and compared them with the performance of a standard, good quality monofocal IOL.

Optical Performance

The quality of an optical image is often expressed in terms and units that are not familiar to the ophthalmologist. For this reason, we feel it is important to define some of the terms used in this study. Further explanation of these terms can be found in *Modern Optical Engineering*.⁶

Resolution Efficiency. Resolution efficiency is a measure of the resolving power of a lens expressed as a percentage of the resolving power of a perfect lens of the same power that is limited by diffraction only.

For example, an optically perfect 20 D IOL has a maximum resolving power of approximately 320 line pairs per millimeter through a 3 mm pupil because of the diffraction limit. If an actual 20 D lens were measured and found to have a resolving power of 160 line pairs per millimeter, it would be half as good as the diffraction limited lens and have a resolution efficiency of 50%. Typically, a lens is considered to be of good resolving quality if it exceeds 60% resolution efficiency, although lower values may be sufficient to prevent the IOL from being the limiting factor in a patient's vision.

Contrast. Contrast is defined as the difference in the maximum and minimum brightness divided by the sum of the maximum and minimum brightness of a target or image.

$$\text{Contrast} = \frac{\text{max} - \text{min}}{\text{max} + \text{min}}$$

For example, the black letter "E" on a Snellen acuity chart is about 3 foot-lamberts of luminance and the surrounding white background is approximately 97 foot-lamberts. Consequently, the contrast of the target is

$$\text{Contrast} = \frac{97 - 3}{97 + 3} = 0.94 = 94\%$$

The typical contrast of a standard Snellen projector chart is therefore 94%. Other contrast acuity charts, such as the Regan acuity charts which come in contrasts of 4%, 11%, 25, 50%, and 96%, are also available.

Modulation Transfer Function (MTF). The MTF

of an optical system is the modulation or contrast of the image formed by the system for various size targets (spatial frequencies) which are usually black and white bars with a 100% contrast. As the size of the 100% contrast targets decreases, the ability of the optical system to maintain a high contrast image also decreases.

For example, in Figure 2, monofocal, the dashed line shows the performance of a diffraction limited lens. As the target size (spatial frequency) gets smaller, the modulation (contrast) of the image decreases. The solid line represents the actual measurement of a good quality monofocal lens, which is slightly less than the perfect diffraction limited lens.

Strehl Ratio. The Strehl ratio is the area under the MTF curve for an actual lens expressed as a percentage of the area under the curve for a perfect diffraction limited lens. In our previous example (Figure 2, monofocal), the Strehl ratio for the monofocal lens is 73%. This means that the area under the MTF curve for the monofocal lens was 73% of the area under the diffraction limited curve. The Strehl ratio is therefore an overall indicator of the optical performance of a lens at all target sizes (spatial frequencies).

Through Focus Response (TFR). The through focus response curve is a graph of the modulation (contrast) performance of a lens for a specific target size (20/40 in this study) as a function of defocus. It therefore gives us the optical performance of a lens at its best focus and the decrease in the contrast of the image as it is defocused in either direction.

For example, Figure 3, monofocal, shows the TFR curve for a good quality monofocal lens. The decrease in modulation of the image as it is defocused is very rapid and by two diopters in either direction the modulation has dropped to zero.

5% Cut-Off. As the MTF and TFR curves begin to decrease from their peaks, they will at some point cross the 5% modulation value. The point at which this crossing occurs is referred to as the 5% cut-off value. The value of 5% is somewhat arbitrary but appears to correlate fairly well with visual testing in which the contrast of the image is so low that the eye is no longer able to recognize the image.

The 5% cut-off value on the MTF curve correlates well with the maximum resolving power or resolution efficiency of a lens. On the 20/40 TFR curves, the 5% cut-off values would correlate with the maximum defocus in diopters that could be tolerated before the quality of the 20/40 image would no longer be recognizable.

Contrast Threshold/Sensitivity. Contrast threshold is the lowest contrast at which a given size target can be correctly recognized. The contrast threshold

is lowest in the range of Snellen visual acuities between 20/200 and 20/100 (3 to 6 cycles/degree) at which the threshold is approximately 1%. As the visual acuity letters get smaller, the contrast threshold begins to increase. At a patient's limiting visual acuity (20/10 to 20/20), the letters must be of high contrast and consequently the contrast threshold exceeds 90%.

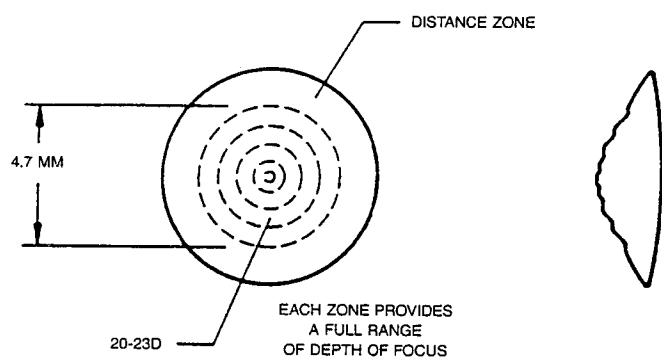
Contrast sensitivity is the reciprocal of the contrast threshold. For example, if a patient had a contrast threshold of 1% (0.01) for 20/100 Snellen acuity letters, the contrast sensitivity would be 100 (1/0.01). If the patient required 100% contrast letters to see 20/15, the contrast sensitivity for 20/15 letters would be 1 (1/1.0). A plot of the contrast sensitivity for various acuities is called the contrast sensitivity curve.

MATERIALS AND METHODS

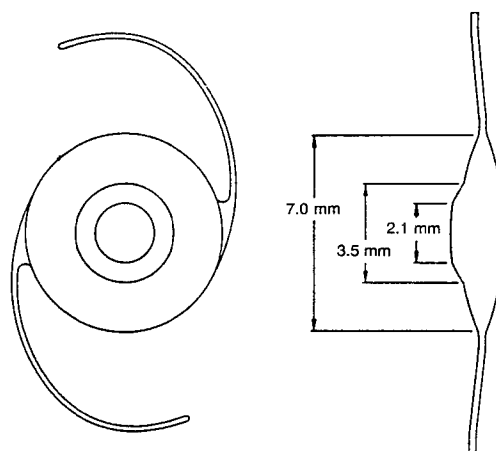
Five different 20 D multifocal IOLs were obtained from the inventory of five surgeons currently involved in the Food & Drug Administration's core study. The multifocal lenses tested were the Allergan Medical Optics Array, the Pharmacia Annular, the 3-M Diffraction, the Morcher Diffraction and the Wright Aspheric (Figure 1). A sixth lens, which was monofocal, was tested for comparison.

Laboratory Testing

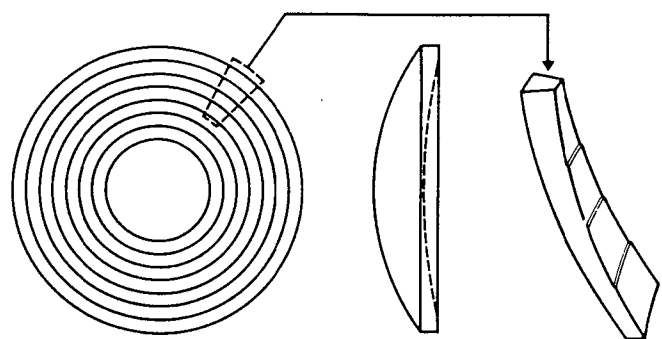
First, the resolution efficiency of each lens was measured in water using the method we have previously described for IOLs.^{7,8} Second, the MTF of each lens was determined in water on an Ealing instrument. The water chamber in which the lenses



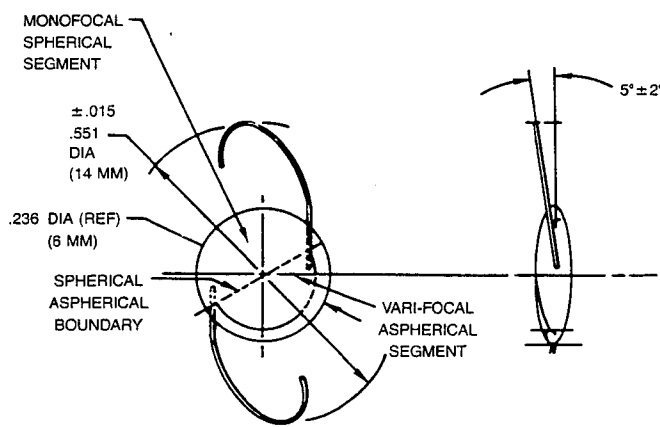
Allergan Medical Optics Array



Pharmacia Annular



3M and Morcher Diffraction



Wright Medical Aspheric

Fig. 1. (Holladay) Diagrammatic line drawings of the five multifocal IOLs.

were tested was constructed with a 28 D artificial cornea located 17 mm anterior to the IOL to simulate the average vergence of incident rays on the anterior surface of the IOL in vivo. The Strehl ratio⁸ (ratio of the area under the actual MTF to a diffraction limited lens expressed as a percentage) was then calculated for each lens.

Third, a TFR curve was generated at a spatial frequency of 15 cycles/degree which corresponds clinically to a Snellen visual acuity level of 20/40. All laboratory testing was done at the Allergan Research Facility (A.L., V.P., T.W., R.S., and H.O.) through a 3 mm aperture with the lens perfectly aligned, with no decentration or tilt, to simulate ideal implant conditions.

Photographic Testing

After the laboratory testing had been completed, the six lenses were sent to the University of Texas Medical School, Media Center, for photographic testing (H.D.). The results of the laboratory testing were not made available to H.D. or J.T.H. until the photographic testing was completed.

A water-filled optical chamber was used in which the anterior and posterior surfaces were optically flat and the thickness was 3 mm. Each lens was immersed in the same chamber with an edge-supporting fixture that prevented IOL decentration or tilt within the chamber during testing. A 3 mm aperture was placed just anterior to the lens and the water chamber with the IOL and aperture were then placed in a specially built camera. The IOL was the only element in the system with optical power.

Black and white negatives were then taken using Kodak Panchromatic Plus-X 4 × 5 sheet film, ISO 100, and color transparencies were taken with Kodak Ektachrome 6118, tungsten 3200K, ISO 32 film. The exposure times were empirically determined to give the optimal exposure for this film and aperture. First, negatives of the high contrast (96%) Regan acuity chart⁹ at 10 feet (3 m) were taken using each IOL. With each lens, the best focus was obtained before the photograph was taken.

Second, without changing the focus, 18 additional negatives were taken with ophthalmic refracting lenses approximately 12 mm in front of the IOL to determine the depth of focus (the reduction in acuity as a function of spherical defocus in diopters). The first 16 lenses ranged from -0.25 D to -4.00 D in 0.25 D increments and the 17th and 18th lenses were -4.50 D and -5.00 D, respectively. Each of the 19 photographic negatives for each of the six IOLs was then viewed through a 40 × microscope to determine the maximum number of letters that could be read from each negative. The number of letters correct was then converted to the Snellen

equivalent as would be done clinically for the Regan acuity chart at ten feet.

Third, a near acuity chart was placed at 33 cm and, without changing the focus, a black and white negative of the chart was made. The negatives were analyzed as with the distance chart to determine the greatest number of letters that could be recognized correctly.

Fourth, negatives of the Pelli-Robson contrast sensitivity chart were taken at five, ten, and 20 feet (1.5, 3.0, and 6.0 m) with each lens at best focus. The angular size of the letters on the Pelli-Robson at these distances correspond to Snellen equivalents of 20/426, 20/213, and 20/106. We were unable to test the contrast sensitivity at the 20/40 Snellen equivalent with the Pelli-Robson chart because of space limitations prohibiting testing at the necessary distance of 50 feet (15 m).

Negatives of the Pelli-Robson chart were analyzed at the appropriate magnification so the visual angle of the letters on the chart would be exactly the same as the chart would appear at the five, ten, and 20 feet distances under normal clinical testing. Using a magnification that simulates clinical testing was mandatory so that any retinal or cerebral processing by the observer would be similar to that experienced by the patient. The number of letters that were correctly identified were then converted to contrast threshold values according to the instructions and calibration of the Pelli-Robson chart for each of the three distances for all six lenses. The reciprocal of the values for contrast threshold was then determined to convert to units of contrast sensitivity.

Finally, a Kodak color chart was photographed at 5 feet with all six lenses using Ektachrome 6118 color film.

RESULTS

The laboratory measurements which included the MTF's and 20/40 TFR curve for each of the six lenses are shown in Figures 2 and 3. The resolution efficiency and Strehl ratio of each lens are shown on the MTF figures for reference. The resolution efficiencies for the multifocal lenses were comparable to the monofocal lenses and the Strehl ratios were from two to three times lower than the monofocal lens.

The photographically determined high contrast Snellen acuity measurements are shown in Table 1 along with the corresponding resolution efficiency and 5% MTF cut-off value measured in the laboratory. The photographic measurements and the laboratory 5% MTF cut-off values show good correspondence. The photographic method indicates that the multifocal lenses were limited to a Snellen acuity of

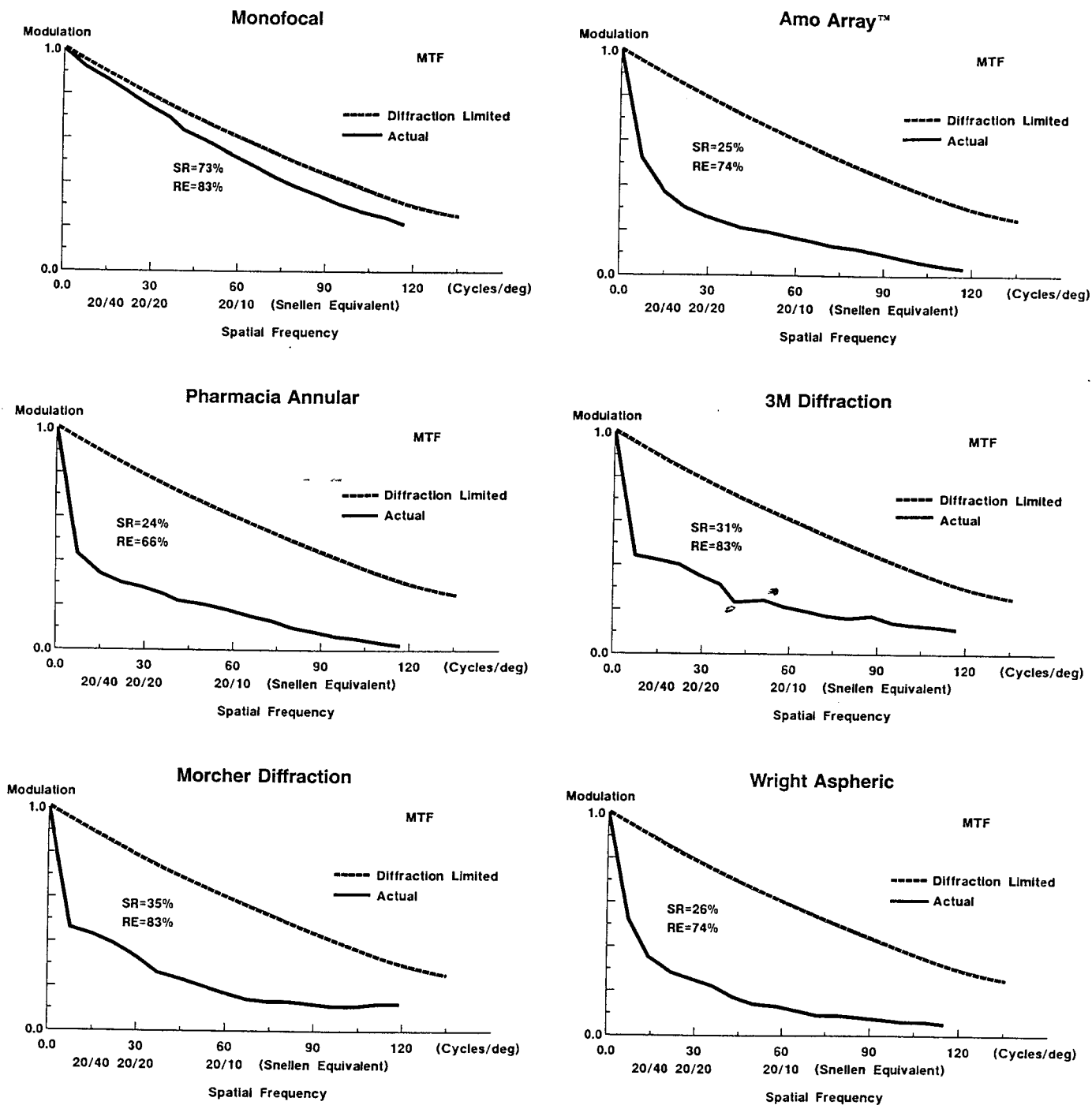


Fig. 2. (Holladay) Modulation transfer functions (MTF) of the six lenses tested. The resolution efficiency (RE) and the Strehl ratio (SR) are shown on the graphs for reference.

20/14 to 20/18, while the monofocal lens was limited to 20/10. The 5% MTF cut-off for the monofocal lens was from 12% to 41% higher than the multifocal lenses. The resolution efficiencies of all six lenses were comparable.

The photographically measured defocus curves are shown in Figure 4. These values should corre-

spond to the positive values of defocus on the TFR curves. Positive lenses were not used in the photographic testing so there was no comparison to the negative values on the TFR curves. The correspondence of the values by laboratory and photographic methods was almost exact for all lenses tested. These curves show that all the multifocal lenses have from

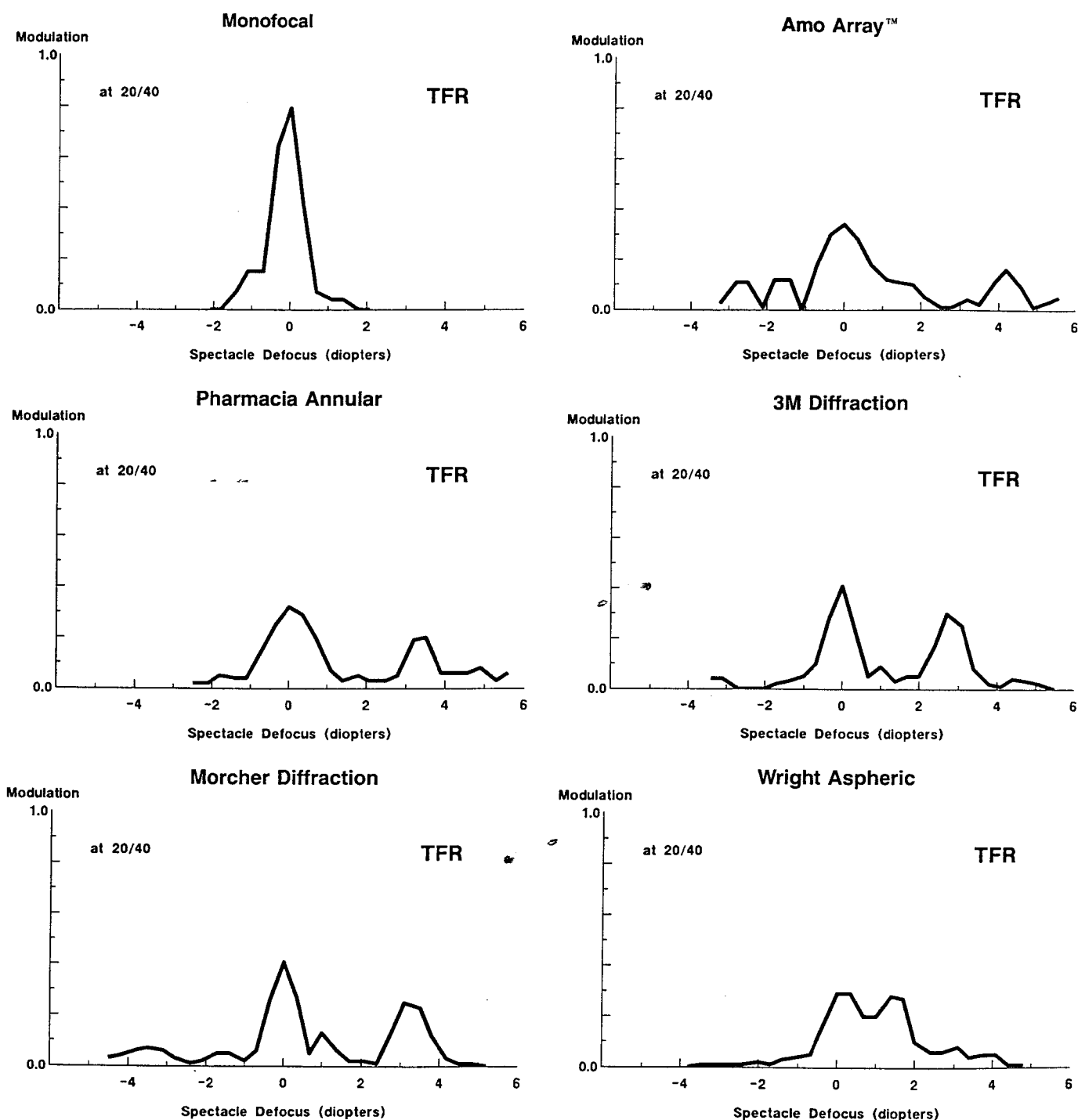


Fig. 3. (Holladay) Through focus response (TFR) curves at 20/40 (15 cycles/degree) spatial frequency for the six lenses tested.

two to three times more depth of field than the monofocal lens.

The Snellen acuity for the multifocal lenses ranged from 20/23 to 20/56 on the near card, whereas the monofocal lens could only resolve 20/80. The variation in near acuities with the multifocal lenses was primarily due to placing the test target at exactly

33 cm (3 D). As can be seen from the acuity versus defocus plots (Figure 4) and the TFR curves (Figure 3), some of the lenses were not designed for best near acuity at 33 cm (3 D). These lenses had far better near acuities at distances just anterior or posterior to the 33 cm (3 D) distance. A summary of the laboratory and photographic measures of depth-

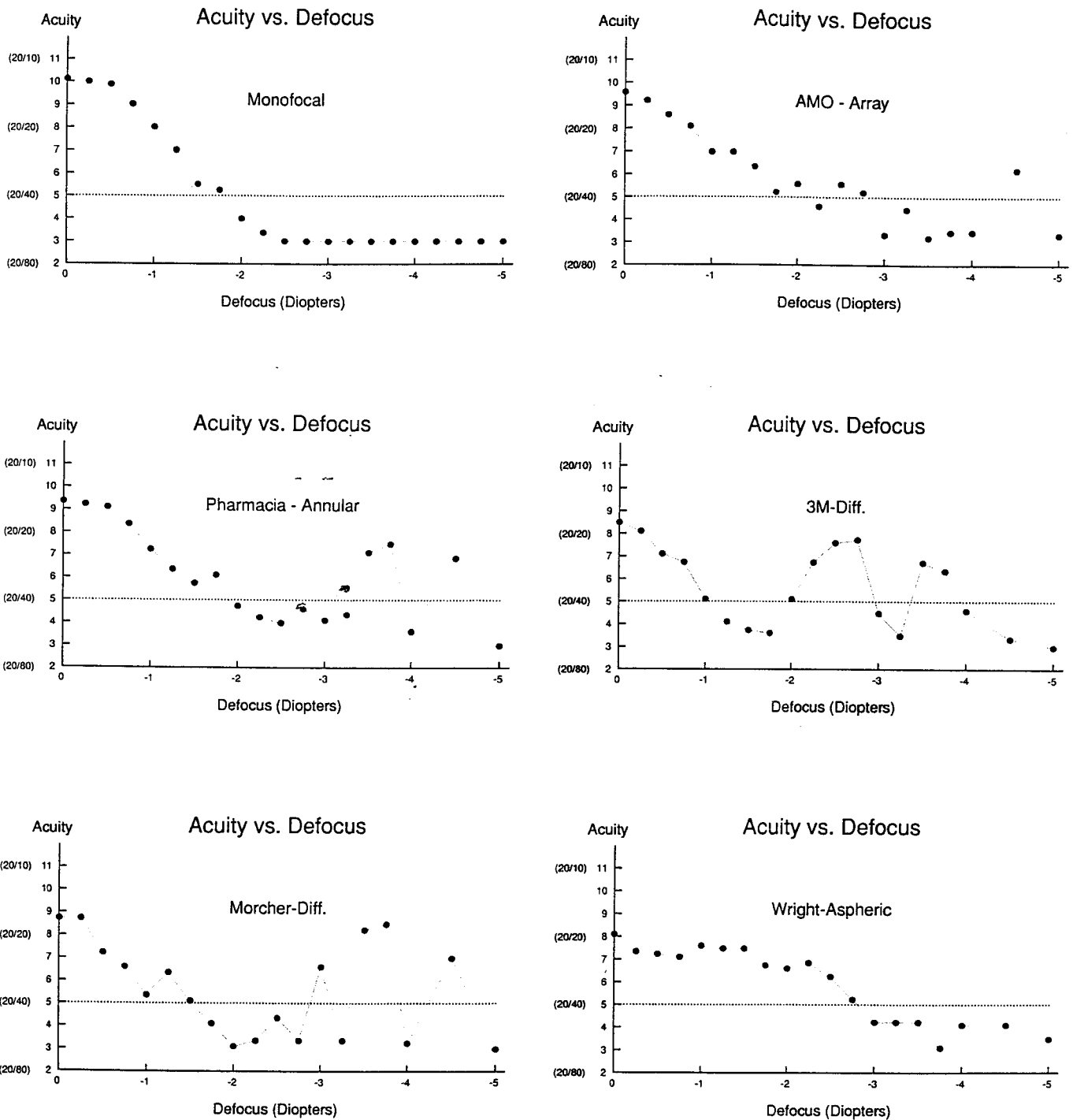


Fig. 4. (Holladay) Acuity versus defocus plots for the six lenses tested.

of-field are shown in Table 2.

Laboratory and photographic testing of contrast is summarized in Table 3. The contrast sensitivities were from 1.5 to 2.0 times lower than the monofocal lens at 20/426 and 20/213 Snellen equivalents. At 20/106, the multifocal lenses had contrast sensitivities ranging from 1.8 to 2.9 times lower than the

monofocal IOL. The laboratory measurements of contrast are shown in the last two columns of Table 3. The modulation peaks of the 20/40 TFR curves ranged from 32% to 42%; they were 80% for the monofocal lens. These values indicate that the contrast of the multifocal image is from 1.9 to 2.5 times lower than the monofocal lens. The Strehl

Table 1. Resolution efficiencies for the six lenses.

Lens	High Contrast Chart	Measured Resolution Efficiency	MTF* 5% Cut-off
Monofocal	20/10	83%	94%
AMO-Array	20/18	74%	56%
Pharmacia-Annular	20/15	66%	53%
3M-Diffraction	20/16	83%	82%
Morcher-Diffraction	20/17	83%	84%
Wright-Aspheric	20/14	74%	63%

*modulation transfer function

ratio for the multifocal lenses ranged from 24% to 35% and was 73% for the monofocal lens. These ratios are from 2.1 to 3.0 times lower than the Strehl ratio for the monofocal lens.

The color transparency of the Kodak color chart appeared as the original with the monofocal lens. Each of the multifocal lenses showed color mixing between adjacent colors yielding 15 colors rather than the original eight.

DISCUSSION

Our study compared a group of multifocal lenses with a good quality monofocal lens under ideal conditions (optically aligned with no decentration or tilt) using a 3 mm pupil. No optical quality differences among the multifocal lenses can be determined to be significant in this study since the sample size was only one for each design. The next phase of our study will increase the sample size and expand the test conditions to include different size pupils, corneal astigmatism, and decentration and tilt of the IOL. These conditions may demonstrate differences among multifocal lenses.

Resolution

Laboratory measurements of the lenses showed no significant difference in the resolution efficien-

Table 2. Depth-of-field measurements for the six lenses.

Lens	Defocus to 20/40	Resolution at 33 cm	TFR* at 5%
Monofocal	1.5 D	20/80	1.0 D
AMO-Array	4.5 D	20/36	4.5 D
Pharmacia-Annular	4.5 D	20/56	4.5 D
3M-Diffraction	3.7 D	20/30	3.5 D
Morcher-Diffraction	3.7 D	20/30	4.0 D
Wright-Aspheric	2.7 D	20/23	3.0 D

*through focus response

cies of the six lenses ranging from 66% to 83% (Table 1). The 5% MTF cut-off values for the five multifocal lenses, however, were from 12% to 41% lower than the monofocal lens, which was 94%. Photographic testing showed a 1.0 to 1.5 line improvement in the best corrected acuity with the monofocal lens, which was comparable to the laboratory findings of 12% to 41% lower 5% MTF cut-off values with the multifocal lenses. The reduction in best corrected Snellen visual acuity as a function of contrast has been studied by Regan and Neima,⁹ Legge, Rubin and Luebker,¹⁰ and Burton.¹¹ Their studies have shown that the reduction in best corrected acuity will decrease by three lines (factor of 2) for every one log unit (factor of 10) decrease in contrast.

Using the minimum decrease in contrast with a multifocal lens of 50% (0.30 log), the expected decrease in best corrected acuity would be one line. These values correlate well with our photographic and 5% MTF cut-off findings. A one-line decrease in best corrected acuity does not imply that patients cannot achieve 20/15 acuity with a multifocal lens; it simply means that if a patient can see 20/15 with a multifocal lens which provides a 50% lower contrast image, the patient would have been able to achieve 20/12.5 with the monofocal lens (one line better) if all other parameters were equal.

Table 3. Contrast measurements for the six lenses.

Lens	20/426 Contrast Sensitivity	20/213 Contrast Sensitivity	20/106 Contrast Sensitivity	20/40 TFR* Modulation Peak	Strehl Ratio
Monofocal	17	11	8.3	80%	73%
AMO-Array	11	6.7	2.9	36%	25%
Pharmacia-Annular	11	6.7	4.8	33%	24%
3M-Diffraction	8.3	5.6	3.2	42%	31%
Morcher-Diffraction	8.3	5.6	4.8	40%	35%
Wright-Aspheric	11	8.3	3.2	32%	26%

*through focus response

Early clinical results concerning best corrected acuity have been variable in their findings and in some cases have been compared to historical controls rather than matched controls. Some investigators, however, have found fewer multifocal lens patients achieving 20/15 than their corresponding controls, but these findings are still preliminary (J.L. Pearce, M.D., "Comparison of Visual Results with a 3-Piece Multifocal Lens Vs. a 1-Piece Biconvex PMMA Multifocal Lens"; S.F. Brint, M.D., "Clinical Criteria for Successful Implantation of Bifocal IOLs"; H.V. Gimbel, M.D., "Visual and Refractive Results of a Large Series of 3M Multifocal IOLs"; A. El-Maghraby, M.D., "A Randomized, Controlled, Prospective Clinical Trial Evaluating the Safety and Efficacy of the 3M Multifocal IOL," Symposium on Cataract, IOL and Refractive Surgery, Los Angeles, March 1990).

Contrast

Both laboratory and photographic testing demonstrate a reduction in the image contrast of the multifocal lens from 1.5 to 2.9 times less than the monofocal lens. Our photographic study demonstrates that testing a higher spatial frequency (20/106) rather than lower spatial frequencies (20/426 and 20/213) is a more sensitive index of contrast loss. Early clinical results have confirmed a decrease in contrast sensitivity testing using the Pelli-Robson chart at 3 m (Snellen equivalent of 20/213) of 0.14 log units for distance focus and a 0.24 log unit for near focus.¹² Using the Regan medium contrast acuity chart (11% contrast), the best corrected acuity in the multifocal patients was one to three lines less than in the monofocal control group.^{12,13}

In addition to low spatial frequency contrast sensitivity testing (20/106, 20/213, 20/426, and 20/640), mid-frequency from 20/40 to 20/50 must also be performed if we are to determine the effect of decreased contrast on reading, highway exit signs, etc. It is clear that contrast sensitivity testing at 20/640 (1 m) or 20/213 (3 m) provides insufficient information to predict these important results. Testing at 6 m (20/106) is still not close enough to 20/40 to obtain these important values.

Depth of Field. Although the acuity versus defocus plots (Figure 4) and the TFR curves (Figure 3) tell us everything about the acuity at various distances, there is no agreement upon a convention of reporting the depth of field using a single number. There are at least three methods of reporting this value. Unfortunately, none of these methods corresponds to the actual definition of depth of field in photography or optical engineering. We have used the first method for the values in Table 2, and also

explain the principles of the other two methods. Each of these methods has advantages and disadvantages in the laboratory and clinically.

1. The most commonly used clinical method is to obtain the best corrected refraction and then defocus the image with spherical minus trial lenses until the maximum spherical defocus for which 20/40 Snellen letters can still be accurately recognized (Figure 4).² In the laboratory this would correspond to the distance in diopters from the highest peak on the 20/40 TFR curve to the highest positive defocus value above 5% modulation (Figure 3). This method corresponds to the typical method of measuring a patient's accommodative amplitude using ophthalmic trial lenses and a 20/40 target.

2. Clinically, we can also defocus the image using plus as well as minus lenses. This value will be larger than using minus lenses alone and would be clinically applicable if the patient's far point were at an intermediate distance or the spectacle correction were prescribed for an intermediate distance. This value for depth of field would tell us how far behind and in front of the intermediate far point the patient would still be able to see 20/40. In the laboratory, this value would be determined from the TFR curves, measuring the distance from the highest negative defocus value above 5% modulation to the highest positive defocus value above 5% modulation. In most cases, this value will exceed that measured by the first method, as can be seen in Figure 3.

3. The third method is the most complex. Clinically, the acuity versus defocus curve would be measured and the width in diopters of each peak at the 20/40 level would be determined. The sum of each of these values would be the total depth of field. In the laboratory, this requires measuring the width of each peak at the 5% modulation level and adding the defocus values together. The sum of these values would be considered the depth of field. This method would give the actual usable accommodation range above 20/40 Snellen acuity, discounting those regions in which the acuity is less than 20/40.

None of these methods alone provides sufficient information to predict the actual clinical performance of the multifocal lens. Therefore, we feel that an acuity versus defocus plot or TFR curve must be available to the clinician specifically for refractive purposes for each multifocal design. For example, a very flat defocus curve such as the aspheric multifocal (Figure 4, Wright Aspheric) will make endpoint recognition between typical refracting lenses (0.25 D or 0.50 D) difficult. This necessitates relatively large changes in the refracting lenses for the patient to see the difference. Also, a lens with multiple focus peaks (Figure 4, AMO Array, Pharmacia Annular, 3M and

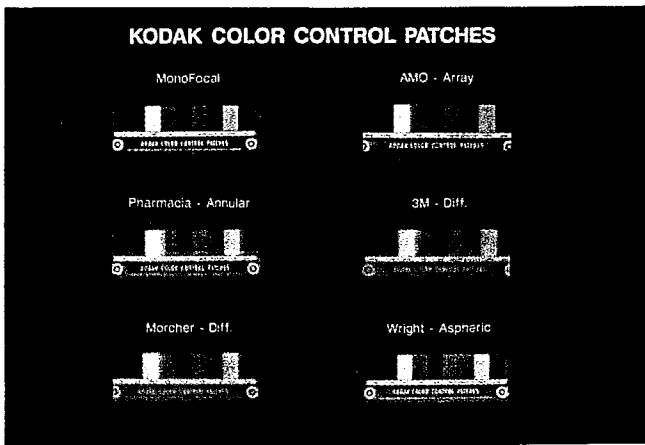


Fig. 5. (Holladay) A color transparency of the Kodak color chart was taken with all six lenses using Ektachrome 6118 color film. Note the color mixing between adjacent colors for the multifocal lenses.

Morcher Diffraction) may make it difficult for the clinician to know which peak the patient is actually using.

Color. The effect on the color chart depends on the size and proximity of the colors. The defocused colored image or images fall on the focused retinal image and create color mixing. Instead of eight colors as seen with the monofocal lens, there are 15 colors as seen with the multifocal lenses. The concept that the brain can "filter out" the defocused image in this situation is not valid since the retina and brain simply see a band of color mixture between the original colors exactly as seen in Figure 5.

SUMMARY

In summary, our laboratory and clinical results using ideal conditions demonstrate that a two- to three-fold increase in depth of field is associated with at least a 50% lower contrast in the retinal image. This decrease in contrast will result in a one-line drop in best corrected visual acuity when the IOL is the limiting factor. A 50% reduction in the retinal image will result in a two-fold decrease contrast sensitivity for the patient with a multifocal lens. Contrast sensitivity testing must be done at the 20/40 Snellen equivalent to measure accurately and

most sensitively the clinical impact on reading vision and other similar tasks. Also, best corrected Snellen visual acuity must be measured with 50%, 25%, and 11% contrast charts (nominal values), as well as the standard 96% high contrast chart.

The clinical effect of these findings is unknown because we have never sacrificed contrast to improve another parameter, such as depth of field, in our patients. An important part of these core studies is to determine the personality profile and vocational needs of individuals and correlate them with the satisfaction of the patients, as has been done by Percival.¹⁴ These data will help the surgeon and patient make a better informed decision prior to implantation.

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