0896–1549/91 $0.00 + .20

Principles and Optical Performance of Multifocal Intraocular Lenses

*Jack T. Holladay, MD**

Implantation of a monofocal intraocular lens (IOL) after cataract extraction has become one of the most successful surgical procedures in medicine; more than one million operations are performed each year. More than 90% of these patients achieve a best corrected visual acuity of 20/40 or better.[14] Although the monofocal lens exhibits approximately 1.5 diopters of pseudoaccommodation,[8,9] 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)[1] and planned myopic 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 require 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. The line drawings of the multifocal IOL are shown in Figure 1.

OPTICAL PERFORMANCE

The quality of an optical image often is expressed in terms and units that are not familiar to the ophthalmologist. For this reason, we believe 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.*[13]

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.

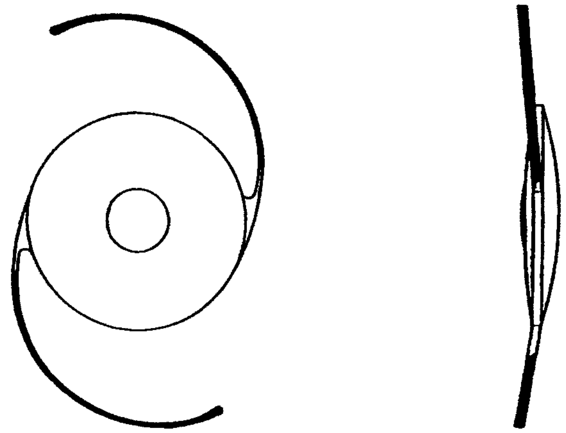
For example, an optically perfect 20 D IOL has a maximum resolving power of approximately 320 line pairs per millimeter through a 3-mm pupil because of the diffraction limit. If an actual 20-D lens was measured and found to have a resolving power of 160 line pairs per millimeter, it would be half as 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

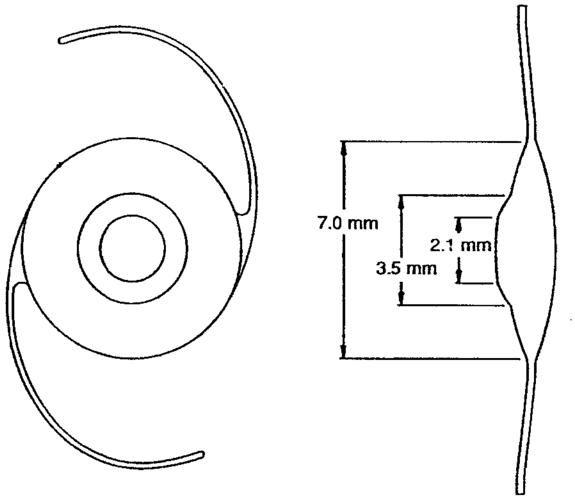
Contrast is defined as the difference in the maximum and minimum brightness divided

Adapted from Holladay JT, van Dijk H, Lang A, et al: Optical performance of multifocal intraocular lenses. J Cataract Refact Surg 16:413–422, 1990; with permission.

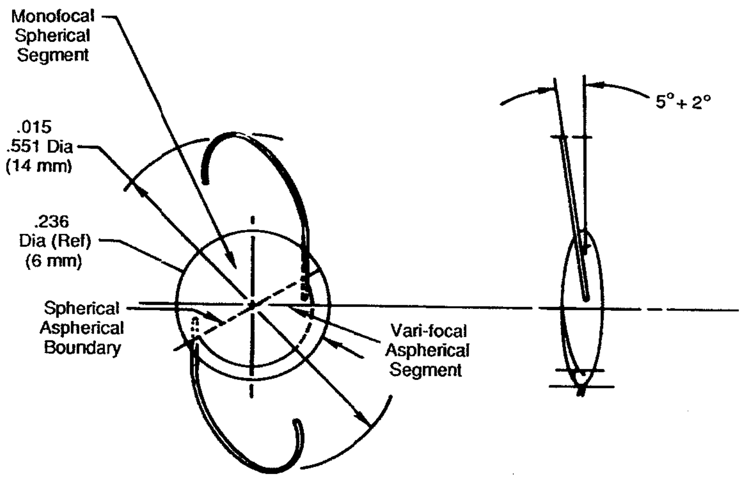
* Professor of Ophthalmology, University of Texas Medical School; and Department of Ophthalmology, Herman Eye Center, Houston, Texas



A **Iolab "Bull's-eye"**



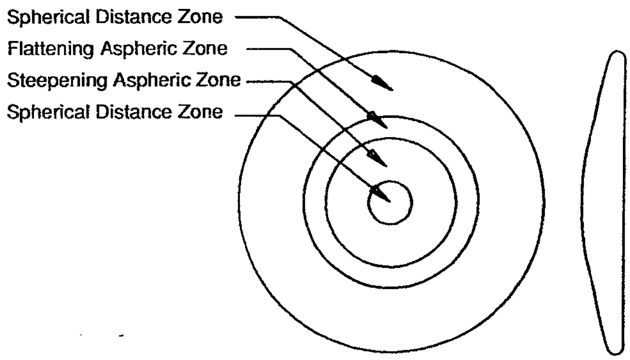
B **Pharmacia Annular**



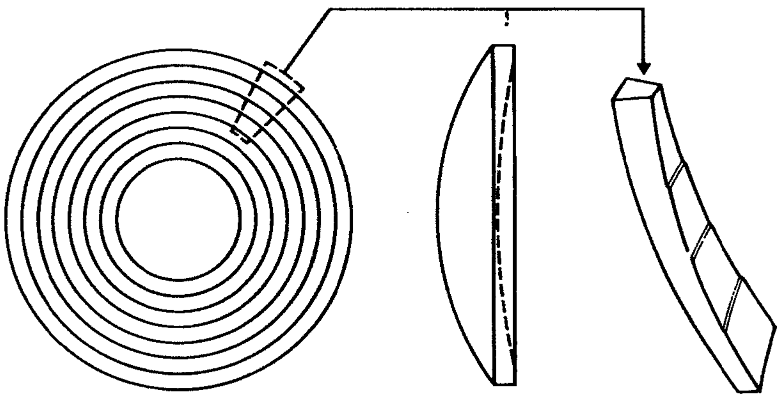
C **Wright Medical Aspheric**

Figure 1. *A–F*, The five multifocal IOLs. (*From* Holladay JT, van Dijk H, Lang A, et al: Optical performance of multifocal intraocular lenses. J Cataract Refract Surg 16:413–422, 1990; with permission.)

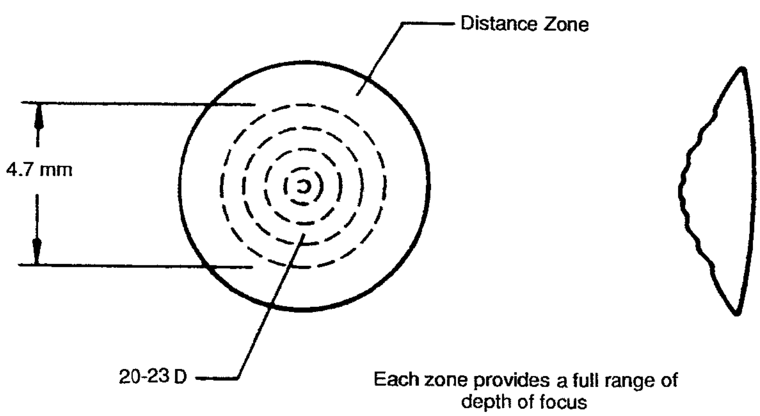
(Illustration continued on opposite page)



D **Ioptex Multiple Aspheric**



E **3M and Morcher Diffraction**



F **Allergan Medical Optics Array**

Figure 1. *(Continued).*

by the sum of the maximum and minimum brightness of a target or image.

$$\text{Contrast} = (\text{max} - \text{min})/(\text{max} + \text{min})$$

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

$$\text{contrast} = (97 - 3)/(97 + 3) = 0.94 = 94\%$$

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

The modulation transfer function (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*A*, 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

The through focus response (TFR) 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 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 2 D in either direction, the modulation has dropped to zero.

Five Percent 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 correlate with the maximum defocus in diopters that can be tolerated before the quality of the 20/40 image is no longer recognizable.

Contrast Threshold/Sensitivity

Contrast threshold is the lowest contrast at which a given size target can be identified correctly. The contrast threshold is lowest in the range of Snellen visual acuities between 20/200 and 20/100 (3–6 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 (20/10–20/20), 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 has a contrast threshold of 1% (0.01) for 20/100 Snellen acuity letters, the contrast sensitivity is 100 (1/0.01). If the patient required 100% contrast letters to see 20/15, the contrast sensitivity for 20/15 letters is 1 (1/1.0). A plot of the contrast sensitivity for various acuities is called the contrast sensitivity curve.

MULTIFOCAL INTRAOCULAR DESIGN

The basic principle underlying the multifocal lens is the simultaneous creation of more than one image point for a single object point. The corollary of this principle is that multiple object points (e.g., distance and near) simultaneously can be brought into the same image point. If the lens is designed to have two focal points it is called a bifocal lens, and if it has more than two focal points it is a multifocal lens.

Although multifocal lenses can be categorized by optical characteristics such as refractive or diffractive and spheric or aspheric designs, it is more important clinically to consider these lenses as dependent or independent of the pupil for function.

Most of the lenses are designed to have a 3- to 4-D addition in the IOL, which is approximately 1.33 times that expected in the spectacle plane, thus resulting in a 2.50-D to 3.50-D effective add. The specific optical performance characteristics of five multifocal lenses are shown in Figures 2–5 and Tables 1–3.

Pupil-Dependent Lenses

Bullseye. The bullseye design (Fig. 1*A*) has a 2-mm diameter central zone for near vision, and the remainder of the lens is designed for distance vision. Because most patients have an average pupil size of 3 mm, the lens splits half the light for near and half for distance at normal light levels. When the patient is reading, the pupil usually constricts, causing more of the light to be directed to the near image. Unfortunately, the pupil also constricts in bright light, such as outdoors, which also shifts most of the light to the near image, limiting the distance vision. Also, patients with small, miotic pupils become too myopic as the patient is only using the near portion of the lens.

Annular. The annular design (Fig. 1*B*) moves the near portion from the center to a paracentral annulus, which has an inner diameter of approximately 2.1 mm and an outer diameter of 3.5 mm. The central zone and the peripheral zone are for distance vision. The design eliminates the chance of a patient with very small pupils having only near vision (e.g., less than 2.1 mm). With very small pupils the patient is using only the central portion of the lens, which is designed for distance. The lens is performing like a monofocal lens in this situation. When the pupil is 5 mm to 6 mm, most of the light is used for the distance image.

Single Aspheric. By generating an aspheric surface on one or both of the surfaces, a multifocal lens with a continuous focus from distance to near can be obtained. In this design (Fig. 1*C*) the central area of the lens is still weighted for near, with a gradual decrease in power toward the periphery. This aspheric design therefore is similar to the cornea, which also is apheric and decreases in power toward the periphery. There are no discrete changes in lens power over the surface of the lens.

Multiple Aspherics. This lens design (Fig. 1*D*) has spheric central and peripheral zones similar to the annular lens, but there is more than one annular zone. In addition, the annular zones are not spheric, rather they have aspheric surfaces that allow annular zones to have multifocal properties by themselves.

Pupil-Independent Lenses

Diffraction. The diffraction lenses (Fig. 1*E*) use refraction and diffraction to create the multifocal effect. Diffraction takes place at the edge of an aperture, whereas refraction takes place in the remainder of the area. By placing concentric rings (approximately 20) in a steplike fashion on either surface, a significant amount of diffracted light can be created. By adjusting the separation of the rings, the height of the steps, the curves on the steps, a multifocal effect can be attained. Because each pair of rings creates the multifocal effect, optical performance becomes almost independent of the pupil.

Array. The Array lens (Fig. 1*F*) has five concentric zones in which each zone has a specific aspheric curve, which creates the multifocal effect. Each zone is designed to create independently the multifocal effect such that it is almost independent of the pupil size.

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 (Fig. 1). A sixth lens, which was monofocal, was tested for comparison.

(Text continued on page 306)

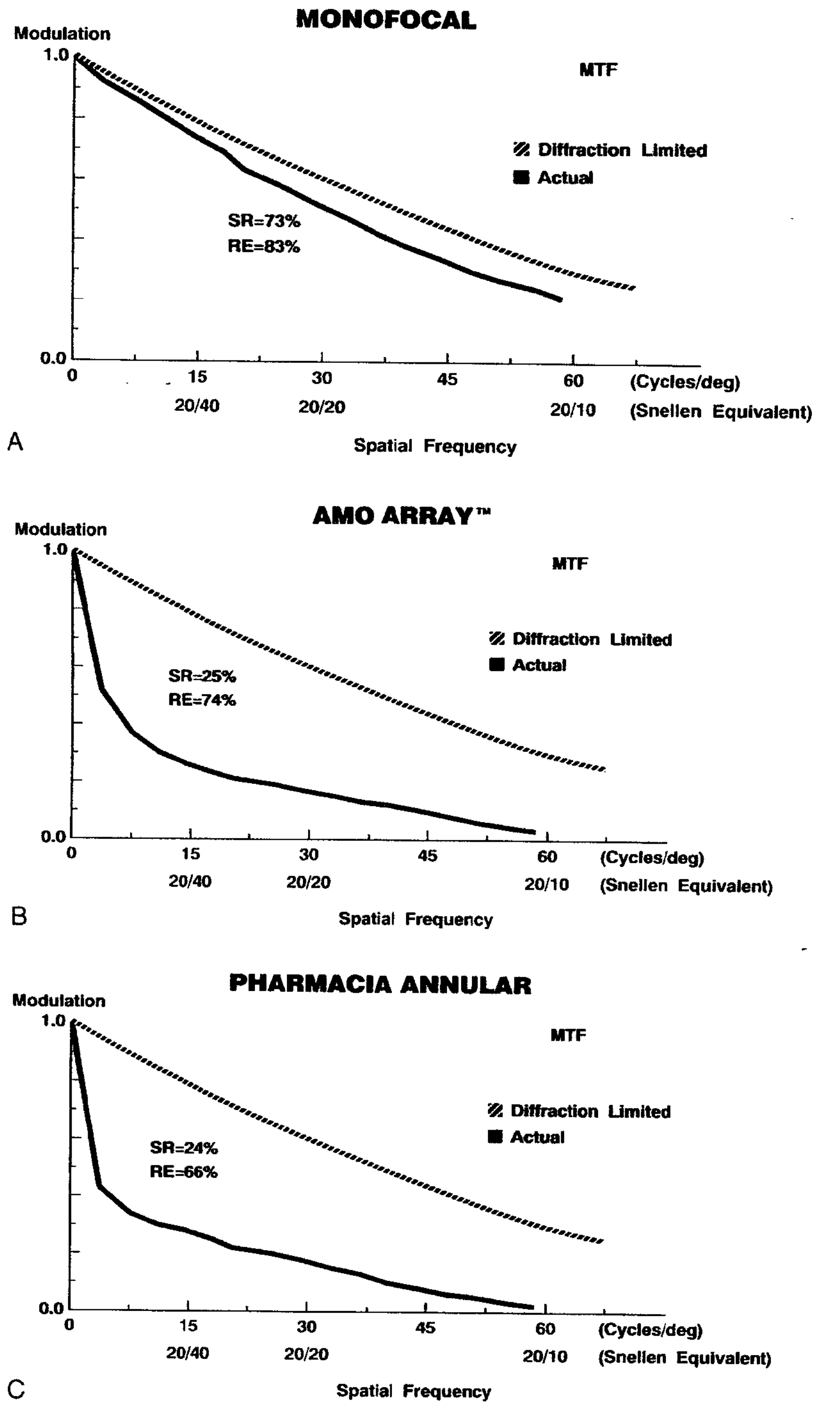


Figure 2. *A–F,* Modulation transfer functions *(MTF)* of the six lenses tested. The resolution efficiency *(RE)* and the Strehl ratio *(SR)* are shown on the graphs for reference. (*From* Holladay JT, van Dijk H, Lang A, et al: Optical performance of multifocal intraocular lenses. J Cataract Refract Surg 16:413–422, 1990; with permission.)

(Illustration continued on opposite page)

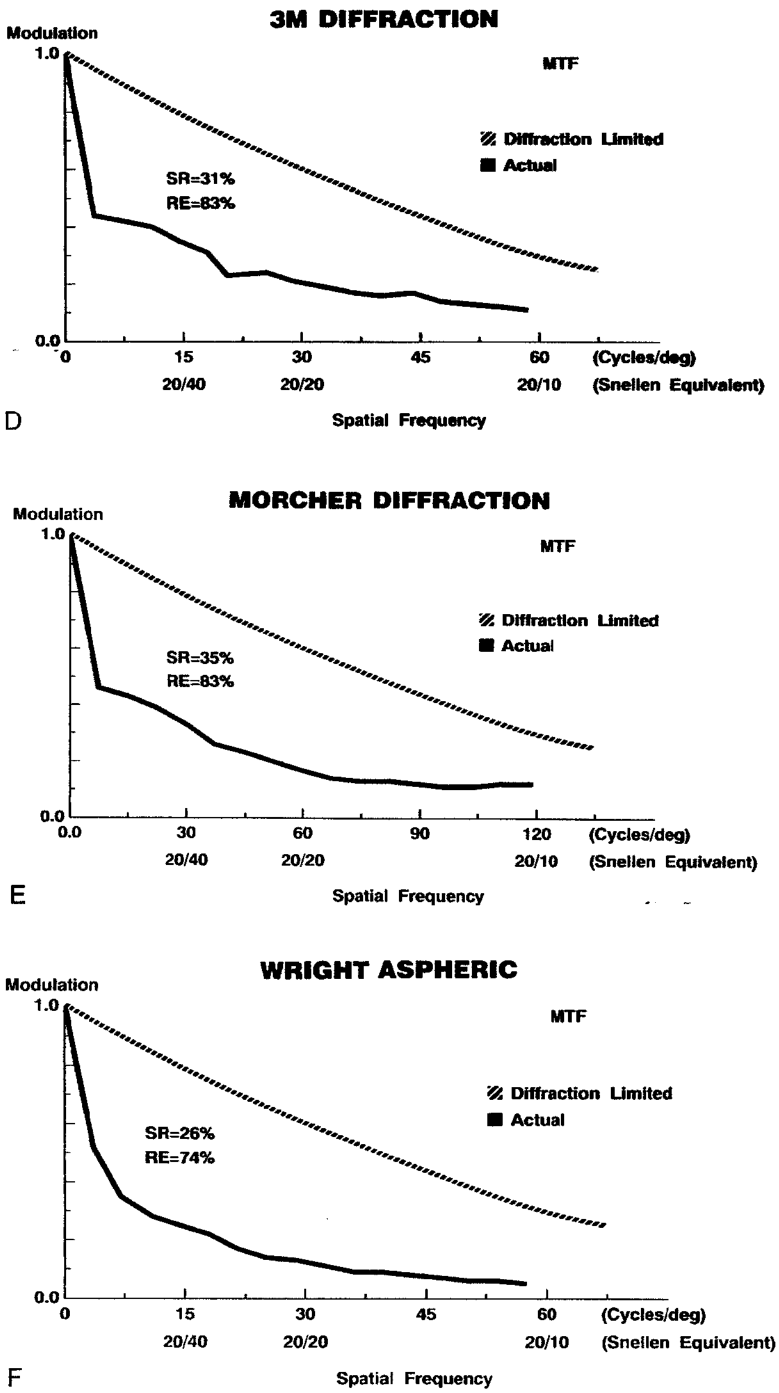


Figure 2. *(Continued).*

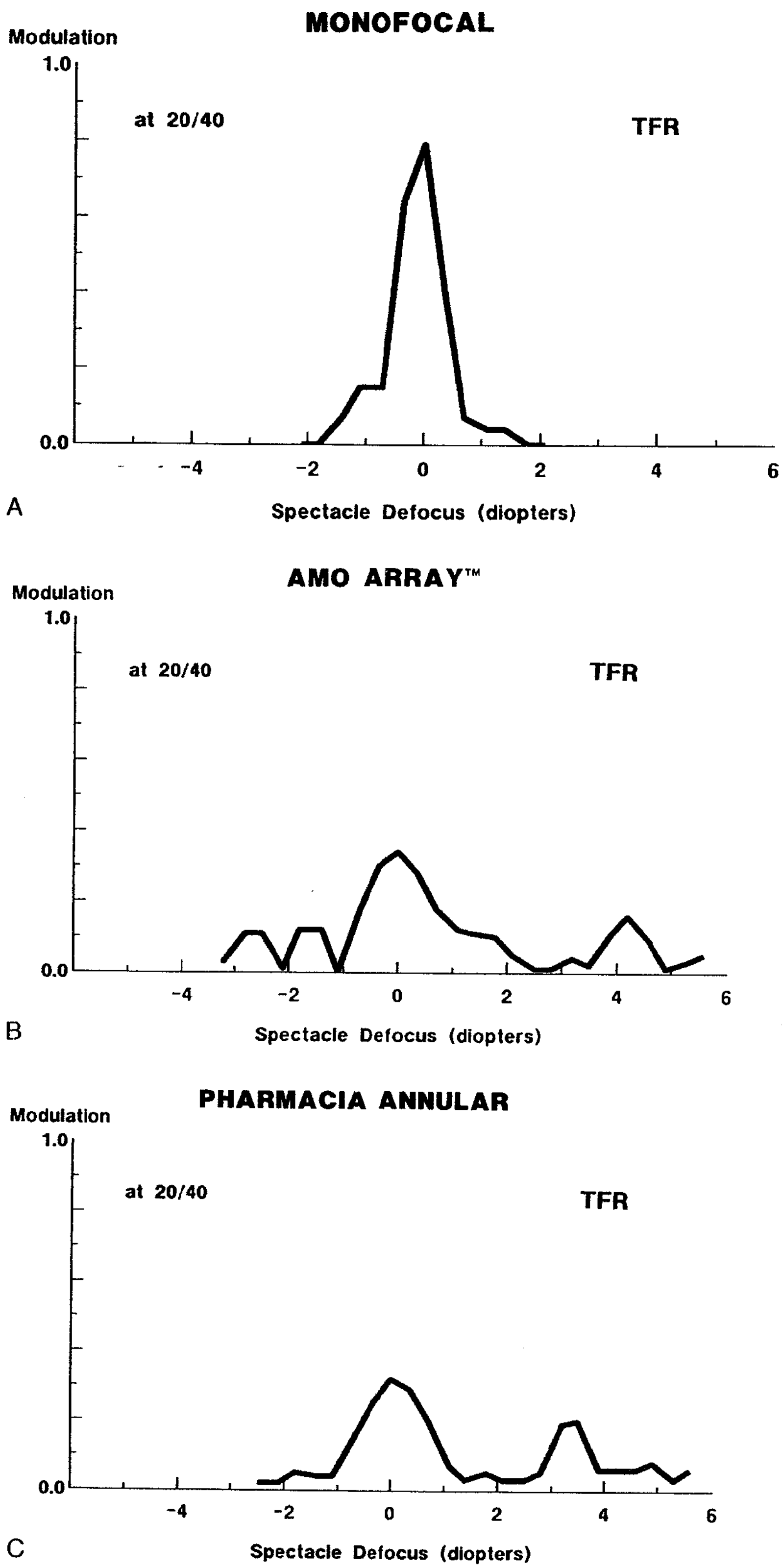


Figure 3. *A–F,* Through focus response *(TFR)* curves at 20/40 (15 cycles/degree) spatial frequency for the six lenses tested. (*From* Holladay JT, van Dijk H, Lang A, et al: Optical performance of multi-focal intraocular lenses. J Cataract Refract Surg 16:413–422, 1990; with permission.)

(Illustration continued on opposite page)

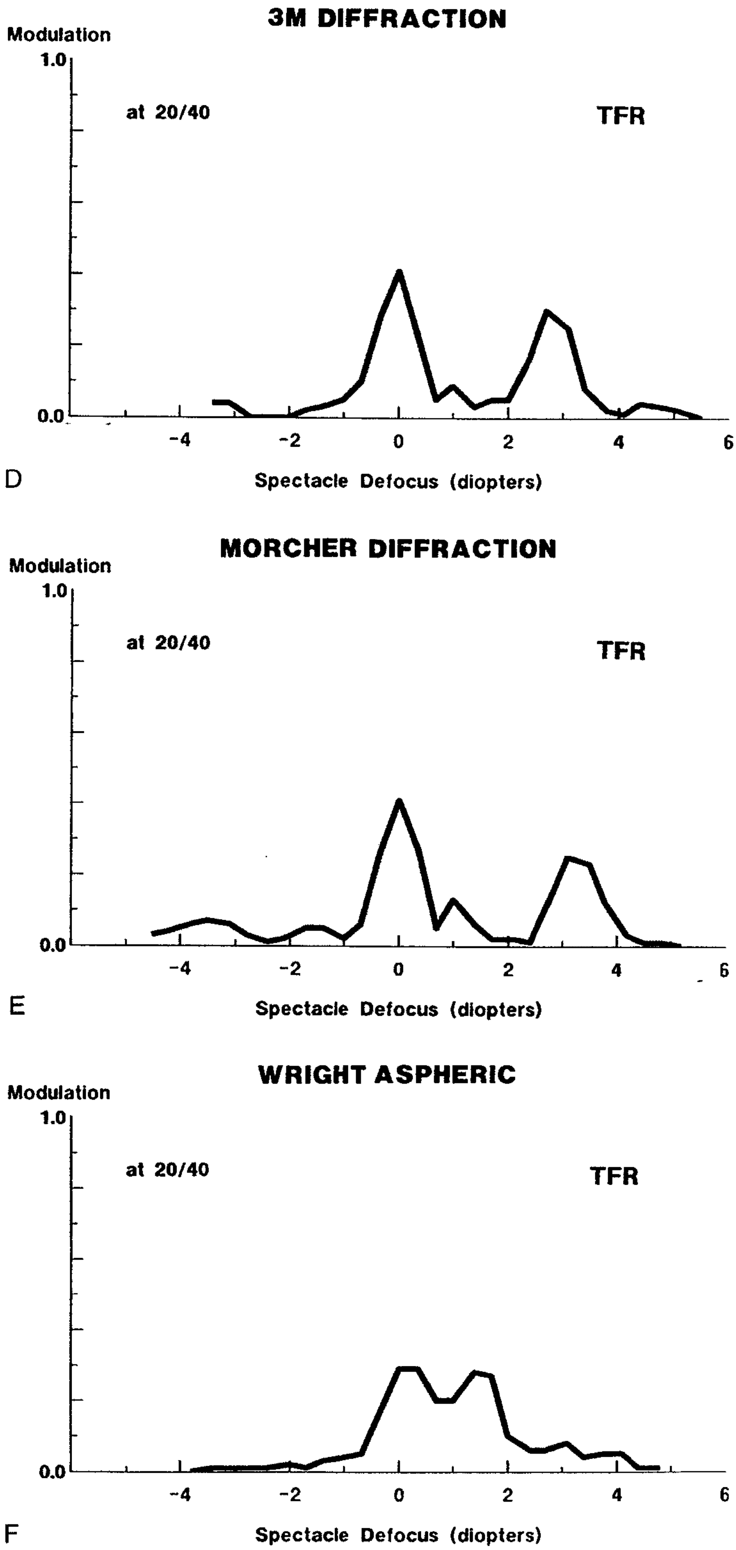


Figure 3. *(Continued)*.

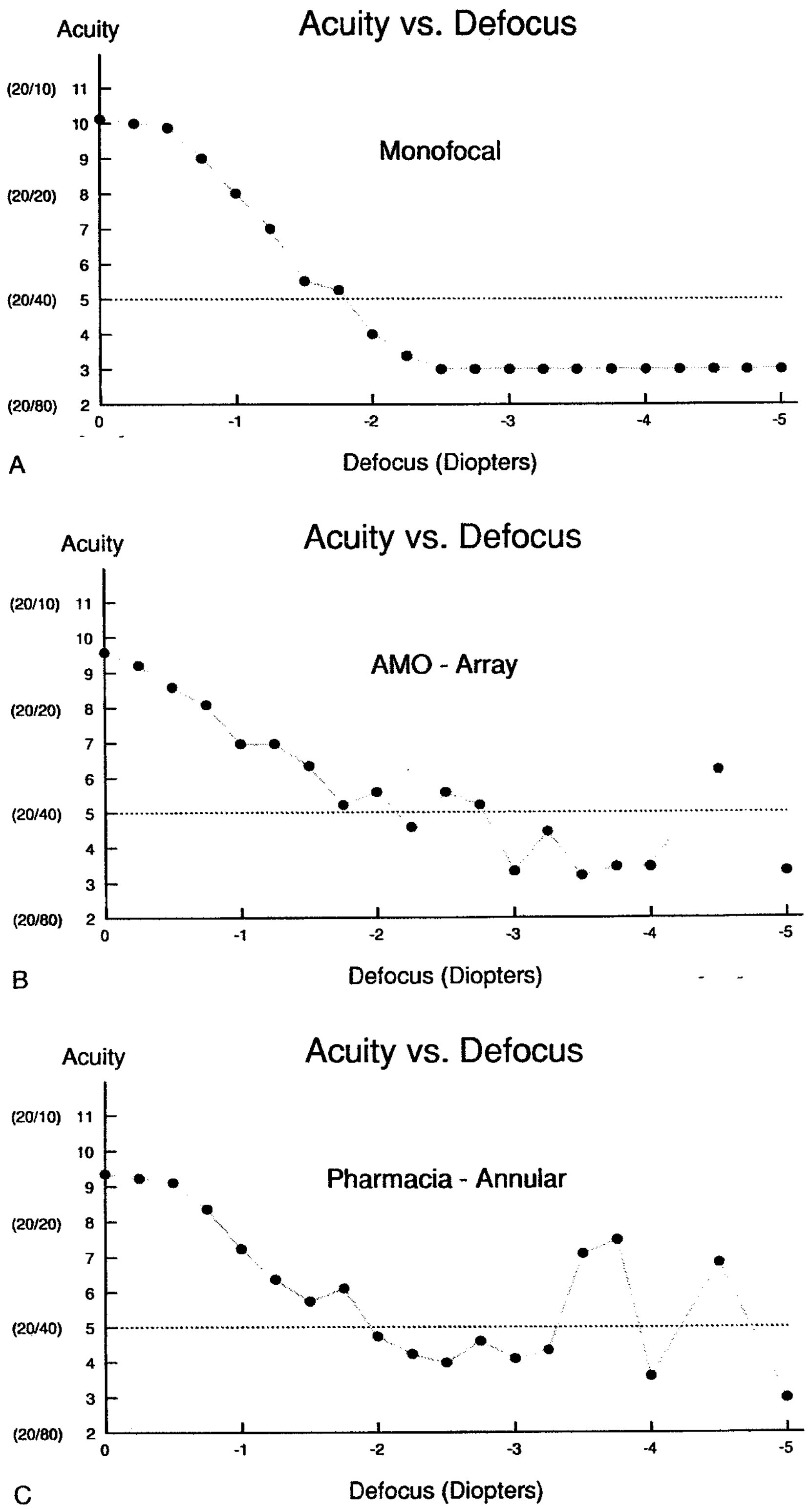


Figure 4. *A–F,* Acuity versus defocus plots for the six lenses tested. (*From* Holladay JT, van Dijk H, Lang A, et al: Optical performance of multifocal intraocular lenses. J Cataract Refract Surg 16:413–422, 1990; with permission.)

(Illustration continued on opposite page)

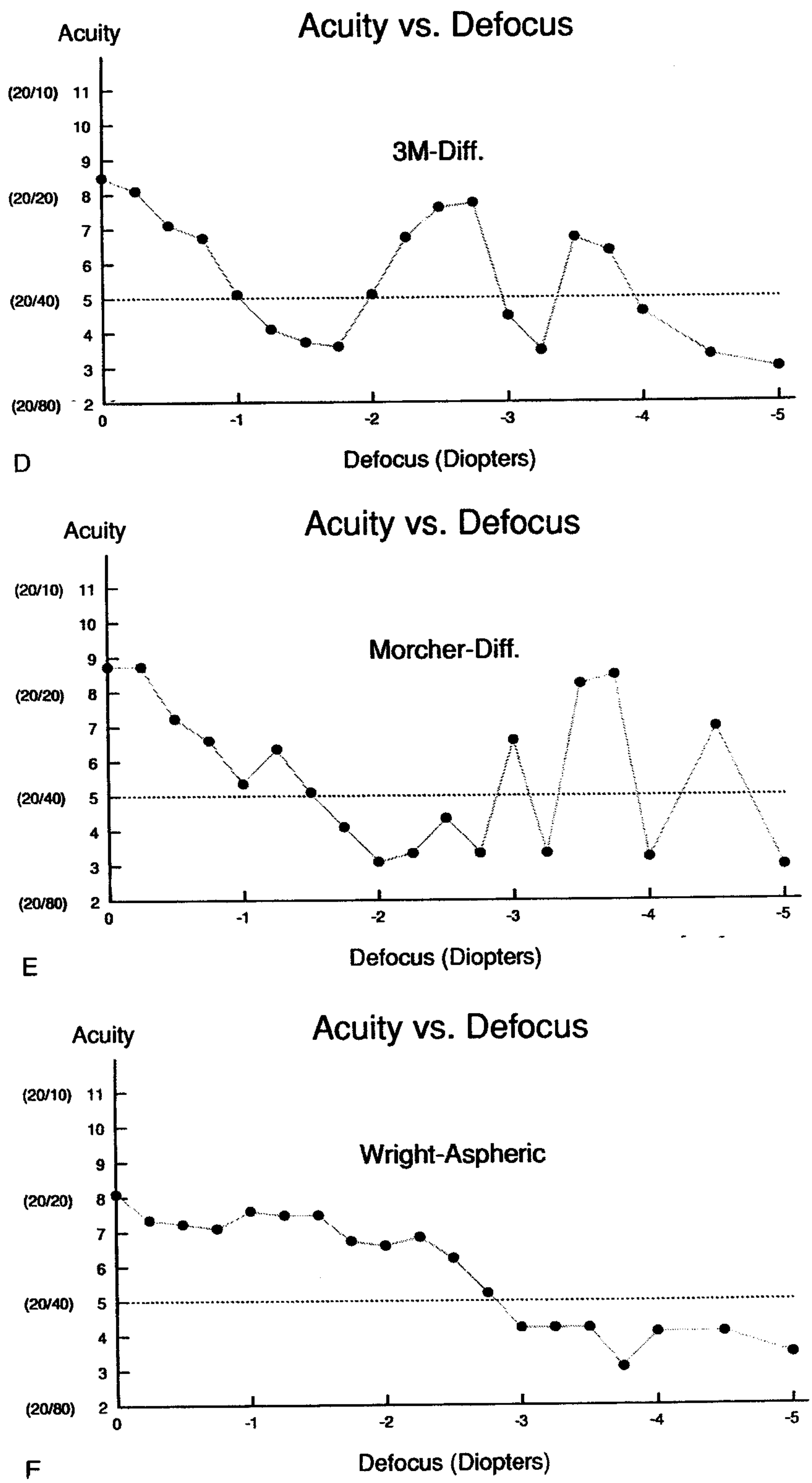


Figure 4. *(Continued).*