Intraocular lens resolution in air and water

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ABSTRACT

The resolution of 96 polymethylmethacrylate intraocular lenses with convexo-plano optics, ranging in power from 13 to 27 diopters, was measured in air and water. The resolution of each lens was expressed in linear units of resolving power, which is the maximum number of line-pairs that can be resolved per millimeter, as described in the current ANSI Standard Z80.7-1984. There was no clearly defined relationship between linear resolving power measured in air and that measured in water. Measurements on high power lenses (> 20 diopters) indicate that it is possible for an intraocular lens to meet the current 100 line-pair per millimeter standard for resolution and still be a limiting factor in a patient's best attainable visual acuity. An alternative method for evaluating lens resolution is to determine the resolution efficiency (the relative percentage performance of a lens compared to a diffraction-limited lens of the same dioptric power). Using these units, a consistent and predictable relationship from air to water was demonstrated. Our findings confirm that if a minimum standard of 30% resolution efficiency in air is established, in contrast to linear resolving power, the lens will perform near its diffraction limit when implanted in the eye. For intraocular lenses of materials other than polymethymethacrylate, a minimum resolution efficiency in air other than 30% may be required.

Key Words: diffraction limited, intraocular lens, resolution, resolution efficiency, resolving power, standard

The optical and physical requirements for American intraocular lenses are defined in ANSI Standard Z80.7-1984.[1] The primary optical requirements of a lens are (1) a minimum resolving power of 100 line-pairs per millimeter (lp/mm) measured in air,[2,3,4] (2) a dioptric strength in aqueous that is within ±0.50 diopters (D) of the labeled value in all meridians, and (3) a maximum astigmatic power in aqueous of 0.25 D in any two orthogonal meridians. Recommended in the standard is an optical bench arrangement for measuring these characteristics in air and a series of optical constants and equations for converting dioptric power and astigmatism measurements in air to corresponding values in aqueous.

The change in dioptric strength and astigmatism from air to aqueous for an intraocular lens (IOL) is a

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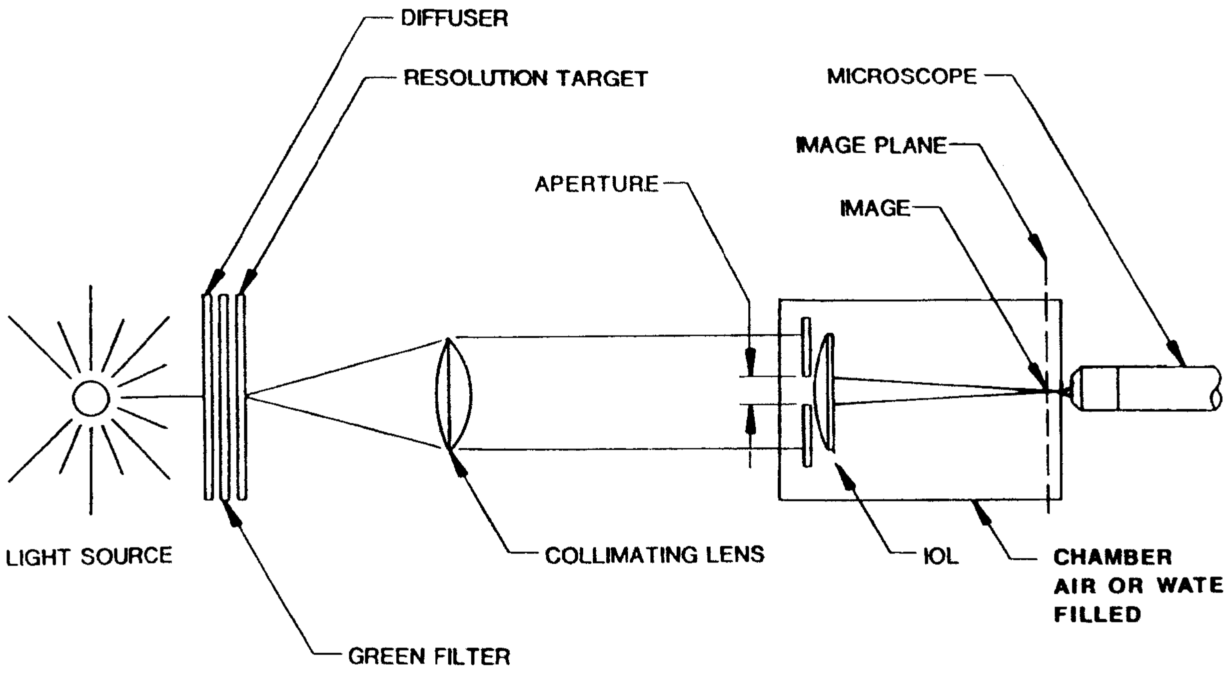

Fig. 1. (Holladay) Optical bench apparatus as described in ANSI Standard Z80.7-1984 modified so resolution and dioptric power measurements could be made in air or water.

basic geometric optics calculation. A polymethylmethacrylate (PMMA) IOL (index of refraction = 1.491) will be reduced by a factor of 3.18 in dioptric power when measured in aqueous rather than air.[5] For example, a PMMA IOL that measures 62.01 D of power and 0.32 D of astigmatism in air will have 19.50 D of power and 0.10 D of astigmatism in aqueous.

Although dioptric power and astigmatism are discussed in the ANSI standard, a method of converting the resolving power of an IOL from air to water is not discussed. We describe the first published experiment comparing the resolution of PMMA IOLs in air and water. As a result of our findings, we propose a new standard in air that is independent of lens power and will assure a nearly diffraction-limited performance in water.

MATERIALS AND METHODS

Ninety-six PMMA IOLs with convexo-plano optics and ranging in power from 13 D to 27 D in aqueous were tested. The 96 lenses were chosen from several hundred lenses in order to represent a wide range of resolution efficiency in air. All lenses were from one manufacturer. An optical bench, as shown in Figure 1, was used to measure the resolving power of each lens in air and water using the U.S. Air Force 1951 Resolution Target.* The measurements were made by two independent observers to minimize observer bias. When a discrepancy in measurements occurred, a third measurement was taken and the average value was used.

From the resolving power, the resolution efficiency was calculated for each lens in air and water. Resolution efficiency is defined as the percentage ratio of the actual resolving power of a lens to that of a perfect lens of the same focal length that is only limited in resolution by diffraction.

The diffraction limit (Vo) was calculated using the small angle formula:

$$Vo = (n \times d) / (f \times L)$$

where Vo = diffraction limited resolving power (lp/mm), n = refractive index of the surrounding medium (air = 1.0003, water = 1.3333), d = diameter of the aperture for the optical system in millimeters (3 mm), f = actual focal length of the lens in millimeters in air or water and, L = wavelength of illuminating light in millimeters (0.000555 mm).[1] For example, if an IOL were +19.39 D in aqueous, it would have a power of 61.66 D in air and a corresponding focal length of 16.22 mm in air. Using this formula, the diffraction limit (Vo) for this lens in air is 333 lp/mm. For instance, if the resolving power of the lens measured 199 lp/mm, its resolution efficiency would be 60% (199/333).

**Available from Melles-Griot, Irvine, California. Target consisted of bright lines on a dark background. The largest element corresponded to a resolution efficiency of 6.4% (using a 350-mm focal length collimator); the interval between elements is given by a ratio of 1:12.*

After the 96 lenses had been measured, they were divided into two major groups, (1) "passed" or (2) "failed" lenses, based on their ability to meet the previously described ANSI Standard Z80.7-1984 for resolving power and astigmatism. Group 1 (passed lenses, n = 47) was divided into two subgroups based upon their resolution efficiency in air: (A) "superior" lenses (n = 37): a resolution efficiency > 60%; (B) "average" lenses (n = 10): a resolution efficiency < 60%.

Group 2 (failed lenses, n = 49) was divided into three subgroups based upon their performance in air: (A) "poor" spherical lenses (n = 16): less than 100 lp/mm, but greater than 0 lp/mm resolving power; (B) "bad" spherical lenses (n = 10): no measurable resolving power; (C) "multiple image" lenses (n = 23): confusing, multiple images.

RESULTS

The resolving powers in air and water for all 96 IOLs are shown in Figure 2. In Figure 2B, it is apparent that for better lenses (i.e., greater than 200 lp/mm resolving power in air), the resolution in water generally increases with increased resolution in air. Poorer lenses do not exhibit this relationship; lenses with low resolving power in air show a large variability of resolution in water. It is apparent that resolving power in air is not a reliable predictor of resolution in water.

The data points were replotted using the resolution efficiencies of each lens (Figure 3), and several observations could be made.

Lenses in Group 1A ("superior" lenses) maintained essentially the same resolution efficiencies in water as in air, ranging from 73% to 85%. The average resolution efficiency was 75% (SD = 6.0%) in air and 77% (SD = 4.5%) in water. There was no statistically significant difference in the lenses in air or water. The resolution efficiency of six lenses actually became 9% lower in water. The improvement factor in resolution efficiency from air to water ranged from 0.9 to 1.1. The appearance of the Air Force Target in air and water for one of these lenses is shown in Figures 4A and 4B.

Lenses in Group 1B ("average" lenses) showed a significant improvement in water, where they all achieved a resolution efficiency of 73%. The average resolution efficiency in air was 45% (SD = 6.0%). The improvement factor from air to water ranged from 1.4 to 2.2. There was no statistical difference in the resolution efficiencies in water between Groups 1A and 1B, indicating that average and superior lenses in air were all superior lenses in water.

Lenses in Group 2A ("poor" spherical lenses) demonstrated the greatest improvement in their resolution efficiencies from air to water. Their average resolution efficiency in air was 26% (SD = 5.0%) and all these lenses also increased to 73% resolution efficiency in water. These lenses had improvements in their resolution efficiencies from air to water ranging from 2.0 to 4.0. The appearance of the Air Force Target for one of these lenses in air and water is shown in Figures 5A and 5B.

Lenses in Group 2B ("bad" spherical lenses) had

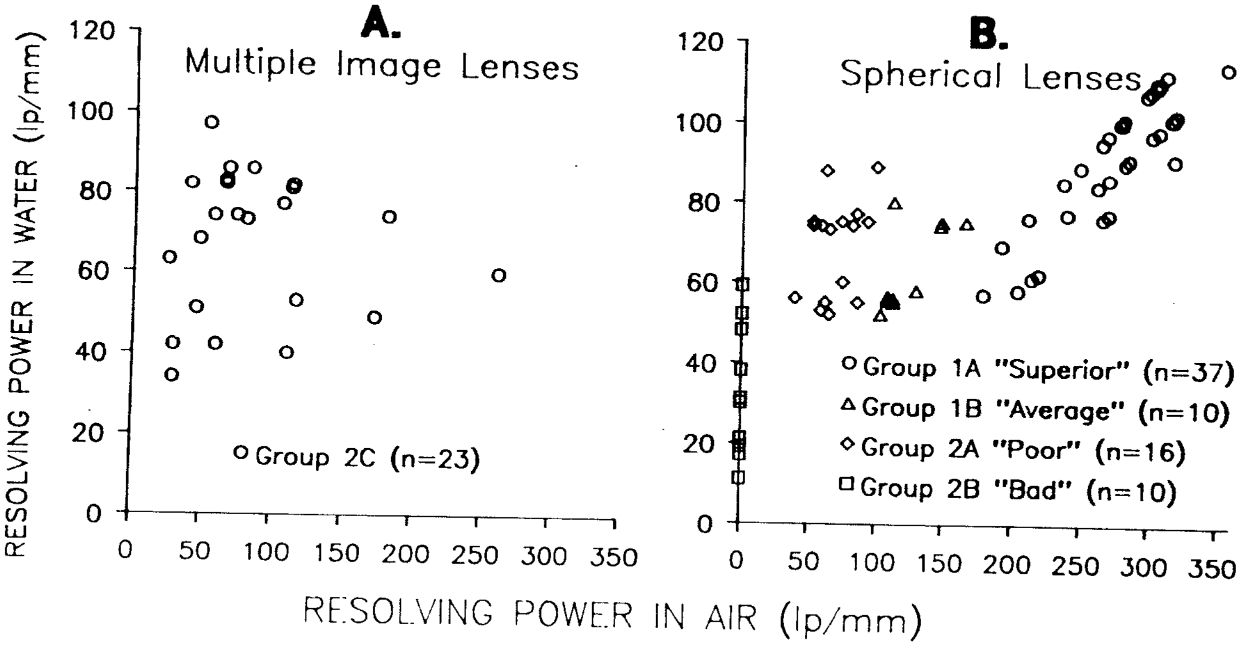

Fig. 2. (Holladay) The resolving power of "multiple image" and "spherical" IOLs in air and water: (A) multiple image lenses (n = 23) with confusing, multiple images; (B) spherical lenses (n = 73) of various resolutions. No observable relationship in resolving power measured in air and water can be seen for either lenses.

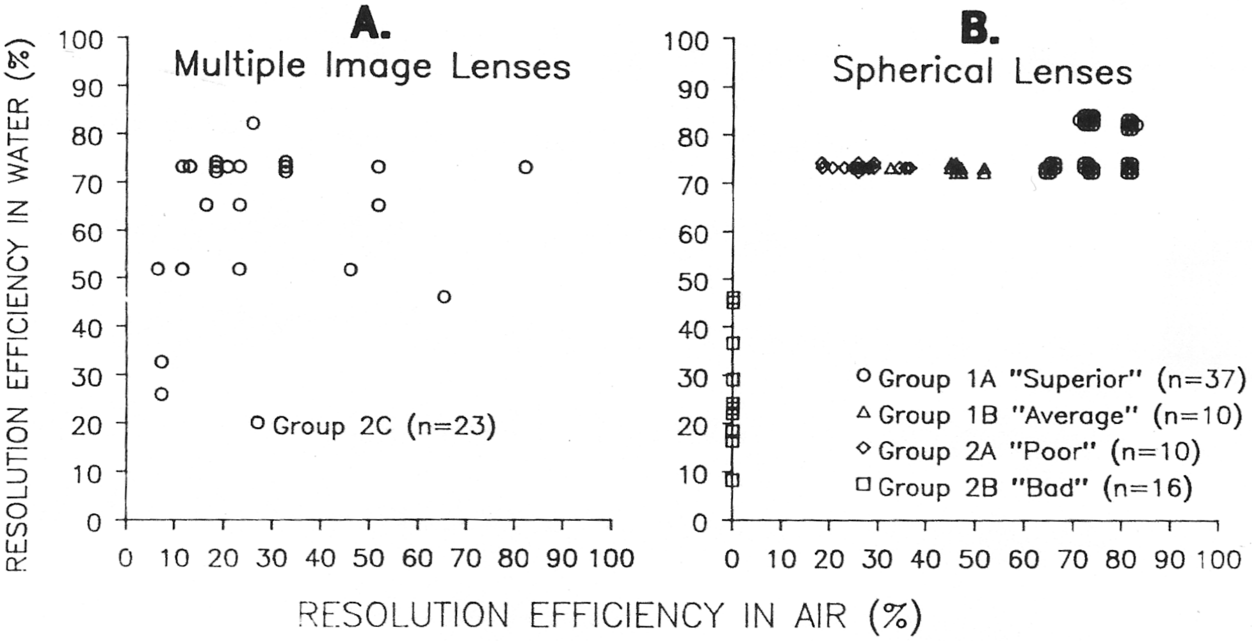

Fig. 3. (Holladay) The resolution efficiency for the same "multiple image" and "spherical" IOLs in air and water: (A) multiple image lense (n = 23) with confusing, multiple images; (B) spherical lenses (n = 73) of various resolutions. The improvement for multiple imag lenses, although significant, was much less predictable, but all spherical lenses that exceeded a resolution efficiency of 18.4% in a had greater than 73.0% resolution efficiency in water.

measurable resolving powers in water even though in air they were unable to resolve the largest element on the Air Force Target. Their resolution efficiencies in water varied widely, averaging 27.0% (SD = 12.5%) and the best lens in this group had a resolution efficiency in water of 46.1%. Part of the explanation of the wide variability in this group was the difficulty in deciding which element on the target was ju resolvable.

Lenses in Group 2C ("multiple image" lense improved as a group but the change was not a predictable as the spherical lenses in previous group The lack of predictability resulted from the confusin multiple images produced by irregular astigmatisr

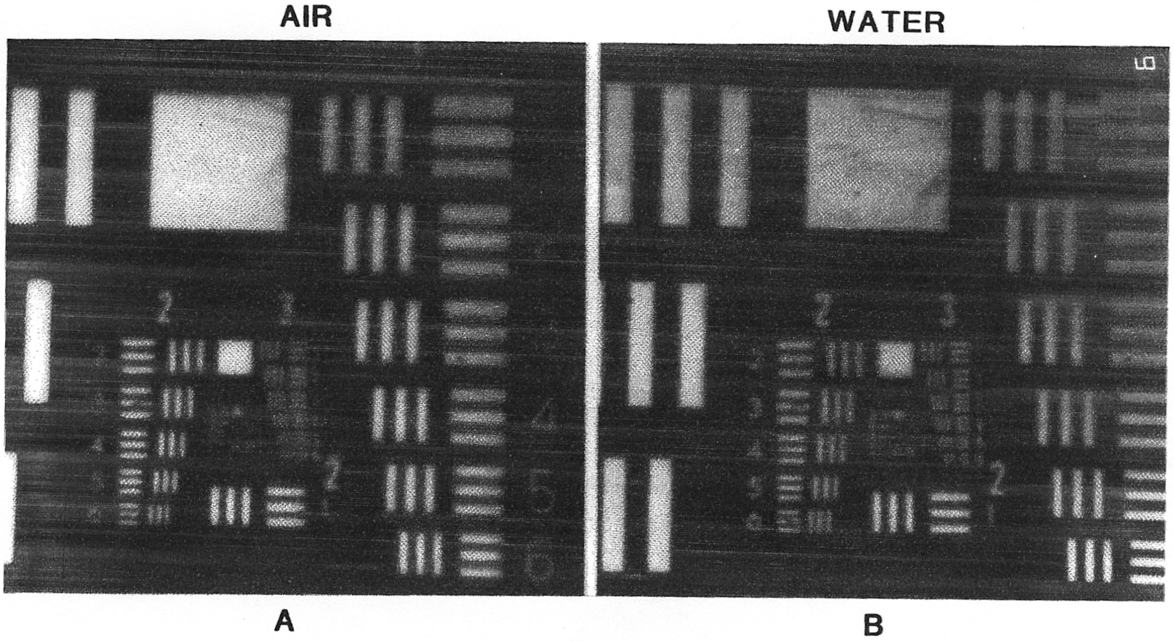

Fig. 4. (Holladay) Appearance of the Air Force Test Target for a "superior" spherical IOL in air and water. (A) The resolution efficiency in a is 82%; (B) the resolution efficiency in water is 73%.

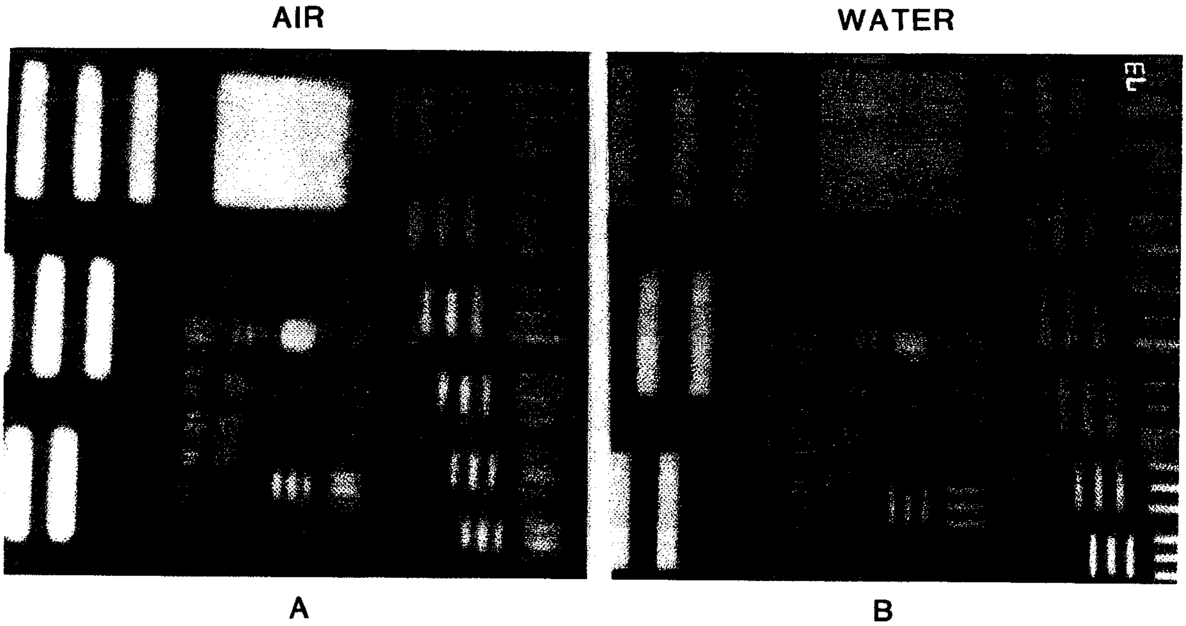

Fig. 5. (Holladay) Appearance of the Air Force Test Target for a "poor" spherical IOL in air and water. (A) The resolution efficiency in air is 23%; (B) the resolution efficiency in water is 73%.

(Figure 6). The resolution efficiency of two lenses in this group became worse in water. The resolution efficiencies for this group in air averaged 28% (SD = 19.5%) and in water averaged 64% (SD = 15.0%), which was markedly worse than Groups 1A, 1B, and 2A. The improvement factors for this group ranged from 0.9 to 8.0.

All spherical lenses (Groups 1A, 1B, 2A, and 2B) with resolution efficiencies greater than 18% in air equaled or exceeded 73% resolution efficiency in water without exception. For all groups, the change in resolution efficiency from air to water was not a function of IOL dioptric power, consistent with the hypothesis that resolution efficiency is a uniform measure of optical quality for a lens of any dioptric power.

DISCUSSION

Our choice of 60% resolution efficiency for dividing "passed" lenses into "superior" and "average" arises from a parenthetical comment on page 11 of the American National Standard Z80.7-1984 which states that a 60% resolution efficiency "is the minimum acceptable under this standard." This statement has created some confusion since a 19.5 D PMMA IOL has a diffraction-limited resolving power in air of 335 lp/mm and a 60% resolution efficiency would be 200 lp/mm. If this 60% resolution efficiency is the minimum requirement, the majority of IOLs currently used must be manufactured to a 200 lp/mm standard, not 100 lp/mm. Is there a double standard?

To clarify the meaning and origin of the 60% requirement, the chairman and secretary of the Z80.7-1984 were contacted. They stated that the 60% resolution efficiency was only an example of the correct

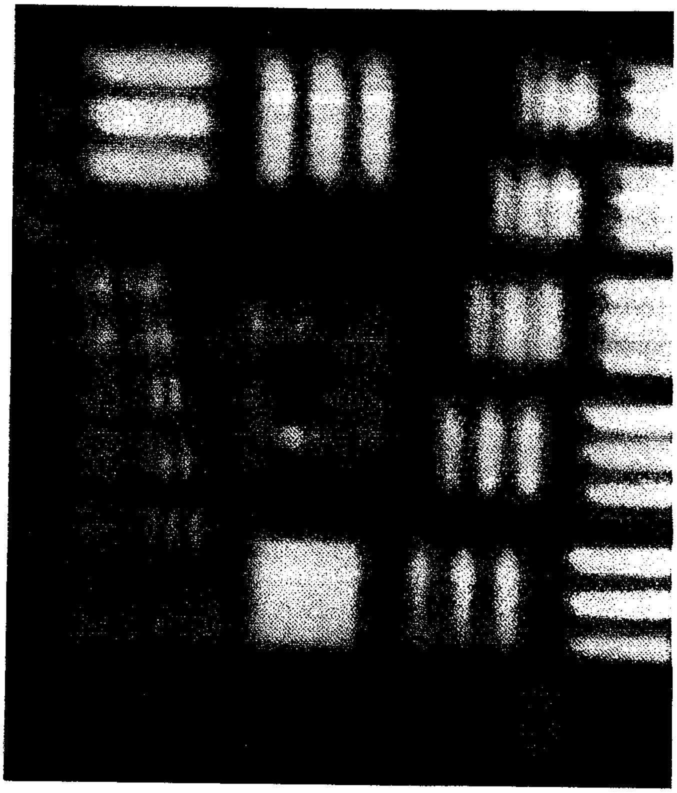

Fig. 6. (Holladay) Appearance of the Air Force Test Target for a "multiple image" IOL in air. Notice the multiple images that make resolution measurements for these lenses confusing.

method for calculating this quantity and no mention of "minimum acceptable" was discussed by members of the committee (personal communication, Robert C. Drews, M.D., and Mr. Melvin Nimoy, secretary, April 1987).

To complicate matters, the diffraction-limited resolving power of a 6 D IOL is 101 lp/mm in air for a 3-mm aperture. Lenses that are less than 6 D which cannot meet the 100 lp/mm minimum resolving power are now being manufactured for patients with high myopia.[6] This paradox has also created a problem for the Food and Drug Administration, which must approve these lenses.

This discrepancy has also clouded the issue for requirements of lenses made from "soft" materials such as silicone and hydrogel, since these lenses may be unable to achieve as high a resolving power as PMMA lenses in air yet they may perform as well in water or aqueous.

Our experiment proves that a standard of 60.0% resolution efficiency in air is too high because lenses with resolution efficiencies as low as 18.4% in air will also attain resolution efficiencies equal to or greater than 73.2% in water (Figure 3).

A significant improvement in lens resolution from air to water is not surprising. An IOL that exhibits a relatively small degree of aberration because of surface errors (e.g., departures from a true spherical or plano surface) will have less aberration in water than in air. Specifically, the wavefront error,[7] i.e., the departure of the converging wavefront from a perfect spherical shape, for a PMMA lens in water will be less than the error in air by a factor of 3.2. However, a consistent improvement factor on bad and poor lenses cannot be established from our data, in part because of the variation in the measurements with these lenses.

A second influence that must be considered is the effect of diffraction. If the lens is near the diffraction limit in air (wavefront error of less than one quarter wavelength), the reduction in wavefront error for the immersed lens cannot significantly increase its performance.[8] Obviously, the linear resolving power of a lens cannot remain the same in water as in air if the value in air exceeds the resolution limit in water. The corollary in units of resolution efficiency would be that the lens cannot improve above 100% when immersed in water.

From these considerations, we would expect a diffraction-limited lens with a resolution efficiency near 100% to decrease its linear resolving power by a factor of 3.2 and maintain nearly 100% resolution efficiency when immersed in water. Our data generally support these theoretical considerations in that superior lenses maintained approximately the same resolution efficiencies in water as in air and the poor and average spherical lenses improved significantly in resolution efficiency (Figure 3B).

Multiple image lenses, however, were very unpredictable. When the surface of a lens departs significantly from a spherical surface (confusing multiple images), the prediction of performance requires detailed knowledge of both the wavefront errors (from either direct measurement or exact calculation) and the measure of performance that is to be used. Significant research has gone into determining the prediction of performance based on knowledge of wavefront error, particularly in high performance systems such as the space telescope, microscope objectives, and lenses used in integrated circuit fabrication.[9] However, determining the lens resolution in air is not sufficient to determine its wavefront error, and therefore is not sufficient to determine the exact resolution in water.

In our study, rejecting lenses with multiple images was sufficient to eliminate lenses that departed significantly from a spherical surface and were unpredictable. In our study, without exception, all lenses without multiple images were sufficiently spherical to assure a minimum of 73% resolution efficiency in water if they exceeded 18% in air (Figure 3B).

It should be noted that the maximum achievable resolving power of the human eye is approximately 250 lp/mm (0.80 minutes of arc or 20/08 Snellen acuity).[8,10-13] Calculating the diffraction-limited resolving power for a normal eye (equivalent focal length = 22.8 mm) with a 3-mm pupil yields a resolving power of approximately 320 lp/mm, indicating that the best possible resolution efficiency attainable by the human eye is 78% (250/320, experimental range from 65% to 85%).[2] A Snellen acuity of 20/10 corresponds to 63% resolution efficiency and 20/20 corresponds to 31%.

Assuring that the IOL is near diffraction-limited performance in water does not permit exact prediction of the performance of the pseudophakic eye. Such a prediction would require detailed knowledge of the postoperative corneal topography, the lens position relative to the cornea and pupil, and any inhomogeneities in the ocular media. However, near-diffraction-limited performance will assure that errors in the IOL would not by themselves reduce the performance of the system below the near-diffraction-limited level.

When measuring an IOL in air in the range of 20% to 30% resolution efficiency, the change between elements on the Air Force Test Target is approximately 3%. To assure an adequate standard for resolution, we propose that a minimum resolution efficiency of 30% for PMMA IOLs in air be chosen as the minimum standard. This standard in air would assure that the actual performance of the lens in water would be greater than 73% resolution efficiency.

Most manufacturers currently use the 100 lp/mm standard, which for a 20-D IOL represents a 28.6% resolution efficiency. Our proposal of a minimum 30%

resolution efficiency therefore will not materially affect the standards for mid-power IOLs used today. It will, however, increase the standards for high plus lenses (> 25 D). This change is important because these IOLs require a greater resolving power than the mid- and low-power lenses to achieve the same resolution efficiency.

A resolution efficiency standard of 30% in air will also provide an attainable guideline for the low-power lenses (< 10 D), where the necessary resolving power is less than mid-power lenses to achieve the same resolution efficiency. A 30% resolution efficiency in air would still assure greater than a 73% resolution efficiency for these lenses in water so that the lens will perform near its diffraction limit when in the eye.

The standard of 100 lp/mm resolving power for IOLs in air has served us well during these early years of IOL development, but no one could have foreseen the constantly expanding power range that now extends from high minus lenses (−100 D) to high plus lenses (+35 D).[6,14] Because of this wide power range, linear resolving power in air is a poor and inconsistent standard for IOL optical performance. Figure 2 graphically illustrates this point.

In contrast to resolving power (Figure 2), resolution efficiency is a uniform measure of IOL quality, independent of IOL power. It provides a predictable relationship from air to water (Figure 3B). Also, this relationship provides a scientific basis for allowing manufacturers to continue making their quality control measurements for IOLs in air. The data indicate that PMMA lenses that meet a 30% resolution efficiency in air also yield a resolution efficiency of at least 73% in water. These findings along with the large body of clinical data existing for mid-power lenses support our proposed 30% resolution efficiency standard.

Our study also demonstrates that a requirement that would specifically reject lenses with multiple images must be added to the standard. This requirement is necessary because lenses with multiple images may still exceed the most stringent requirements for astigmatism and resolution (Figure 3). The unpredictability of the resolution in water for these lenses is an important reason for rejecting them, but a more important reason for adding this requirement to the standard is to prevent the monocular diplopia or polyplopia that would be experienced by the patient after implantation.

It is important to emphasize that our data apply only to PMMA lenses and not to lenses of different materials such as silicone and hydrogel. These soft materials have lower indices of refraction, requiring steeper radii to achieve the same IOL power in aqueous. Theoretically, they will require a slightly lower standard in air to exceed the same 73% resolution efficiency in water.

For lenses of new materials to equal the resolution performance of PMMA, the generic standard for IOLs of any material must assure near-diffraction-limited performance in aqueous (greater than 70% resolution efficiency in water), similar to PMMA in water. As lenses made of new materials emerge, it is incumbent on the manufacturer to (1) prove that these new lenses can exceed 70% resolution efficiency in water and (2) determine if a consistent, corresponding resolution efficiency standard in air can be established. This new standard will assure a performance near the diffraction limit when in the eye.

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