

Letters to the Editor

Is Resolving Power Independent of Wavelength Possible? An Experiment with a Sonic "Macroscope"

ALBERT V. BAEZ

University of Redlands, Redlands, California

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THE usual criterion of resolution is based on the diffraction limit $\sin\theta = 1.22\lambda/a$ given by Rayleigh, where θ is the minimum angular separation of two point luminous objects, λ is the wavelength, and a is the diameter of the circular aperture used. In microscopes this yields an expression for the minimum resolvable distance s between two point luminous objects: $s = \lambda/2n \sin i$ where $n \sin i$ is the numerical aperture of the system. An optimum value for a microscope is about $s = 0.3\lambda$.

A recent letter by O'Keefe suggests that "it is possible to go beyond the resolving power of visible light."¹ I shall assume that he means that one can obtain minimum resolvable distances considerably smaller than the wavelength of the radiation used. First, let us say that in contact radiography the practical limit on resolution is set by the granularity of the film and in the scanning type microscope² the practical limit on resolution is the size of the source of radiation. It turns out that diffraction limitations do exist and do play some part in the ultimate resolution obtainable even in the two extreme cases just mentioned. These will be discussed more thoroughly in a paper now in preparation. However, if we grant that source size or film granularity, whichever is larger, sets the practical limit on resolution in these cases we may use a radiation whose wavelength is considerably larger than either and obtain resolution as suggested in one case by O'Keefe.

As an illustration of this idea we performed an experiment with sound. At first one might object to a change from electromagnetic radiation (or photons, whichever way we look at the problem) to a pressure wave. However, if we keep in mind the fact that the gross diffraction behavior of either light or sound is given by the laws of physical optics, it may be granted that the experiment with sound is instructive.

An audio-frequency oscillator was connected to an audio amplifier whose output went to a loudspeaker placed in a large box and padded with insulating material. A hole about 0.5 in. in diameter was made in the box. A microphone with a directional shield over it was placed close to the hole. The audio-frequency oscillator was set at 2400 cycles/sec, corresponding to a wavelength of about 5.5 in. The hole, therefore, was about 0.1 of a wavelength in size. The output of the microphone entered a tape recorder and a cathode-ray oscilloscope. The important relevant result is the following: The background noise before the experiment started measured 6 units on the vertical oscilloscope scale. With the oscillator turned on and the microphone close to the hole, but with a hand covering the hole, the reading was 10 units on the vertical oscilloscope scale. With the hand removed, the reading was 26 units on the vertical scale. The importance of having the object in very good contact with the hole may be illustrated by the following readings. If two fingers whose total diameter exceeded the diameter of the hole were placed over the hole, the reading was 19 units, but if a third finger was brought up close to the other two, even though the third finger was away from the actual vicinity of the hole, the reading went down to 11 units, indicating that radiation tended to "leak out" by various means including diffraction, reflection, scattering, etc. There is no doubt, however, that an object smaller than the wavelength of the radiation was "resolved."

It may be argued that one must carry over by analogy the results of this experiment into light with considerable care because

light is an electromagnetic phenomenon whereas sound is a pressure phenomenon. However, both experience diffraction so that the radiation coming out of a hole which is small in comparison with the wavelength tends to spread out into a Huygens wavelet as the hole size dimensions. Nevertheless, if the absorption of the object for the given wavelength permits it, it should be possible to resolve objects smaller than the wavelength, regardless of the type of radiation used. It would be particularly useful where apertures smaller than the wavelength involved are easy to make as they might be with ultrasonic radiation and with infrared radiation. What could make this useful is the fact that interesting absorption discontinuities occur in different wavelength regions. In the infrared around 40μ , for example, using a hole about 10μ in size one might get information which approaches the microscopic by this technique whereas ordinary optical methods would be limited essentially by Rayleigh's criterion.

The question posed in the title has been answered only partially. Other factors besides diffraction affect resolution as the wavelength changes and these will be discussed later.

¹ J. A. O'Keefe, *J. Opt. Soc. Am.* 46, 359 (1956).² H. H. Pattee Jr., *J. Opt. Soc. Am.* 43, 69 (1953).

About the Spherical Aberration of the Eye

ALEXANDRE IVANOFF

*Ecole Supérieure de Physique et de Chimie Industrielles, Paris, France, and
Muséum National d'Histoire Naturelle, Paris, France*

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I RESUMED in 1953 the study of the spherical aberration of 10 eyes, in their horizontal meridian, by means of a parallax method previously described in several publications.¹ The results obtained² were essentially the same as those of the year 1946, and in particular the value of the aberration varied very rapidly near the achromatic axis. This last peculiarity, rather surprising at first, caused criticism of my results.³ The error does not lie, in fact, in the method of measuring nor in the experimental results, but as G. Westheimer⁴ pointed out, in the fact that I supposed the aberration to be null on the axis, which is the same as admitting that the extremity of the caustic lies just on the retina. This is not really the case and the interpretation of my experimental results must be rectified by interpolating each curve with regard to the distances to the axis which are less than 0.5 mm (Fig. 1). This interpolation can generally be carried out with less than 0.05 diopter error.

I recently published⁵ the average of the results I achieved in 1953, thus corrected, and I maintained that an average has not a

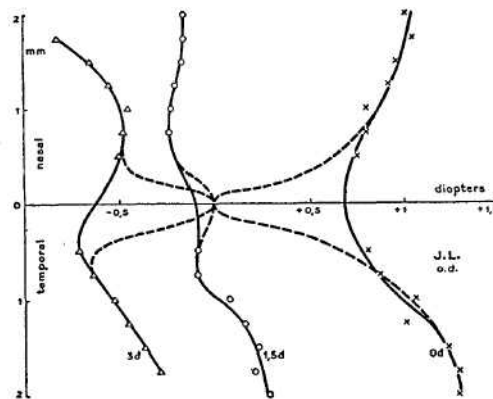


FIG. 1. An example concerning one of the investigated ten eyes. In dotted line, the earliest interpretation of the results ascribing to the aberration a zero value on the axis. In full line, the correct interpretation achieved by interpolating each curve between 0.5 mm on nasal side and 0.5 mm on temporal one. The value of the aberration thus obtained on the axis (set equal to zero on Figs. 2 through 11) is corresponding to the interval between the extremity of the caustic and the retina in the measuring conditions.

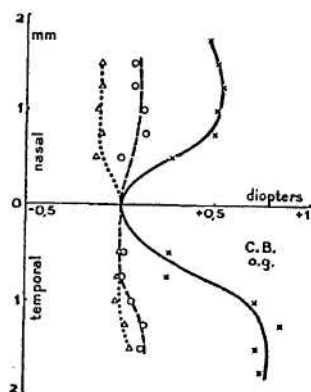


FIG. 2.

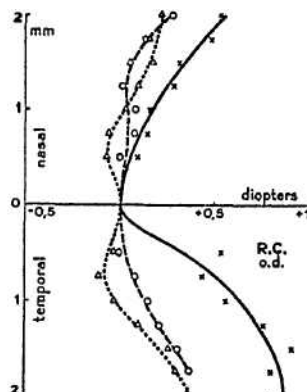


FIG. 3.

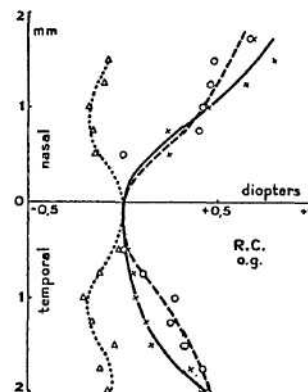


FIG. 4.

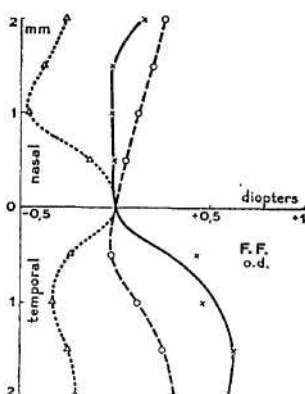


FIG. 5.

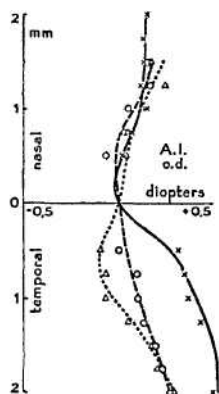


FIG. 6.

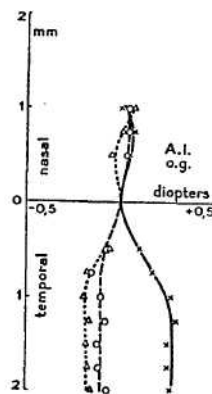


FIG. 7.

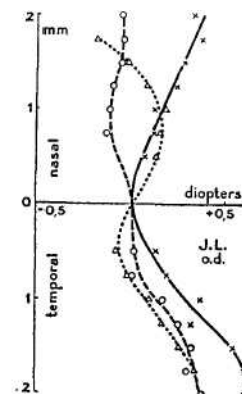


FIG. 8.

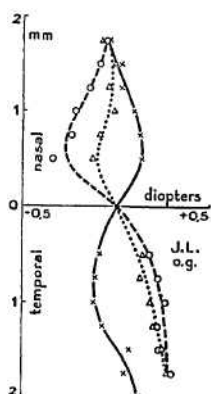


FIG. 9.

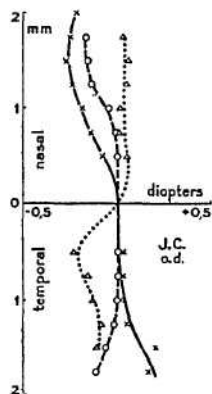


FIG. 10.

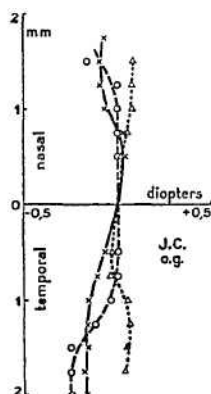


FIG. 11.

FIG. 2 through 11. Spherical aberration of the investigated ten eyes.

great significance for so variable a size, from one eye to another. Considering the many debates which the spherical aberration of the eye has caused in these years, I think it useful to publish the results I obtained in 1953, concerning each of the investigated ten eyes, rectified in the way mentioned. These results are given in Figs. 2 through 11, with the value of the spherical aberration on the x axis (positive when under-correction) and the distance to the achromatic axis on the y axis. The curves designated by — correspond to the unaccommodated eye; those curves designated by --- correspond to the eye with 1.5 diopters of accommodation, and those curves marked . . . correspond to the eye with 3 diopters of accommodation. As we have already mentioned, the interpolation for the distances to the axis, which are less than 0.5

mm, could have an error probably less than 0.05 diopter, except when the aberration rapidly changes on both sides of the axis. This occurs only once (unaccommodated eye of Fig. 2).

We can see that:

(1) The highest value of the spherical aberration (at least for the distances to the achromatic axis that do not go beyond 2 mm) amounts to 0.8 diopter in 3 cases out of 10, to 0.5–0.6 diopter in 3 cases out of 10, and to 0.25 diopter in 4 cases out of 10.

(2) The passage from the under-correction to the over-correction when the eye accommodates 3 diopters is distinct in 4 cases out of 10 (Figs. 2, 3, 4, and 5) and occurs only on one side of the axis in 3 cases out of 10 (Figs. 6, 7, and 8). In the other cases the spherical aberration is perceptibly independent of the state

of accommodation or even varies in the opposite direction to the general rule.

(3) The worth of the aberration changes rapidly on both sides of the axis in one case out of 10 (Fig. 2) and only on one side of the axis in 3 cases out of 10 (Figs. 3, 4, and 5).

(4) There is never symmetry with respect to the achromatic axis; the value of the aberration is generally larger on the temporal side of the cornea than on the nasal (except in the case of Fig. 4).

Figure 12 represents the average of the results. This average expresses the general tendencies (value of the weak aberration, passage from the under-correction to the over-correction, when the eye is accommodating) but does not offer much interest, for it diverges notably from all the individual results.

All these results are connected with the horizontal meridian. Considering the great asymmetry of the eye,⁶ the total value of the

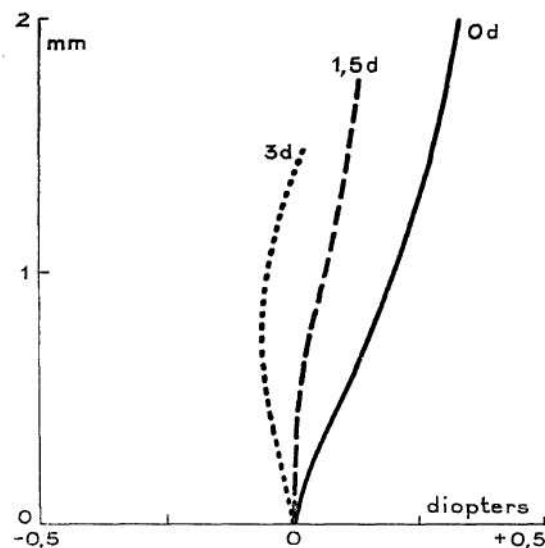


FIG. 12. Mean spherical aberration of the investigated ten eyes.

spherical aberration (measured by the method of the annular openings in as much as the spherical aberration of the investigated eye does not vary rapidly close to the axis) can notably differ from it. But I think that for most eyes the effects of the spherical aberration are weak.

M. Koomen, R. Scolnik, and R. Tousey propose⁷ another difference between the parallax method and the annular pupil one, namely that the first one utilizes the achromatic axis as the reference axis, while the second one uses an axis of maximum symmetry. According to these authors, the strong asymmetry of certain spherical aberration curves, such as determined through the parallax method, would be caused by the fact that the achromatic axis notably differs from the axis of maximum symmetry for the eyes concerned. This is theoretically possible, but I think that the achromatic axis and the axis of maximum symmetry are generally close to each other, whatever the state of accommodation, and that accordingly an eye, which is strongly asymmetrical in regard to its achromatic axis, shows the same asymmetry in regard to its axis of maximum symmetry. Contrary to the parallax method, that of annular pupil does not evidently show this asymmetry.

¹ A. Ivanoff, *Les Aberrations de L'oeil* (Editions de la Revue d'Optique Theorique et Instrumentale, Paris, 1953).

² A. Ivanoff, *Ann. opt. ocul.* 2 no. 3, 97 (1953).

³ Koomen, Tousey, and Scolnik, *J. Opt. Soc. Am.* 39, 370 (1949).

⁴ G. Westheimer, *Optica Acta* 2, 151 (1955).

⁵ A. Ivanoff, *Optica Acta* 3, No. 1 (1956).

⁶ A. Ivanoff, *Compt. rend.* 231, 373 (1950).

⁷ Koomen, Tousey, and Scolnik, *J. Opt. Soc. Am.* 46, 903 (1956).

Spherical Aberration of the Eye and the Choice of Axis

M. J. KOOMEN, R. SCOLNIK, AND R. TOUSEY
Naval Research Laboratory, Washington 25, D. C.

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WE are pleased that Professor Ivanoff has published a correction¹ of his earlier² curves of the spherical aberration of the eye. In 1949, we³ criticized his finding of large aberration close to the axis and reported that we were unable to find such an effect within the central zone of 0.5 mm radius, using a method similar to his. Westheimer's recent paper⁴ has given a very clear picture of the error in Ivanoff's original treatment of the data, and Ivanoff's corrected average curves are now compatible with other spherical aberration measurements, our own⁵ included.

Apart from the above, there remains a difficulty in Ivanoff's method which he has not discussed adequately and which may account for the unsymmetrical nature of many of his individual curves. We refer to the fact that the choice of the reference axis, upon which the points of intersection of the various rays are determined in the process of measurement of the spherical aberration, has a strong effect on the shape of the curve of spherical aberration. An improper choice may lead to a highly unsymmetrical curve. For reference axis Ivanoff chose the "achromatic axis," which is the ray to the center of the fovea entering the eye at a point such that there is no dispersion. Spherical aberration, however, is always referred to the axis of symmetry. For the eye, of course, there is no axis of perfect symmetry, even for a single meridian, but there is an axis relative to which the eye exhibits the greatest degree of symmetry. It is this axis of maximum symmetry to which the spherical aberration should be referred. Although Ivanoff's achromatic axis may occasionally coincide with the axis of maximum symmetry, his results suggest that it frequently does not. It is easy to imagine that the achromatic axis may be displaced, or even inclined to the axis of maximum symmetry because of a combination of refractive irregularities in the eye. Furthermore, the process of locating and correctly maintaining the achromatic reference axis is a very difficult part of Ivanoff's experiment.

The effect of an incorrect choice of reference axis can easily be illustrated. In Fig. 1 is shown a simple lens having ordinary

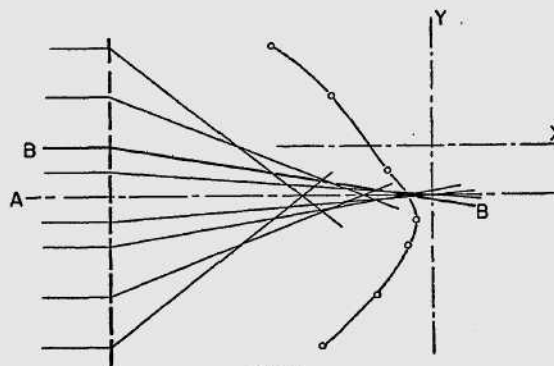


FIG. 1.

undercorrected spherical aberration. The various parallel incident pencils, after refraction by the lens, cross one another as indicated. Suppose ray B is chosen as reference axis, in place of the axis of symmetry, A; the points of intersection of the various rays with B determine the spherical aberration curve, and are plotted in the coordinate system (X,Y). Here X is the amount of the aberration, and Y the distance from the position where ray B enters, and which is taken to be the "center" of the eye. This curve suggests, qualitatively, Ivanoff's solid curves of Figs. 4 and 6, whose abscissas are plotted in the opposite sense. A similar, though more distorted, spherical aberration curve can be gotten by displacing