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Photogrammetric Measurement of the Human Optic Cup*

An improved method of projecting patterns onto the optic cup so that the cup surface is easier to define is described.

Changes in the configuration of the optic cup in the human eye may be good indicators of the presence and progress of glaucoma. The optic cup is a depression in the head of the optic nerve which is located in an opening in the retina at the back of the eye. A schematic representation of the eye is shown in Figure 1. The problem is to measure size changes in the optic cup. There have been many attempts to quantify the optic cup volume[1]. One of these is the technique of optical sectioning developed by Holm and co-workers[2]. In their method, a photographic transparency having a series of parallel lines is projected onto the optic disc. The lines are projected at an angle to the plane of the optic disc. The disc, with the lines projected onto it, is photographed from an angle in the opposite direction. Typically, the total angle between the projection and photographic axes is 7.5 to 15°. Because of the angular separation of the axes, the lines on the photograph are seen to curve as they traverse the optic cup. From measurements of the area enclosed by the curves, and a knowledge of the separation of the lines, one can compute the volume of the optic cup and other parameters such as the contour of the cup for arbitrary sections. The sensitivity of the precision of the measurements to the line density depends on the cup shape and the location of the lines on the cup. In general, the accuracy of any measurement increases as the number of projected lines increases for arbitrary cup shapes. From a mathematical point of view, this is self-evident when one is trying to find the volume of an irregular body through a numerical integration. However, there are practical limitations to the line density achievable. The major one is diffusion of light in the optic disc. The optic nervehead in the human eye is composed of an assortment of materials which, in combination, form a translucent mass which strongly scatters light. When a pattern of light and dark areas is projected onto the disc, light from the illuminated areas is

Abstract: *Precise measurement of the volume (or contour) of the human optic cup has been proposed by several medical researchers as a method of diagnosing and monitoring the progress of glaucoma in humans. When photogrammetry is used, it is very difficult for the photogrammetrist to determine the location of the surface of the optic cup. An improved method of projecting patterns onto the optic cup so that the cup surface is easier to define is described. The projected pattern is also especially useful in determining the volume of the cup by the method of optical sectioning.*

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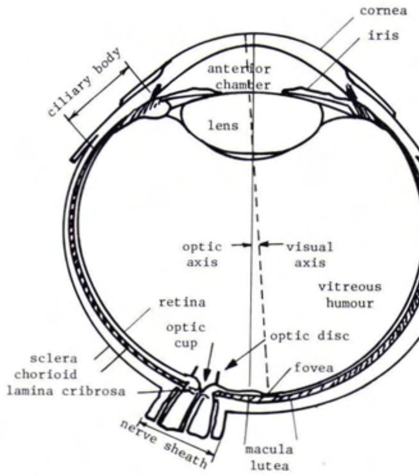


FIG. 1. Horizontal cross section of the human eye.

scattered into the "dark" areas and the lines become difficult to detect on a photograph because of the reduced contrast on the object. On the other hand, it is quite easy to see the lines on the retina where absorption of light is high and scattering is low. The difficulty of obtaining a clear pattern on the optic disc was discussed by Gloster[3]. He found that he could only get a clear image of the pattern on the lamina cribrosa (the part of the sclera at or near the bottom of the optic cup) and not on the retina or, alternatively, on the retina and not on the bottom of the optic cup. Holm has encountered a similar difficulty, but he has been able to obtain good contrast over the entire cup surface by projecting a set of parallel lines with low line density[2].

A further practical difficulty arose in the previous experiments because of the sensitivity of the photographic emulsion to heat. Holm has indicated[4], and we have verified, that when a photographic transparency is used for the grid pattern, the heat from the flashlamp burns the film if the flashlamp is used at other than its lowest power setting. Even at low lamp power, the film will only last for a few flashes of the lamp. Also, if low lamp brightness is used to prevent burning of the photographic slit array, high-speed film (such as Kodak 2484 Film—3000 ASA) must be used to record the weak image. The high-speed films available are so grainy that they severely limit the accuracy of the optical section area measurement. A photographic glass plate does not solve the problem because it will crack at high flashlamp intensities. This problem was eased somewhat[4] by using a low exposure when photographing the grid. Then the "black" areas in the developed negative were not 100 per cent absorbing. This reduced the heating in the film; but, it also reduced the contrast of the projected image. The scattering of light in the optic nervehead, in turn, caused further loss of contrast so that the resulting photographic quality was not optimum.

Krakau and Torlegaard[5] used a relatively low line density to give a good line contrast and then took several photographs with the lines at different locations on the disc. The areas of the optical sections obtained were then plotted as a function of position on the disc. By integrating under a smooth curve drawn through these points, they obtained a value for the volume of the disc. This method has the effect of using a high line density, but it is cumbersome in that several photographs must be taken to get one volume determination. Shapiro[6] *et al.* have experimented with a technique using a fluorescein angiographic procedure along with a line pattern generated by interference of laser beams. This method shows some promise but it has not yet been fully explored.

We have used laser generated interference patterns to produce an array of lines with a 1-to-10 duty cycle which we projected into the human eye. However, we did not use the fluorescent dye. A combination of phase and amplitude gratings was assembled to produce a pattern having sharp lines but also a relatively large depth of field. The results of these experiments will be published shortly.

An alternative to the optical sectioning technique has been to use more or less conventional stereophotography[1]. Typically, stereophotographs of the eye are taken with a monocular fundus camera fitted with an attachment (for instance, the Allen stereo separator) having a rotatable thick glass plate in front of the camera objective. Photographs are taken sequentially and the glass plate is rotated to a new position between photographs. This causes a lateral displacement of the optical axis of the camera to give a stereo effect. Because of the time lag between photographs, the patient may move or the photographer may move the camera. This introduces an unacceptable error into the stereo base. There is available at least one fundus camera that can take simultaneous stereo photographs of the eyeground[7]. This, however, is not a metric camera and therefore is not well suited to photogrammetric applications. Also, in photogrammetry of the optic disc, there is great difficulty in determining the location of the surface of the optic cup in the stereo image. Furthermore, we shall present evidence which indicates that the fundus camera may not be suitable for stereophotography of the optic disc.

In general, two types of camera are used to photograph the back of the eye. One is the monocular "fundus camera" and the other is the binocular, photo-slit-lamp which must be used with a contact lens on the eye. The fundus camera is used in a telescopic mode to photograph the retina through the eye optics. The stereo-photo-slit-lamp camera is used in a microscopic mode by photographing the retina through a contact lens. The power of the cornea is nullified by a Goldmann contact lens. This lens is curved to match the curvature of the cornea. It is placed in contact with the cornea with an intervening layer of liquid methylcellulose. This index-matching liquid largely removes reflections at the interface between the cornea and the contact lens.

A simple testing method to determine which photographic method is better is to examine fine blood vessel detail in photographs taken at comparable magnification with two cameras. Plate 1 demonstrates that, especially at high magnification, the stereo-photo-slit-lamp shows significantly more detail. (It is helpful to view these photographs with a stereo viewer such as the Air Photo Supply Model PS-2.). For example, the fine blood vessel "ladder" shown in Plate 1c (arrow) is much more readily discerned in the photo-slit-lamp photos than it is in the stereo fundus camera photographs. These photographs are the best from several rolls of film taken on the same healthy subject with each camera. Both cameras were manufactured by Zeiss. Whereas the findings are restricted to this special situation, it is plausible that the results will be generally true. This is because the Zeiss fundus camera has been shown to be within a factor of 2 of being diffraction-limited when its optical system is used on-axis[8]. However, there is a degrading effect in fundus photography due to the eye. When the eye optics are used on axis, the optical quality is quite high; but, the optic disc is displaced from the axis of the visual system so that aberrations will affect image quality. Also, in order to get the two views necessary for stereo imagery, the fundus camera must be used off-axis with respect to the eye's cornea-lens optics. It has been shown[9] that aberrations in the eye are quite large off-axis and that the aberrations are mainly in the cornea. These aberrations thus limit the quality of the fundus camera images. On the other hand, the Goldmann lens used in stereo-photo-slit-lamp photography greatly reduces the effect of corneal aberrations so that the image can be of higher quality than in stereo fundus photography.

In our optical sectioning experiments, the goal was to photograph the optic disc with a pattern of lines having high line density and good contrast. The patterns were projected into the human eye and photographed using the Zeiss stereo-photo-slit-lamp. As in the Holm method, the pattern to be projected was placed in the slit-lamp illuminator approximately at the position of the slit jaws. However, instead of using a photographic transparency for the grid pattern, we used a quartz disc coated with an opaque nickel-chrome film. The disc was mounted on a special holder which was threaded into the lamp housing. A pattern of transparent lines had been made in the metal film on the disc film by a photo-etching technique. (Discs with line and other patterns can be obtained commercially from several sources.) The metal film was chosen because, due to its reflective character and high melting point, it would be able to withstand the high-power pulsed light of the flashlamp in the illuminator. Quartz was chosen for its good thermal characteristics and high optical quality; however, Pyrex may be suitable. The line width was either 7 μm or 11 μm and the line spacing was 100 μm, or 10 l/mm. This gave light-to-dark area ratios of 0.078 and 0.12, respectively. Narrow illuminated areas separated by a large dark area gives better line contrast in the disc image because the effects of scattering in the optic nervehead are reduced. Also, within limits, the narrower the whiteline, the higher the accuracy of the optical section area measurement. The limits come about from the need for good line resolution throughout the depth of the optic cup. This is illustrated in Figure 2. Here we have plotted the resolution *(r)* and depth of field *(d)* as a function of aperture *(f/#)* for a diffraction-limited optical system using the relations[10]:

$$r = \lambda f/\# \text{ and } d = 4\lambda(f/\#)^2$$

Because the depth of the optic cup can be as large as 1.25 mm (depending on the individual), we can see from the graph that the smallest acceptable *(f/#)* should be about *f*/24. At this relative aperture the graph shows that the resolution of the camera (exclusive of degrading effects of the eye optics) will be 11 μm. This resolution limit applies both to the camera optics and to the pattern projecting system. Thus, it cannot be ex-

(1) Fundus camera 2.5×

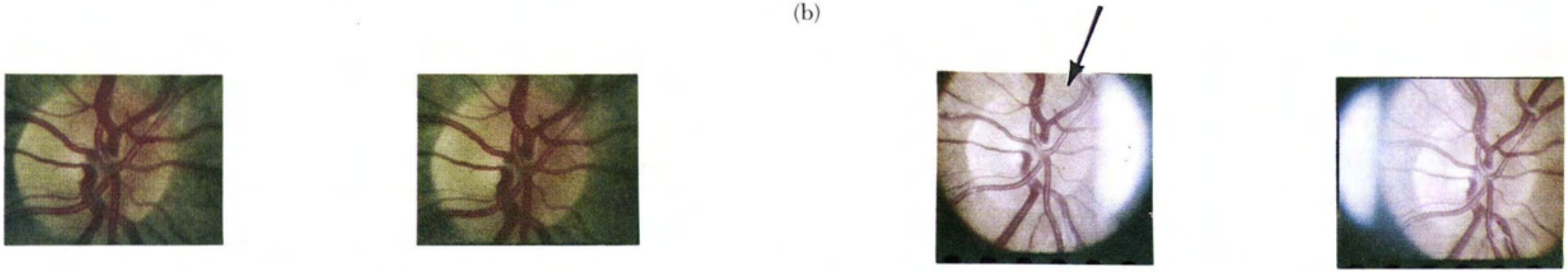
(2) Stereo-photo-slit-lamp
16× (changer), 2× (extender)

(a)

(1) Fundus camera 5×

(2) Stereo-photo-slit-lamp 25× + 2×

(b)

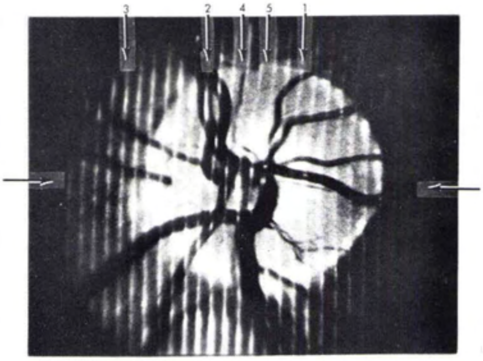


(1) Fundus camera 10×

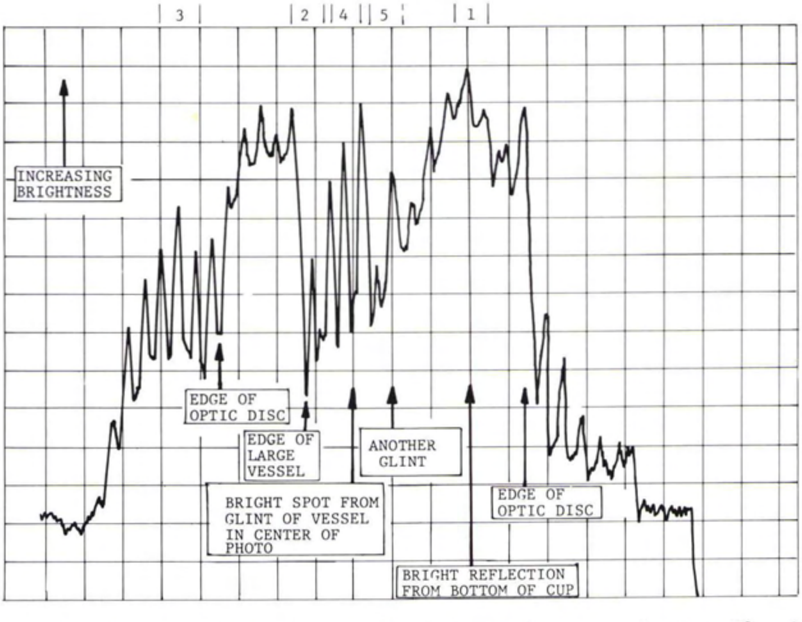
(2) Stereo-photo-slit-lamp 40× + 2×

(c)

PLATE 1. Comparison of fundus camera photography (1) and stereo-photo-lamp photography (2) at various enlargements (a), (b), and (c).



(a) Optical sectioning with a 15° angle. The positions numbered at the top of this photograph correspond to the positions numbered on the graph (Plate 2(b)).



(b) Densitometer trace of Plate 2(a) on a line between the arrows shown in Plate 2(a).

(c) Simultaneous color stereo pair with lines superimposed.

PLATE 2.

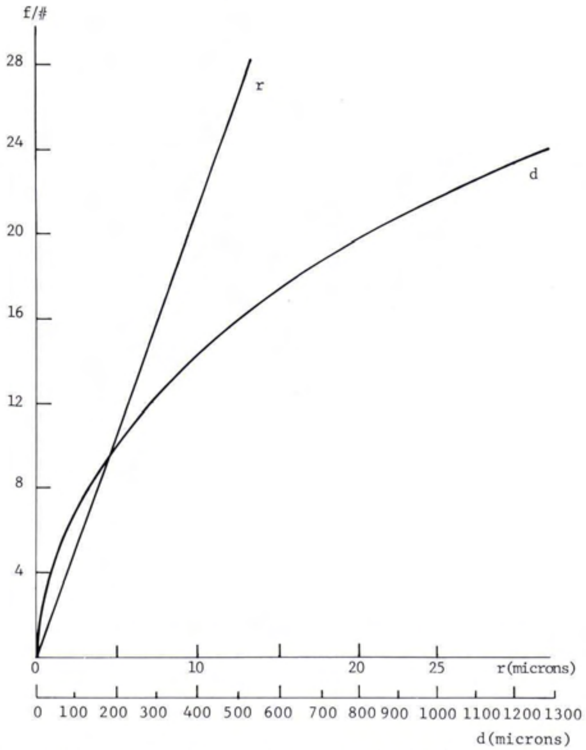


FIG. 2. Resolution *(r)* and depth-of-field *(d)* for a perfect lens.

pected that reduction of the width of the lines to very small sizes will enhance their sharpness. However, reduction of the line width would have an adverse effect in that the light intensity on the optic disc would be reduced, thus increasing exposure times or requiring the more grainy high-speed films.

As another aid in providing high contrast lines in the disc photographs, we used the round apertures provided in the slit-lamp illuminators to limit the illuminated area to the optic disc and its immediate surroundings. This reduced the amount of light scattered around in the eye significantly. Also, very careful focusing was necessary. First, the plane of focus of the projected pattern must be made exactly coincident with the plane of focus of the slit-lamp cameras. Then extreme care must be taken to get good focus on the patient's optic disc.

The positioning of the Goldmann lens is critical. We found that the highest resolution images were obtained when the normal to this lens bisected the angle between the stereo camera lenses in the photogrammetric case and that it should bisect the angle between the projection system and the camera system in the optical sectioning case. Positioning of the lens requires some skill and we found it useful to use a closed-circuit TV system in conjunction with a low-light-level (L^3) TV camera. With the L^3 TV camera, the optic disc image could be recorded on a TV tape recorder along with voice comments from the photographer and other observers. In this case, the viewing lamp in the stereo-photo-slit-lamp illuminator provided sufficient illumination so that the flashlamp was not required. Due to movement of the patient and photographer, the periods during which the disc was in focus were generally quite short. Thus, using a "stop action" technique with the tape-recorded image would significantly increase the yield of useful optical sectioning images.

Plate 2(a) shows the line pattern as projected onto a human optic disc using a 15° angle between camera and projector. Plate 2(b) is a densitometer recording taken across a positive transparency of Plate 2(a) on a cut indicated by the arrows. This recording shows the good visibility of the lines on the optic disc and illustrates the ease with which the line centers may be determined by machine. Thus, future automatic data readout and computer reduction should make the technique clinically useful. Notes on the densitometer plot indicate the edges of the optic disc as well as some prominent features common to the densitometer trace and the photograph. Note that in Plate 2(a) there is good vessel detail as well as high line contrast. Plate 2(c) is a color stereo pair where the lines were projected from a direction mid-way between the objectives. High-speed Ektachrome film processed at 400 ASA was used.

From Plate 2 it can be seen that it is now possible to project a large number of lines onto the optic disc simultaneously and to have the lines visible over the whole depth of the optic cup. Several factors contribute to the enhanced visibility of the lines and the increased utility of the method. First, there is the slit array. By using a substrate of fused silica (non-crystalline quartz) coated with a metallic grid, we were able to surmount the flashlamp heating problem. The durability of this new slit array allowed us to use higher flashlamp intensities which, in turn, meant that we could use fine-grain and even color films. A further advantage of the metallic grid is that, in the metal-coated areas, it is completely opaque. Thus, the patterns projected onto the optic disc have a higher contrast than those projected using a photographic grid. The low grid duty cycle was chosen to minimize the effect of light scattering in the disc. The illuminated line width was chosen to be 11 μm which is close to the resolution limit of the photo-slit-lamp optics.

In addition to providing us with a simultaneous stereo capability, the slit-lamp Goldmann-lens combination reduces the effect of aberrations in the eye optics. Finally, the use of an aperture to confine the illuminated area to the optic disc helped to improve the line contrast by reducing the amount of light scattered and reflected around inside the eye.

By using a conventional photo-slit-lamp camera with special adaptations, we were able to produce simultaneous stereophotographs of the optic cup with a line pattern projected onto the cup. Furthermore, these patterns had both high line density and good contrast as opposed to previous results. These photographs should aid in producing more reliable optical sectioning data because of the higher fringe contrast and higher line density than has been available. Also, this projected pattern technique should aid in conventional stereophotogrammetry of the optic disc because the projected pattern reflected from the surface of the optic cup will allow the photogrammetrist to determine the location of this surface more accurately. Finally, we have found that, contrary to generally accepted opinions, photography using a contact lens on the eye to remove its optical power is superior, in this application, to photography without the contact lens.

The improved slit array projection technique used in our work should increase the precision of the data and enhance the applicability of the optical sectioning technique in a clinical situation. It should also be useful in stereo-photogrammetric applications because it enables the observer to determine accurately the location of the surface of the optic cup.

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REFERENCES

1. Kratky, V., "Ophthalmological Stereophotography," *Photogram. Eng.* 41, 49 (1975).
2. Holm, O., and C.E.T. Krakau, "A Photographic Method for Measuring the Volume of Papillary Excavations," *Ann. Ophth.* 1:327, 1970.
3. Gloster, G., "Concerning Glaucomatous Changes at the Disc," in *The Optic Nerve*, edited by J. Stanley Cant, Proc. of the Second William Mackenzie Memorial Symposium held in Glasgow, 7-10 September 1971.
4. Holm, O.—(Private Communication).
5. Krakau, C. E. T. and K. Torlegaard, "Comparison Between Stereo and Slit-Image Photogrammetric Measurements at the Optic Disc," *Acta, Opthalmologica* 50, 863, 1972.
6. Cohen, B., and J. Shapiro, "Contouring the Human Optic Disc Using Laser Contour Angiography," presented at ARVO meeting, Sarasota, Florida, 1973.
7. Donaldson, D. D., "A New Camera for Stereoscopic Fundus Photography" *Trans. Am. Ophthal. Soc.* G2, 429 (1964)
8. Frisén, L., "Resolution at Low Contrast with a Fundus Camera, Comparison of Various Photographic Films," *Investigative Ophthalmology* 12, 865 (1973).
9. Green, D. G., "Visual Resolution When Light Enters the Eye Through Different Par t of the Pupil," *J. Physiol.* 190, 583, 1967.
10. Born, M. and W. Wolfe, *Principles of Optics*, Third Edition, Pergamon Press, New York, 1965, pp. 435-449.