Photogrammetry of the optic disc in glaucoma and ocular hypertension with simultaneous stereo photography*

Chris A. Johnson, John L. Keltner, Marijane A. Krohn, and Gerald L. Portney

Stereophotogrammetric evaluations of the optic cup were performed for normal, ocular hypertensive, and glaucomatous eyes. Average volume, area, and depth measurements were progressively larger from normal to ocular hypertensive to glaucomatous eyes, although the distributions of individual values exhibited considerable overlap among the three groups. Similar results were obtained for volume, area, and depth asymmetry between each pair of eyes. None of these measurements was able to distinguish accurately between normal and glaucomatous optic cups. However, normal eyes showed a high correlation ($r = +0.85$) between area and depth of the optic cup, whereas this area/depth relationship was reduced in ocular hypertensives ($r = +0.63$) and completely broke down for glaucomatous eyes ($r = +0.04$). Approximately 89% of the glaucomatous eyes and 47% of the ocular hypertensive eyes were beyond the range of normal area/depth correlation values. These findings represent an improvement over most previous attempts to quantitatively differentiate between normal and glaucomatous eyes on the basis of optic disc measurements alone, and support the hypothesis that optic disc damage usually precedes visual field loss in glaucoma. With further technical refinements such as computer image processing, stereophotogrammetry of the optic cup may become a valuable differential diagnostic technique for glaucoma.

Key words: glaucoma, ocular hypertension, stereophotogrammetry, optic disc evaluation, glaucomatous optic disc cupping

Recent studies have shown that both stereo$^{1-16}$ and nonstereo$^{16-20}$ photogrammetric processing of fundus photographs can produce accurate measurements of optic cup topography. Since this technique provides an objective, quantitative evaluation of the optic nerve head, it represents a potentially important diagnostic tool for glaucoma and other optic nerve diseases.

Several investigators$^{1-3, 17}$ have reported volume, area, and depth characteristics of the optic cup in normal populations, based upon photogrammetric analysis. Their results indicate that in normal subjects, these optic cup measurements are highly symmetrical between the two eyes. Portney$^{2, 3}$ and Holm et al.$^{17}$ found that the average volume, area, and depth of the optic cup are larger in glaucomatous eyes than in normal eyes. However, the distributions of individual values exhibit

From the Department of Ophthalmology (C. A. J., M. A. K., and G. L. P.) and the Departments of Ophthalmology, Neurology, and Neurological Surgery (J. L. K.), School of Medicine, University of California, Davis.

Supported in part by National Eye Institute Research grant EY-01841 (JLK) and National Eye Institute Academic Investigator Award K07-EY00095 (CAJ).

Submitted for publication July 24, 1978.

Reprint requests: Chris A. Johnson, Ph.D., Department of Ophthalmology, University of California School of Medicine, Davis, Calif. 95616.

*This paper is dedicated to the memory of Gerald L. Portney, M.D., who died on May 23, 1977. The present investigation represents a continuation of his work on photogrammetric analysis of the optic disc as an objective diagnostic procedure for glaucoma.
considerable overlap between the normal and glaucoma populations, thereby limiting the diagnostic efficacy of these measurements. Comparison of optic cup volumes in unilateral and bilateral glaucoma patients revealed significant asymmetry between eyes, in contrast to the results for normal subjects. Portney\textsuperscript{2, 3} concluded that optic cup volume asymmetry between eyes was the most sensitive photogrammetric measurement for differentiating normal subjects from glaucoma patients.

The purpose of the present investigation was to refine existing photogrammetric methods of evaluating the optic cup and thereby to increase the diagnostic utility of this technique for glaucoma. To enhance the early detection of glaucomatous damage, particular attention was directed toward patients at high risk (elevated intraocular pressure with no demonstrable visual field loss) and patients with early glaucomatous visual field defects.

**Materials and methods**

All participants in the study received a complete eye examination, including refraction, Goldmann applanation tonometry, ophthalmoscopy, biomicroscopy, stereo disc photography, and kinetic and static perimetry. Patients were excluded if good quality stereo disc photographs could not be obtained or if they were unable to perform reliably on visual field testing. One hundred sixty-four eyes of 84 patients were selected for photogrammetric evaluation according to the following criteria: (1) average intraocular pressures less than 20 mm Hg with normal optic discs and visual fields (normals, $N = 40$ eyes), (2) average intraocular pressures greater than 25 mm Hg with normal visual fields (ocular hypertensives, $N = 106$ eyes), (3) early glaucomatous optic disc cupping with early visual field defects (glaucoma, $N = 18$ eyes).

Following this initial classification, all stereo
Fig. 2. Contour map and cross-sectional plots of a representative glaucomatous optic disc.
disc photographs were manually processed by a photogrammetric engineer according to standard techniques.\textsuperscript{21} The photogrammetry data were converted to digital form and analyzed by computer to determine depth, area, volume, and other pertinent geometric measurements of the optic cup.

\textbf{Visual field testing.} A combination of extensive static and kinetic perimetry was used to evaluate visual fields. Kinetic perimetry (with either the Goldmann or Tübingen perimeters) consisted of at least 2 isopters beyond 30° radius, 3 isopters within 30° radius, and numerous spot checks between isopters within the central 40° radius, as previously described by Portney and Krohn.\textsuperscript{22} Static perimetry (with the Tübingen perimeter) consisted of threshold determinations along the 45°, 135°, 225°, and 315° meridians in 1° intervals out to 20° radius and 2° intervals between 20° and 30° radius. Additional static perimetry was performed along both radial (meridian) and circular paths which intersected the length and width of visual field defects plotted by kinetic perimetry. Approximately two thirds of the eyes were evaluated with this procedure, which required about 1 hr per eye. The remaining one third of the eyes were tested according to the method described below.

In view of recent findings\textsuperscript{22} which show that static perimetry is more sensitive and reliable than kinetic perimetry for detection of early glaucomatous visual field defects, 42 eyes were tested with the revised procedure illustrated in Fig. 1 (shown for a right eye). This visual field examination consisted of at least 2 isopters beyond 30° radius (kinetic testing) and static perimetry along four meridians (45°, 135°, 225°, 315°) in 2° intervals and six intermediate meridians in 2.5° intervals across the central 30° radius of the visual field. Additional circular and radial (meridian) static perimetry was performed when it was necessary to further define specific portions of the visual field. All determinations were conducted on the Tübingen perimeter and required approximately 45 to 50 min per eye. This revised procedure thus provided the dual advantages of greater time efficiency and more effective detection of early glaucomatous visual field defects.

Specific criteria were established to define the presence or absence of visual field defects, based upon extensive previous experience and existing guidelines developed by other investigators.\textsuperscript{23-24} According to our standards, areas of visual field loss had to be at least (1) 5° by 5° in size and 0.5 log unit of luminance (apostilbs) deep or (2) 3° by 3° in size and 0.7 log unit of luminance (apostilbs) deep. These values are generally beyond the range of response variability in normal subjects. Visual field defects were also verified on at least two static profiles from adjacent meridians, or a combination of one meridian and one circular static profile. Additional testing with the Fieldmaster automated perimeter was conducted as a confirmatory procedure.\textsuperscript{25} Patients with questionable or borderline results were tested a second time.

To minimize the influence of blur on perimetric determinations within the central 30° radius, patients were given an appropriate refractive correction for distance plus an added near correction for age. Accuracy of this correction was checked at the perimeter bowl by subjective refraction techniques.\textsuperscript{26} Fixation was carefully monitored throughout each testing session, and response variability was determined at several visual field locations to ensure that threshold variations were less than 0.4 log unit of luminance (apostilbs) during perimetric testing.

\textbf{Classification of optic discs.} Optic discs were classified according to whether they appeared to be normal or exhibited early glaucomatous damage. Portney’s cone-cylinder-hemisphere category system\textsuperscript{27-28} (based upon Elschnig’s types I to IV categories) was used to classify normal optic discs. Judgments of glaucomatous damage to the optic
Fig. 4. Frequency distributions of optic cup area for each of the three patient groups.

Fig. 5. Frequency distributions of optic cup depth for each of the three patient groups.

disc were based upon Kronfeld’s criteria of central deep atrophy, mottled or “moth-eaten” appearance of the base of the optic cup, upward or downward extension, marginal excavation and narrow nerve rims. Other indicators of glaucomatous optic cupping (e.g., vertical ovality of the cup, notching of the nerve fiber rim, asymmetry of the cup between eyes, pallor of the optic cup) were also employed to distinguish between normal and glaucomatous optic cups. As with the evaluation of visual field results, conservative criteria were used for classifying normal vs. glaucomatous optic cups. The investigators agreed upon nearly all optic disc classifications, and repeated evaluations at periodic intervals showed a high degree of consistency.

Stereophotography and photogrammetric analysis. Simultaneous stereo disc photographs were obtained with the Donaldson stereo fundus camera. Since Kodak photomicrography film (ASA 16) produced fundus photographs which were underexposed for most eyes, it became necessary to use Kodachrome 25 film (ASA 25). Frisén has reported that the resolution characteristics of Kodak photomicrography film and Kodachrome 25 are approximately equivalent for luminance conditions similar to those employed in this study.

Preliminary investigations revealed that photogrammetric measurements performed on both types of film produced comparable results. Several of the optical specifications provided with our Donaldson stereo fundus camera were in error. The stereo base (reported as 5.75 mm in the specifications provided with the camera) was found to be 2.87 mm by dividing the center-to-center distance of the photographic plate by the magnification of the camera’s objective lens (2x). In addition the 3.25X and 4.25X magnification settings were calculated to be 2.69X and 3.22X, respectively. This was determined by photographing a model eye containing a calibrated line grating and calculating the ratio of image size to object size. With these revised values, photogrammetric measurements of Donaldson stereo photographs were consistent with similar determinations performed on Zeiss stereo photographs (with the Allen rotary prism) of the same optic disc.

Each pair of stereo disc photographs was processed by a photogrammetric engineer using a Wild A-10 photogrammetric plotting instrument (magnification, 6.55x; stereo base, 200 mm). Previous studies have reported that the variability of this procedure (using simultaneous stereo photographs) is approximately 10%.
Table I. Optic cup volume, area, and depth measurements in normal, ocular hypertensive, and glaucomatous eyes

<table>
<thead>
<tr>
<th></th>
<th>Normal (N = 40 eyes)</th>
<th>Ocular hypertensive (N = 106 eyes)</th>
<th>Glaucoma (N = 18 eyes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (mm³):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.13</td>
<td>0.20</td>
<td>0.41</td>
</tr>
<tr>
<td>S.D.</td>
<td>0.13</td>
<td>0.16</td>
<td>0.24</td>
</tr>
<tr>
<td>Range</td>
<td>0.001-0.53</td>
<td>0.007-0.74</td>
<td>0.14-1.15</td>
</tr>
<tr>
<td>Area (mm²):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.65</td>
<td>0.98</td>
<td>1.58</td>
</tr>
<tr>
<td>S.D.</td>
<td>0.37</td>
<td>0.47</td>
<td>0.32</td>
</tr>
<tr>
<td>Range</td>
<td>0.01-1.33</td>
<td>0.16-2.10</td>
<td>0.70-2.61</td>
</tr>
<tr>
<td>Depth (mm):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.34</td>
<td>0.43</td>
<td>0.55</td>
</tr>
<tr>
<td>S.D.</td>
<td>0.20</td>
<td>0.19</td>
<td>0.14</td>
</tr>
<tr>
<td>Range</td>
<td>0.01-0.79</td>
<td>0.11-0.92</td>
<td>0.36-0.88</td>
</tr>
</tbody>
</table>

and z coordinates were established for 400 to 700 data points on each optic disc (according to an arbitrary "count" scale used by the photogrammetric plotting device) and then transferred to punch cards for subsequent computer processing. Horizontal (x) and vertical (y) counts were converted to millimeters according to the photogrammetric plotter-to-camera and camera-to-eye magnification ratios, and depth (z) counts (in arbitrary units) were converted to millimeters by the following equation:

$$\Delta Z = R \cdot \left( \frac{b_1}{M_1} \cdot b_i \right) \cdot \Delta P$$

where $\Delta Z$ is the change in depth (in mm); $M_1$ is the magnification of the Donaldson fundus camera (2.69x or 3.22x); $b_1$ is the stereo base of the Donaldson fundus camera (2.87 mm); $M_2$ is the magnification of the Wild A-10 photogrammetric plotter (6.55x); $b_2$ is the stereo base of the Wild A-10 photogrammetric plotter (200 mm); $R$ is the ratio of the magnification and stereo base of the Donaldson stereo fundus camera to the magnification and stereo base of the Wild A-10 photogrammetric plotter, i.e., $R = (M_1 \cdot b_1)/(M_2 \cdot b_2)$; $f_0$ is the distance between the posterior principal point of the eye and the fundus (17.2 mm); and $\Delta P$ is the horizontal parallaxes measured on the photographs.

Volume, area, and depth measurements were then calculated by the computer. A significant problem in determining optic cup volume is specifying the top of the optic cup. Since the rim of the optic cup has considerable topographic variation about its circumference, volume measurements may show substantial variation as a result of different criteria employed to establish the top of the optic cup. Comparisons among different optic cups exacerbate the problem because of marked variation in the overall configuration of the cup from one eye to another. In the present study, the top of the optic cup was defined by the lowest point on the rim of the cup orifice. This point was determined by a computer algorithm which began at the bottom of the optic cup (greatest depth, or largest z value) and checked the x, y coordinates around the cup for successively smaller depth values. A "spill-over" at the lowest point of the optic cup rim was thereby defined by an abrupt, extremely large change in x, y coordinates at some position along the cup orifice. This permitted a standard, objective criterion to be applied to all optic cups undergoing photogrammetric analysis.

An illustrative example of a contour map and cross-sectional graphical plots derived from photogrammetric processing of stereo disc photographs is shown in Fig. 2.

Results

Figs. 3 to 5 present the frequency distributions of volume, area, and depth of the optic cup, respectively, for normal, ocular hypertensive, and glaucomatous eyes. Each of these optic cup measurements exhibited differences in the distribution of values among various patient groups. Small optic cup volumes, areas, and depths occurred more frequently in normals, followed by ocular hypertensives. Patients with glaucomatous optic disc cupping and visual field loss showed a higher percentage of optic cups with large volume, area, and depth values. A chi-square analysis of these data revealed
The asymmetry of optic cup volume area, and depth between eyes was determined for patients with (1) bilaterally normal eyes (N = 20 patients), (2) bilaterally ocular hypertensive eyes (N = 45 patients), and (3) early glaucomatous optic disc cupping and visual field defects in either one or both eyes (N = 15 patients). Frequency distributions of volume, area, and depth asymmetry between fellow eyes are presented in Figs. 6 to 8 for the three patient groups. Each of the optic cup measurements in glaucoma patients showed (on the average) greater asymmetry...
between eyes. Ocular hypertensive patients tended to exhibit slightly greater asymmetry than normals. A chi-square analysis of these results showed statistically significant differences among the three patient groups for volume asymmetry ($\chi^2 = 66.0, p < 0.001$), area asymmetry ($\chi^2 = 95.6, p < 0.001$), and depth asymmetry ($\chi^2 = 29.2, p < 0.005$) between fellow eyes. However, these values also exhibited considerable overlap among the three groups, thereby limiting the clinical usefulness of these measurements for an individual patient. Table II presents means, standard deviations, and ranges for volume, area, and depth asymmetry between fellow eyes in the three groups of patients.

The most important finding was obtained for the relationship between area and depth of the optic cup. As shown in Fig. 9 (left graph), there was a high positive correlation ($r = +0.85, p < 0.0001$) between optic cup depth and area in normal eyes. That is, normal optic cups which were large in area also tended to be quite deep, and vice versa. This strong relationship between area and depth was not present for optic cups which had sustained glaucomatous damage, as indicated by the right graph in Fig. 9. Here, the correla-
Table III. Percentage of ocular hypertensive and glaucomatous eyes that exceeded the range of normal optic cup measurements

<table>
<thead>
<tr>
<th></th>
<th>Ocular hypertensive</th>
<th>Glaucoma</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(N = 106 eyes)</td>
<td>(N = 18 eyes)</td>
</tr>
<tr>
<td>Volume</td>
<td>5.7</td>
<td>22.2</td>
</tr>
<tr>
<td>Area</td>
<td>23.6</td>
<td>35.6</td>
</tr>
<tr>
<td>Depth</td>
<td>2.8</td>
<td>11.1</td>
</tr>
<tr>
<td>Volume asymmetry</td>
<td>6.6</td>
<td>27.8</td>
</tr>
<tr>
<td>Area asymmetry</td>
<td>7.5</td>
<td>33.3</td>
</tr>
<tr>
<td>Depth asymmetry</td>
<td>3.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Area/depth relationship</td>
<td>47.2</td>
<td>88.9</td>
</tr>
</tbody>
</table>

Fig. 10. Relationship between optic cup area and depth for ocular hypertensive eyes with normal optic cups and ocular hypertensive eyes with clinical evidence of early glaucomatous optic cupping.

Additional optic cup area/depth relationships were determined for ocular hypertensive eyes with normal optic discs (Fig. 10, left graph) and ocular hypertensive eyes that appeared to have early glaucomatous optic cupping (Fig. 10, right graph). Although the absence of a visual field defect made the distinction of glaucomatous optic cupping somewhat questionable for the latter group, the results in Fig. 10 provided tentative support for these subjective observations of the optic disc. Area/depth correlations for the two ocular hypertension groups represented intermediate values between normal and glaucomatous eyes (see Fig. 9).

Discussion

The present findings indicate that in proceeding from normal to ocular hypertensive to glaucomatous eyes, there are increases in the average volume, area, and depth of the optic cup, the average optic cup volume, area, and depth asymmetry between fellow eyes becomes larger, and the optic cup area/depth relationship progressively breaks down. Do these measurements provide a
means of accurately differentiating between normal and glaucomatous optic cups for potential clinical diagnostic use? To evaluate this question, we determined the percentage of ocular hypertensive and glaucomatous eyes that exceeded the range of values found in normal eyes for each of the seven optic cup measures (volume, area, depth, volume asymmetry, area asymmetry, depth asymmetry, and the area/depth relationship). The findings are presented in Table III.

Depth and depth asymmetry between fellow eyes showed rather poor results, whereas volume, area, and volume and area asymmetry between fellow eyes produced somewhat better separation between the three groups. However, the area/depth relationship revealed the most impressive findings; 89% of the glaucomatous eyes and 47% of the ocular hypertensive eyes were beyond the range of area/depth values for normal optic cups. It should be noted that the two glaucomatous optic cups (11%) that fell within the range of normal area/depth values were from the same individual, who happened to be a high myope. Therefore our photogrammetric magnification factors, which are based upon Gullstrand’s reduced schematic eye, introduced errors that may have appreciably underestimated the overall dimensions of the optic cup. Future evaluations that provide corrections for large refractive errors might produce even greater separation among normal, ocular hypertensive, and glaucomatous eyes.

There are at least two hypotheses that may be proposed to account for the relationship between glaucomatous damage and optic cup characteristics. (1) Large optic cups may generally be more susceptible to sustaining glaucomatous damage. (2) Glaucomatous damage to the optic disc produced changes in the size and shape of the optic cup. The consistent, graduated increases in optic cup measurements across the three patient groups in this study appear to support the second hypothesis. In particular, the area/depth relationships presented in Figs. 9 and 10 are highly consistent with the second hypothesis and would be difficult to explain solely on the basis of large optic cups. Many previous investigators have reported that glaucomatous damage to the optic cup usually precedes visual field loss. Our current photogrammetric data generally support this interpretation.

The results of this study represent a significant improvement over most previous attempts to differentiate between normal and glaucomatous eyes on the basis of optic disc evaluation alone, and at the same time to avoid the problems and variability introduced by methodologic differences in the measurement of cup/disc ratios. Recent multivariate analysis studies by Susanna and Drance and Drance et al. exhibit detection rates which are comparable to our current photogrammetric results, although many of the statistical evaluations were performed on subjective clinical observations. Stereophotogrammetry offers the advantage of objective measurements of the optic cup characteristics and may produce a higher degree of uniformity and standardization among different examiners. We feel that both stereophotogrammetric evaluations of the optic cup and multivariate statistical analysis may be of potential value for clinical diagnostic purposes in glaucoma.

We are indebted to Dr. V. Ralph Algazi and Mr. James Stewart from the Department of Electrical Engineering, University of California, Davis, for performing the computer processing of photogrammetric data.

REFERENCES


