

Photogrammetric Measurement of the Optic Disc Cup in Glaucoma*

Takenori Takamoto, Ph.D.
Assistant Professor

Bernard Schwartz, M.D. Ph.D.
Professor and Chairman

Department of Ophthalmology
New England Medical Center and
Tufts University School of Medicine
171 Harrison Avenue
Boston, Massachusetts 02111

ABSTRACT

Cupping of the optic disc associated with the atrophy of the optic nerve is one of the earliest recognizable signs of glaucoma. Measurements of the optic cup changes would provide objective evaluation in early diagnosis and therapy of glaucomatous eyes, by following the course of the patient in relation to the loss of visual field and medical or surgical control.

A semi-analytical photogrammetric technique, the radial section method, has been devised to provide general references so that any differences in optic discs can be compared objectively. The coefficient of variation of the cup parameters is about 4% for cup diameter, and about 5% for cup depth and volume.

Due to the small size of the dilated pupil and refractive index of the eye, the accuracy of photogrammetric measurements of the optic disc is limited. However, optimal geometry of fundus stereophotography can be obtained by convergent stereophotography. On model experiments with 15 degrees of convergent angle, the new method improves the accuracy eight times in cup depth and more than two times in cup diameter measurements over that of non-convergent method.

INTRODUCTION

Eye diseases and systemic diseases with ocular manifestations have been studied by examining living vascular and nerve tissue under magnification. The information can be recorded on photographs, which can provide a ready means of estimating changes in established lesions and can be a valuable diagnostic method.

Atrophy of the optic nerve, associated with cupping of the optic disc, is one of the earliest signs of glaucoma. Both these characteristics of

*In proceedings of the International Society for Photogrammetry, Hamburg, Federal Republic of Germany, July 1980.

the optic disc have been the mainstays for the diagnosis of glaucoma and also for following the course of the patient in relation to the loss of visual field and with regard to decision-making for medical or surgical control. Unfortunately the evaluation of these signs has been mostly subjective and differs considerably from observer to observer (Schwartz 1973).

One of the early attempts to measure depth from fundus stereophotographs was parallax measurements (Weber 1958; Mikuni 1967). Since the feasibility of the photogrammetric measurement of the optic cup was demonstrated by Crock (1969, 1970) and Saheb (1972), the measurements have been used in the study of glaucoma (Portney 1975, 1976; Schwartz 1976, 1978; Johnson 1979).

FUNDUS PHOTOGRAMMETRY

Fundus photography

The most significant difference of fundus photography which photographs the optic disc from conventional photography is that the fundus camera and object to be photographed are not in the same optical space. The optical media refract the images between the fundus camera and the ocular fundus. The function of the fundus camera is twofold; one is to produce an aerial image of the ocular fundus, and the other is to record the aerial image on a film with specific photographic magnification.

Since the fundus camera has been designed based on telescopic principles, magnification of the images on the film varies with the refractive power of the eye. Usually the fundus camera is not calibrated, and image distortions of the camera are not known. Because of the unknown geometry of the fundus stereophotographs, reconstructions of the stereomodel of the fundus have been approximate, and the measurements are limited to relative units. However, topographic changes in the same eye can be obtained with high precision by a semi-analytical photogrammetric method (Takamoto 1979a).

Optimum photographic parameters

Our initial studies on the photogrammetric measurement of cupping involved a systematic approach to the evaluation of the Donaldson simultaneous stereographic camera for the optimal conditions of film type, magnification, aperture, and exposure to obtain maximum reproducibility of measurements of stereophotographs (Takamoto 1979a). Image qualities of the optic discs exposed on several films were subjectively evaluated in a stereo plotter. There were no significant differences between black-and-white and color films. The color films were preferred because the details of the color images were more easily stereoscopically observed. High resolution color films (Kodak Photomicrography) cannot be used on patients with dark pigmentation because the resolution was highly degraded with under-exposed images. Better images were obtained with a high speed color film (Kodak Ektachrome 200). A large aperture size was favorable to the results because of the limited amount of light for observation and a consequent lower exposure level.

To improve the low exposure level of the Donaldson Fundus Camera, a film speed enhancement technique, concurrent photon amplification, was applied to the camera (Czwakiel 1975). By adding non-image light simultaneously to

that of the primary imaging exposure, contrast was reduced and shadow detail was increased without loss of resolution. The modification involved the installation of mini-lamps inside the camera chamber with their brightness precisely controlled.

The most significant error is caused by image distortions due to the optical system of the camera and the eye. Small magnification was preferred for the photographs because only a small central area of the film format was used and less image distortions were found.

Fundus stereophotography

Stereophotographs taken sequentially with a tilting parallel glass plate (Allen 1964) are less reproducible than simultaneous stereophotographs taken with the Donaldson Camera (Rosenthal, 1977). This may be due to movement of the camera or the patient's eye between exposures. Simultaneous stereophotographs can be obtained in one photoframe with the fundus camera with a twin prism (Falconer 1976) or the Topcon stereoscopic fundus camera (Matsui 1978). However, small format size reduces the horizontal field by more than one-half and the margin of each image is subject to distortion. Also, the twin prism should be very close to the pupil and is, therefore, inconvenient to use clinically. The Donaldson stereocamera (Donaldson 1965) covers about 23 degrees of field of stereoscopic view, which is adequate for the optic disc cup, while the Topcon stereo camera only covers about 15 degrees.

The geometry of fundus stereophotographs is more complicated than in conventional photography because it involves two optical systems, a human eye and a camera, and the telescopic system of the fundus camera. Stereo-image formation of the ocular fundus was studied by Kratky (1975) who reported its geometric instability in the position of the effective projection centers, which are defined by relative position of the eye and a fundus camera.

Photogrammetric data reduction

The method of data reduction in fundus photogrammetry and for stereo-model reconstruction can be accomplished by the use of analog plotters (Portney 1975), digital processing of scanned images (Kottler 1974), and semi-analytical (Takamoto 1979a) and analytical methods (Kratky 1975, Takamoto 1980). The prime systematic error of the digital method is due to the finite depth sensitivity (0.08 mm to 0.19 mm: Rosenthal 1977), which is much larger than the semi-analytical photogrammetric method (0.01 mm: Takamoto 1979a).

Relative measurements will be done by our newly developed semi-analytical photogrammetric method, in which the scale and orientation of individual optic discs are adjusted exactly in the same space, that is, without any tilt in either the horizontal or vertical areas (Takamoto 1979a). Such exact scale and orientation is important for follow-up photographs to determine changes in the optic cup with time.

In conventional photogrammetry, the use of an analog plotter requires feeding in the calibrated camera parameters, such as the focal length, the principal points, and the stereo base. In the fundus stereophotographs, these camera parameters are not calibrated and the use of an analog plotter is limited to approximate measurement (Kratky 1975). Systematic errors caused by image distortions and calibration errors can only be corrected by analytical data processing.

AN ANALYTICAL PHOTOGRAMMETRIC METHOD

Measurements on a model object

The attainable accuracies of the fundus stereophotographs of a calibrated artificial model taken by three different methods (the Zeiss fundus camera with an Allen stereo separator, a twin-prism separator, and the Donaldson fundus stereo camera) were estimated by analytical photogrammetric methods. Among the three conventional methods, the results were very similar (+1.7% in depth and $\pm 0.3\%$ in horizontal-vertical) (Takamoto 1980).

In our analytical photogrammetric method, image points were measured of their relative positions in a two-dimensional space on each photograph and were transformed into a three-dimensional object space using the Direct Linear Transformation (Abdel-Aziz 1971, 1974; Karara 1974). The method requires no stereometric parameters, such as camera base, focal length, and the location of principal points, because the transformation by-passes the traditional intermediate step of measuring image location relative to camera optical system (Karara 1979). However, the Direct Linear Transformation requires a few control points, of which relative positions in the object space are known, to define the transformation coefficients.

Convergent Stereophotography

In the effort to improve the accuracy of photogrammetric measurements of the optic disc, a convergent stereophotographic method was introduced and was compared with conventional stereophotographic methods on a model object. The principal advantage of the convergent stereophotography is that it allows an increase in base-depth ratio than in the vertical case (Marzan 1975). In close-range photogrammetry convergent photographs increased its accuracy considerably than vertical photographs (Kölbl 1976; Kenefic 1971; Veress 1971; Faig 1973).

Convergent stereophotographs were taken consecutively with the Zeiss fundus camera with its optical axis swung laterally toward the model object by about 30 degrees from the first position to the second position. An analytical photogrammetric method, the Direct Linear Transformation was used to process these stereophotographs. With 15 degree of the convergence angle, the accuracies were improved eight times in depth ($\pm 0.2\%$) and more than two times in horizontal-vertical ($\pm 0.1\%$) over that of the three conventional methods.

THE RADIAL SECTION METHOD

A new data processing technique, the radial section method, was developed to measure the changes in the optic disc topography objectively (Takamoto 1979b). This method provides generalized topographic information concerning the disc and the cup from which topographic parameters such as diameter, height, areas and volumes of the disc and the cup, and their cup-disc ratio can be computed.

Topographic information was extracted from 200-300 points as a digital model by a semi-analytical photogrammetric method from stereophotographs taken with the Donaldson fundus camera. The model was transformed into a polar-coordinate system in which the horizontal plane was parallel to the optic disc edge with the pole at the center of gravity. Topography of the

optic disc was represented by means of a radial section of each quadrant.

Whatever the optic disc orientation is in relation to the fundus camera, this method re-orientates the optic disc as if it were taken vertical to the optic disc plane and the results were free from error caused by the optic disc orientation. Also a polar-coordinate system was developed which provides a general reference space for any disc topography. Direct comparison between different eyes or the same eye over a certain period of time can be made. Visual comparison was made more effective by plotting the mean radial section graphically. In addition to the above methods, computer programs have been evolved which allow for comparison by the superimposition of one stereo model of the optic cup measured at one time, with a second stereo model of the same optic cup measured at a second time. Thus, relative differences can easily be determined (see Fig. 1).

Our current semi-analytical photogrammetric system with the radial section method can process one stereophotograph in 20 minutes from the time of optic cup digitization to computation of cup parameters and its computer graphic plot. The processing time will be upgraded or decreased to 10 minutes with an on-line computer system.

The optic disc cup parameters

The objective definition of the top of the cup and that of the disc edge were the critical elements for the measurement of the optic disc topography. The disc margin was determined by looking for abrupt changes in color and brightness. The top of the cup was defined as the point of maximum slope changes of the radial section. The top of the cup was automatically computed for each quadrant, using the above criteria. Subsequently, topographical parameters were also determined as follows: cup depth as the perpendicular distance between the bottom of the cup and a plane fitted to the cup edge (top of the cup) which is usually perpendicular to the vertical axis of the polar-coordinate system; cup width as the diameter of the top of the cup; cup area as the area of the top of the cup; cup volume as the space lying below the top of the cup.

Topographical parameters were measured in five normal optic discs with various cup shapes. The coefficient of variation of the cup parameters was about 4% for cup diameter, and about 5% for cup depth and volume (Takamoto 1979b).

Measurements on a human eye

Photogrammetric measurements are now being made from Donaldson stereophotographs routinely in selected individual cases to aid in both diagnosis and management. An example is a young patient's eyes for the measurements of optic cup changes in the period of a few months.

In the topographic profile of Fig. 1, the bottom corners of the cup were extended rather prominently, especially in the nasal and inferior quadrants. The entire bottom of the cup deepened by 1% of the cup depth. Along the edge of the cup and the disc, the largest change was seen in the edge of the cup in the superior quadrant, which shows 6% changes in radius. The diameter of the cup and the disc .59mm and .64mm, and the depth of the cup was .44mm. The ratio of cup volume changes was approximately 40%, in which the largest changes were found in the nasal quadrant.

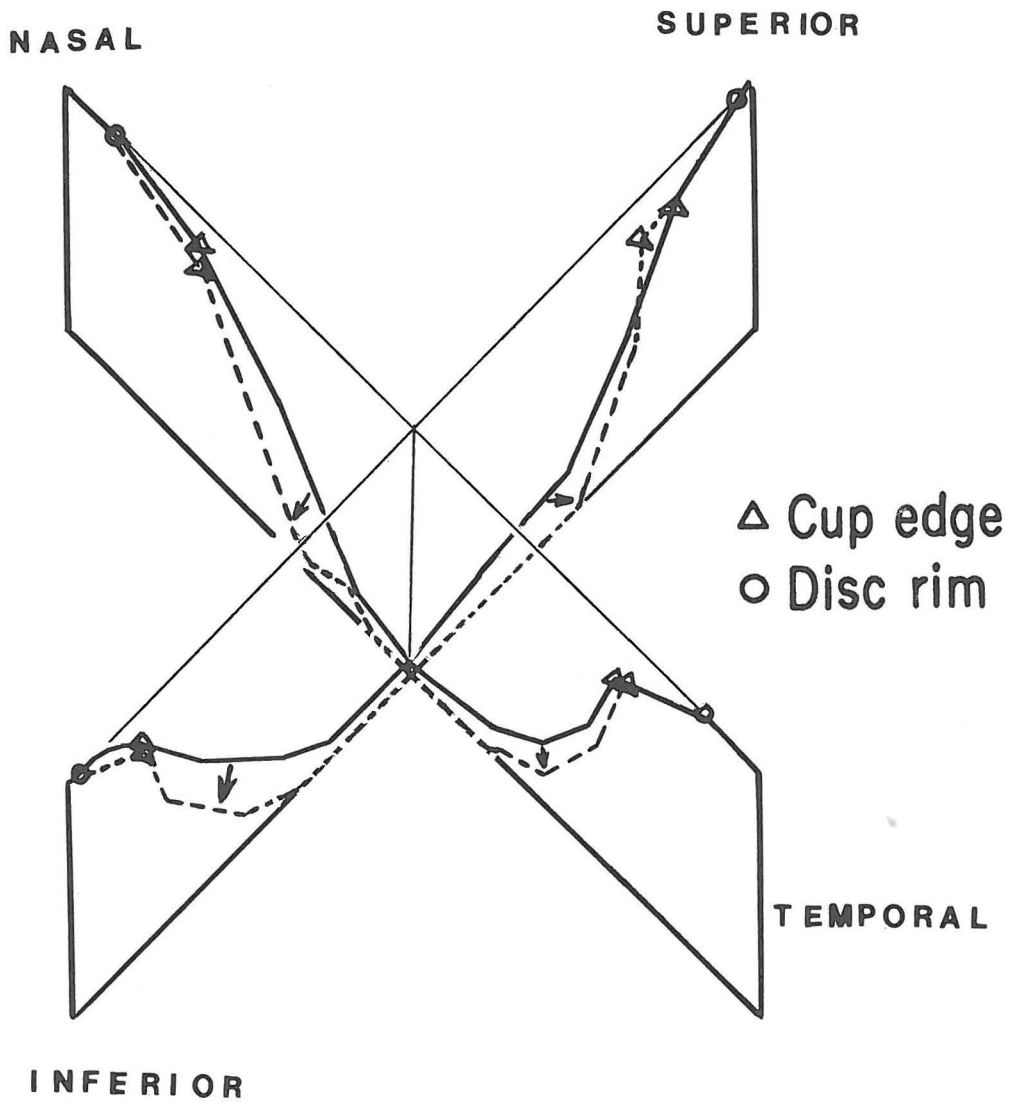


Figure 1. Radial section of left eye, in which cupping is increased significantly.

QUANTITATIVE MEASUREMENTS OF FUNDUS PATHOLOGY

A non-invasive technique is being utilized to obtain significant measurements of structural and functional change of the ocular fundus using stereophotographs. The ophthalmologist, unlike the internist, or other colleagues in medicine, cannot obtain samples of blood or tissue to determine physiological function. Thus, the photogrammetric technique can be used to develop clinically useful tests.

Development of photogrammetric methods allow not only for the measurements of the cupping of the optic nerve but also for the measurements of the other diseases of the optic nerve and the ocular fundus such as the evaluation of papilledema, optic atrophy and choroidal and retinal tumors. The availability of relative measurements in melanoma would provide the relative rate of tumor growth and especially correlation with prognosis in relation to enucleation of the eye. Fundamental information can be obtained by evaluating the development of posterior staphyloma in relation to other myopic characteristics, especially pathologic development of the myopic eye. Similarly anterior segment disease such as iris tumors and corneal changes could be measured. Thus photogrammetric techniques could have a widespread use for obtaining more quantitative data in relation to ocular disease.

Modification of fundus camera

The field of view of the Donaldson camera, about 23 degrees, is appropriate for the optic disc and small tumor measurements but is not large enough for studies of choroidal melanomas and myopic posterior staphyloma. To photograph melanomas of small or moderate size, a field angle of 45° will be necessary. The resolving power, the depth of focus, and the quality of the sequential stereo fundus photographs of the Nikon Retinapan 45-II camera, which has a field angle of 45°, is currently being evaluated.

Most posterior staphyloma measurements require a large field of view and can be obtained by a contact lens with the fiber optic transillumination system, such as the Pomerantzeff Equator-plus camera (Pomerantzeff 1975) and the Clinitek CA2 camera. The Clinitek CA2 fundus camera and the Equator-plus camera were used to obtain super wide-angle fundus stereophotographs of a normal eye by shifting and orienting the camera so that a common area was imaged in the films. More than 100 degrees of the stereographic field of views were obtained by the Equator-plus camera. Image qualities are fair for photogrammetric measurements.

Photogrammetric monitoring center

The establishment of a photogrammetric laboratory for measurements of optic discs has provided a unique facility. As far as we are aware, it is the only photogrammetric laboratory in a Department of Ophthalmology. Because our system is based on fundus stereophotographs it could one day provide monitoring service on a national basis.

Stereophotographs could be taken by the clinician and sent to a central photogrammetric facility for processing and computation. Also, a permanent record is maintained of the patient. Such methods utilizing stereophotographs have the promise of being cost-effective, not only for diagnosis but for following disease. With a computer terminal system, a network for diagnosing and monitoring patient response to therapy could be available to physicians virtually anywhere in the country.

SUMMARY

Changes in the optic cup in glaucoma can be measured photogrammetrically. Results were very encouraging and less than 5% cup changes are detectable by the photogrammetric measurements. Due to the refractive errors of the eye, the size of the computed cup was approximate. Therefore, topographic parameters were limited to relative measurements.

Recently we have extended the photogrammetric application to measure the growth of tumors of the eye such as choroidal melanoma and the development of changes of the eye in myopic posterior staphyloma. Preliminary investigations in our laboratory suggest that this system is not only time- and cost-effective but also capable of producing high reproducibilities by implementing corrections for stereomodel distortions. The study concludes that the method is a considerable advance on existing methods of clinical tool for the diagnosis of glaucoma.

ACKNOWLEDGEMENT

The work reported upon in this paper was supported in part by a grant from the National Eye Institute of the National Institute of Health EY00936.

REFERENCES

- Abdel-Aziz YI, Karara HM: Direct linear transformation from comparator coordinates into object-space coordinates. In Proceedings of the Symposium on Close-Range Photogrammetry, American Society of Photogrammetry, Falls Church, Va., 1971, pp 1-18.
- Abdel-Aziz YI, Karara HM: Photogrammetric potentials of non-metric cameras. Civil Engineering Studies, Photogrammetry Series No. 36, University of Illinois at Urbana-Champaign, 1974.
- Allen L: Ocular fundus photography. *Am J Ophthalmol* 57:13-28, 1964.
- Crock G, Parel JM: Stereophotogrammetry of fluorescein angiographs in ocular biometrics. *Med J Aust* 2:586-590, 1969.
- Crock G: Stereotechnology in medicine. *Trans Ophthalmol Soc UK* 90: 577-636, 1970.
- Czwakiel RP and Scott EC: Concurrent photon amplification (CPA) applied to small format camera systems. *Proc of the Soc of Photo-Optical Instrumentation Engineers* 58:192-199, 1975.
- Donaldson DD: A new camera for stereoscopic fundus photography. *Arch Ophthalmol* 73:253-267, 1965.
- Faig W, Moniwa H: Convergent photos for close range. *Photogram Eng* 39:605-610, 1973.
- Falconer DG, Peppers NA, Kottler MS, Rosenthal AR: Twin-prism separator for retinal stereophotography. *Appl Optics* 15:29-31, 1976.

Johnson CA, Keltner JL, Krohn MA, Portney GL: Photogrammetry of the optic disc in glaucoma and ocular hypertension with simultaneous stereophotography. Invest Ophthalmol Visual Sci 18: 1252-1263, 1979.

Karara HM, Abdel-Aziz YI: Accuracy aspects of non-metric imageries. Photogram Eng and Remote Sensing 40:1107-1117, 1974.

Karara HM: Handbook of Non-topographic Photogrammetry. Falls Church, Va., American Society of Photogrammetry, 1979.

Kenefic J: Ultra-precise analysis. Photogram Eng 37:1167-1187, 1971.

Kölbl OR: Metric or non-metric cameras. Photogram Eng and Remote Sensing 42:103-113, 1976.

Kottler MS, Rosenthal AR, Falconer DG: Digital photogrammetry of the optic nerve head. Invest Ophthalmol 13:116-120, 1974.

Kratky V: Ophthalmologic stereophotography. Photogram Eng and Remote Sensing 41:49-64, 1975.

Marzan GT: Optimum configuration of data acquisition in close range photogrammetry. In Symposium on Close-Range Photogrammetric Systems. Falls Church, Va., 1975, Am Soc of Photogram, pp 558-574.

Matsui, M, Parel JM, Norton EWD: Simultaneous stereophotogrammetric and angiographic fundus camera. Am J of Ophthalmology 85:230-236, 1978.

Mikuni M, Fujii S, Yaoeda H: Stereophotography of the fluorescence. Acta Soc Ophthalm Jap 71:2156-2165, 1967.

Pomerantzeff O: Equator-plus camera. Invest Ophthalmol Visual Sci 14: 401-406, 1975.

Portney GL: Photogrammetric analysis of volume asymmetry of the optic nerve head cup in normal, hypertensive and glaucomatous eyes. Am J Ophthalmol 80:51-55, 1975.

Portney GL: Photogrammetric analysis of the three-dimensional geometry of normal and glaucomatous optic cups. Trans Am Acad Ophthalmol Otolaryngol 81:OP239-246, 1976.

Rosenthal AR, Kottler MS, Donaldson DD, Falconer DG: Comparative reproducibility of digital photogrammetric procedure utilizing three methods of stereophotography, Invest Ophthalmol Visual Sci 16:54-60, 1977.

Saheb NE, Drance SM, Nelson A: The use of photogrammetry in evaluating the cup of the optic nervehead for a study in chronic simple glaucoma. Can J Ophthalmol 7:466-471, 1972.

Schwartz B: Cupping and pallor of the optic disc. Arch Ophthalmol 89: 272-277, 1973.

Schwartz B: New techniques for the examination of the optic disc and their clinical application. Trans Am Acad Ophthalmol Otolaryngol 81: OP227-237, 1976.

Schwartz B: Takamoto T: Biostereometrics in Ophthalmology for Measurement of the Optic Disc in Glaucoma. Proc. SPIE 166, NATO Symposium on Applications of Human Biostereometrics, 1978 (in press).

Takamoto T, Schwartz B, Marzan GT: Stereo measurement of the optic disc Photogram Eng and Remote Sensing. 45:79-85, 1979a.

Takamoto T, Schwartz B: Topographic parameters of the optic disc by the radial section method. Proceedings of the American Society of Photogrammetry, Falls Church, Virginia, March 1979b, pp 238-251.

Takamoto T, Schwartz B, Marzan GT: Convergent stereophotography for the optic disc measurements with analytical photogrammetry. (Submitted for publication, 1980)

Veress SA, Degross GE: Determination of motion and deflection of retaining walls. Seattle, University of Washington, Final Technical Report 16.1 1971.

Weber J: Über die messung von niveaudifferenzen am augenhintergrund mit successiv-stereo-aufnahmen. Acta Concilium Ophthalmologicum 18: 1826-1830, 1958.