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Stereo Measurement of the Optic Disc*

High reproducibility was obtained by employing the Donaldson Retinal Camera with an aperture size of 4.0 mm and a magnification of 3X.

Abstract: *Glaucoma is a common cause of blindness, and it can be detected in the early stages by studying changes in the optic disc. The basic elements in retinal stereophotogrammetry were analyzed on human optic nerves and the reproducibility of relative measurements was estimated.*

Small aperture size increased the image quality of the film and the depth of field but was limited to 3.2 mm because of the difficulty in focusing under low illumination. Photographs taken with a high magnification have some advantages with regard to sensitivity of the stereomodel measurements, but they are subject to lens distortion because reference points spread out the whole film format as magnification increases. High reproducibility was obtained with aperture size of 4.0 mm and a photographic magnification of 3x. The root-mean-square errors are ± 12 μm in the horizontal-vertical and ± 19 μm in the depth.

Introduction

One of the areas of medicine in which stereophotogrammetry has received wide interest is ophthalmology. Specifically, investigations have been conducted on the quantitative measurements of the optic nerve head (optic disc) so that changes in the disc, as the disease glaucoma sets in, can be studied.[1] Glaucoma is characterized by increased ocular pressure which results in loss of side vision and visual field. It has generally been observed that visual field loss is preceded by changes in the optic disc.[2] Therefore, if these changes are recognized with certainty early enough, visual field loss may be prevented or at least minimized by adequate treatment. The earliest changes of the optic disc in glaucoma on repeated examination in the individual patient can be determined only when there is a high degree of reproducibility.

Three methods of stereo image recording of the optic disc are commonly used clinically. The first employs the Zeiss retinal camera with an Allen tilting parallel glass plate in front of the objective.[3] The tilting of the parallel glass plate is equivalent to displacing the camera so that it obtains the views necessary for stereo effect. The photographs, however, are taken sequentially, and movements of either the camera or the patient's eye between exposures are inevitable. The second method is to use the Zeiss retinal camera with the Stanford twin-prism,[4] also placed in front of the objective. The prisms are mounted apex to apex and a simultaneous stereopair is obtained in one

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photoframe. The stereophotographs are basically convergent. The third method employs the Donaldson Retinal Camera, which takes simultaneous stereopairs on a separate frame.[5] Among the three methods the Donaldson Retinal Camera has provided the best reproducibility.[6]

Stereomodel reconstruction of stereophotographs of the optic disc ranges from the simple parallax methods using the mirror stereoscope and parallax bar,[7,8] through the use of analog plotters[9-11] to digital processing of scanned images.[12] Whatever method is used, however, an accurate reconstruction of the stereomodel of optic disc photographs is not accomplished because the fundus camera is not calibrated, and it is characterized by a narrow angle of field and a narrow stereobase. The narrow field arises from the telescopic nature of the retinal camera optics while the narrow stereobase is due to the small corridor of the eye pupil. Because of the unknown geometry of the retinal stereophotographs, aggravated by the unknown refractive power of the eye, reconstructions of the stereomodel of the optic disc have been approximate, and the measurements obtained are not in absolute units.

This study was conducted on the reproducibility of relative measurements of the optic disc cup, using a semi-analytical photogrammetric method on stereophotographs taken by the Donaldson Retinal Camera together with basic photographic parameters, such as aperture size and magnification of the camera.

METHODS

A semi-analytical photogrammetric method was applied on the stereophotographs taken by the Donaldson Retinal Camera. Model coordinates were observed in the Kern PG-2 stereoplotter, and processed through affine model corrections. Then, the model was analytically transformed with least-squares adjustments to the object space. The intersections of retinal vessels which are at least 2 mm distant from the center of the disc were used as "reference points," in order to fit two or more stereomodels of the same optic disc into each other. The method assumes that vessel intersections do not change in relative positions. By taking one stereomodel of the optic disc as fixed, the other stereomodels are "absolutely oriented" into it, thus placing the stereomodels into one common scale and one common orientation in space. After this "absolute orientation," any significant differences in the configuration of the optic disc and optic cup between two stereomodels may be indications of change.

Three normal eyes with different cup shapes were observed. The disc cup of J. K. was wide and shallow, the disc cup of A. M. R. was wide and deep, and the disc cup of J. P. was small and shallow. After the subject's pupil was dilated, three stereophotographs of the optic discs were taken with the Donaldson Camera using Ektachrome 200 film for each set of combined parameters such as magnification (3× - 6×) and aperture size (1.8 - 4.8 mm). A recentering and refocusing of the camera was done for each exposure. Among the three, the best stereopairs were selected in which (1) there were no disturbing reflections on the photos, (2) the quality of the image was good, and (3) the optic disc was centered on the photoframes so that retinal vessel intersections that were to be treated as "reference points" were within a stereopair.

Ten anatomically recognizable points were selected on the retina and optic disc to be observed for the study (Figure 1). Seven sets of observations were made on each point. The coordinate system is taken as: Z is anterior-posterior, X is lateral, and Y is superior-inferior. There was a 1.9 enlargement from photo-coordinate to stereomodel-coordinate. The photos taken at four times magnification make the stereomodel approximately 7.6 times as large as the actual optic disc size. Final results were presented in object coordinates, of which the scale was approximately the same as the actual optic disc size.

RESULTS

FILMS

Image qualities of the optic disc exposed on several films were subjectively evaluated. There was no significant difference between black-and-white films and color films, but color films were preferred because the details of color images were more easily separated and stereoscopically observed. High resolution color films (Kodak Photomicrography) could not be used on a patient 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.

MODEL COORDINATES

After a stereophotograph was relatively oriented on a Kern PG-2, seven sets of observations were made on ten predetermined

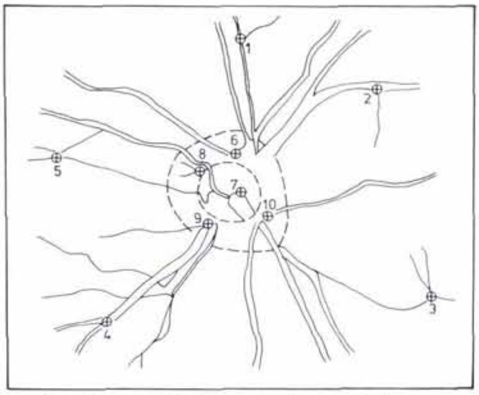
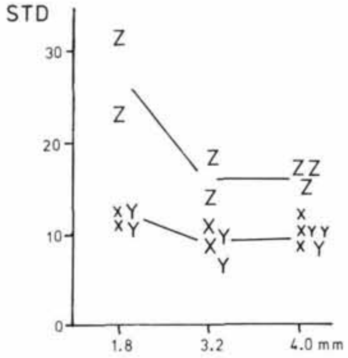


FIG. 1. Sketch of the optic disc and location of reference points 1 to 5 on the retina and 6 to 10 on the optic disc.

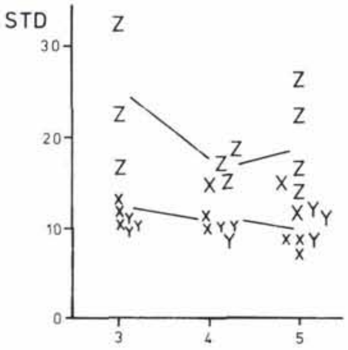
points, five points on the retina and five points on the disc (Figure 1). The standard deviations of the model coordinate observations were plotted (Figure 2). In the figure, each letter (*X*, *Y*, and Z) represents the average of ten standard deviations in the model coordinate (*x*-, *y*-, and *z*-coordinate). Standard deviations were converted to the scale of the model coordinates with a photographic magnification of 4×. The photographs taken with the Donaldson Camera with a large aperture size (4.0 mm) showed the best and most consistent results, and the aforementioned results were most apparent in *z*-coordinate observations. Observation errors were not changed on the photographs taken with a large magnification (5×) of the camera in comparison to those with a smaller magnification (3× and 4×). The model coordinates were processed through affine model corrections and transformed to a common model coordinate system with photomagnification 4×. Reproducibility of model coordinates in each parameter set is shown in Figure 3, in which each letter, *X*, *Y*, and Z, represents the average standard deviation in the specific model-coordinates (*x*-, *y*-, and *z*-coordinate). For each parameter set, four stereophotographs were observed and standard deviations of ten reference points were averaged. The standard deviations of the model coordinates were not noticeably affected in the photographs taken with different aperture sizes but they were improved in the photographs with a larger magnification (6×).

OBJECT COORDINATES

The mean object coordinates of each reference point were computed on from nine to fifteen stereophotographs taken with different combinations of magnification and aperture size of the camera. Deviations from the mean object coordinates were presented as root-mean-square (RMS) errors which were computed from residual errors of ten reference points on each stereophotograph. The results were very similar in the three cases. Two cases, AMR (right eye) and JK (left eye), are shown in Figures 4 and 5. In these figures, *X*, *Y*, and Z represent an average of RMS errors in *X*-, *Y*-, and Z-coordinates of the reference points, respectively. The most prominent improvements are shown on the photographs taken with a large aperture size (4.0 mm). In the case of AMR (right eye), the RMS error of ± 50 μm in the three coordinates (*X*, *Y*, and Z) and 1.8 mm aperture size was reduced to ± 12 μm at 4.0 mm aperture size. Small magnification (3×) also reduced RMS error down to ± 15 μm in the three coordinates from ± 30 μm at magnification 5×.

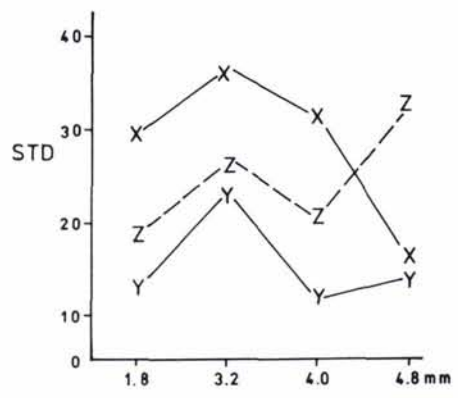


a. APERTURE SIZE

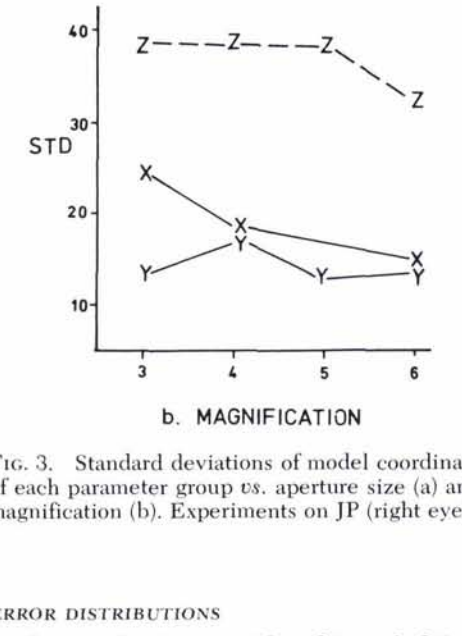


b. MAGNIFICATION

FIG. 2. Standard deviations of observation of model coordinate *vs.* aperture size (a) and magnification (b). Experiments on JP (right eye).

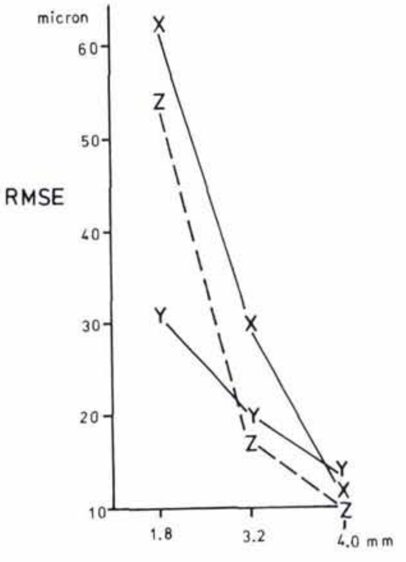


a. APERTURE SIZE

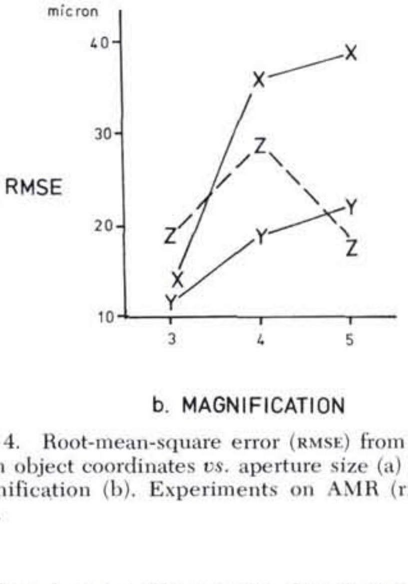


b. MAGNIFICATION

FIG. 3. Standard deviations of model coordinate of each parameter group *vs.* aperture size (a) and magnification (b). Experiments on JP (right eye).



a. APERTURE SIZE



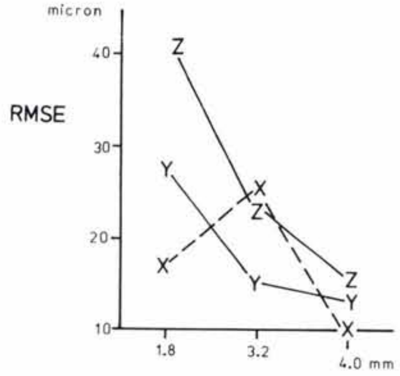
b. MAGNIFICATION

FIG. 4. Root-mean-square error (RMSE) from the mean object coordinates *vs.* aperture size (a) and magnification (b). Experiments on AMR (right eye).

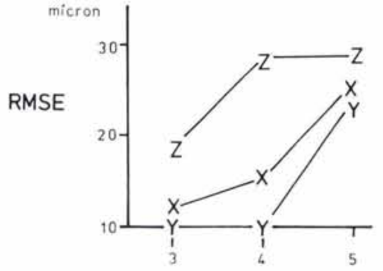
ERROR DISTRIBUTIONS

The residual errors (*dX*, *dY*, and *dZ*) at each reference point on the disc and periphery of the retina are shown in Figures 6 and 7. The residual error is a deviation from the mean object coordinate of a reference point and is plotted as a vector. In the figure, the scale of the vectors is ten times greater than that of the reference point locations. Directions of 12 o'clock, 2 o'clock, and 3 o'clock show +*dZ*, +*dY*, and +*dX*, respectively. Negative residual errors are shown by the reversed direction of positive residual errors. Small and very consistent errors concerning all points were common in the photographs taken with a small magnification (3×) (Figure 6a). On the contrary, large errors were typical at the points on the periphery of the photograph taken with a large magnification (5×). Aperture size also produced some effect on the distribution of the errors. Very small and consistent residual errors were found in the photographs taken with a large aperture size (4.0 mm) (Figure 7c). Large errors randomly appeared in the photographs taken with a small aperture size (1.8 mm). These characteristics were also common in the other two cases.

A summary of errors is listed in Table 1. The errors in the model coordinate were converted to the object scale. The average standard deviations of model-coordinate observations were ± 2 μm in the *x*-*y*-dimensions and ± 10 μm in the *z*-dimensions. The average standard deviations of the model coordi-



a. APERTURE SIZE



b. MAGNIFICATION

FIG. 5. Root-mean-square error (RMSE) from the mean object coordinates *vs.* aperture size (a) and magnification (b). Experiments on JK (left eye).

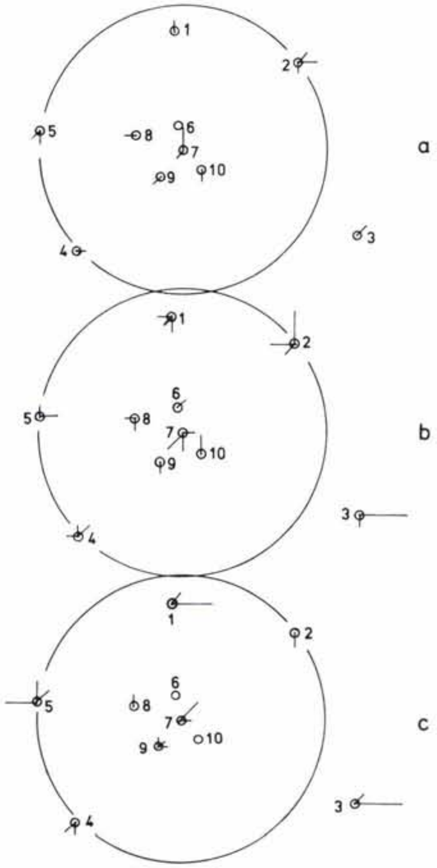


FIG. 6. Distribution of residual errors due to magnification. Magnifications are 3×(a), 4×(b), and 5×(c). Experiments on AMR (right eye).

nate computed from the group of stereophotographs taken with the best photographic parameter set, a large aperture size (4.8 mm) and a large magnification (6×), were ± 3 μm in the *x-y*-dimensions and ± 13 μm in the *z*-dimensions. The average RMS errors of the object coordinate computed from the group of stereophotographs taken with the best photographic parameter set, a large aperture size (4.0 mm), and a small magnification (3×), were ± 12 μm in *X-Y*-dimensions and ± 19 μm in Z-dimension.

DISCUSSION

Large magnification of photographs gave favorable results in the observation accuracy (Figure 2b) and in the reproducibility of model coordinates (Figure 3b). The effect was reversed in the object coordinate accuracy (Figure 4b, 5b). This was caused by image distortion, which clearly showed in the error distribution map (Figure 6c). In the photographs taken with a large magnification (5× - 6×), reference points on the retina were located on the periphery of a film format, where the image distortions were most prominent. On the other hand, in the photographs with small magnification, reference points were imaged on the rather small central area of the film format. Thus, the imaged points were less subject to lens distortions. This effect results in the small object coordinate RMS errors in the small magnification photographs. We expected that photographic images produced by a small aperture size would allow better accuracy because of the large depth of field, but the results were opposite to our expectation. Photographs taken with a small aperture size (1.8 mm) showed the largest RMS errors in object-coordinate (Figure 4a, 5a) and were not systemic errors (Figure 7a). This was caused by poor image quality due to poor focus and under-exposed images. Small aperture size reduced the observation light considerably and made it difficult for an operator to focus images. The poor image quality caused by a small aper-

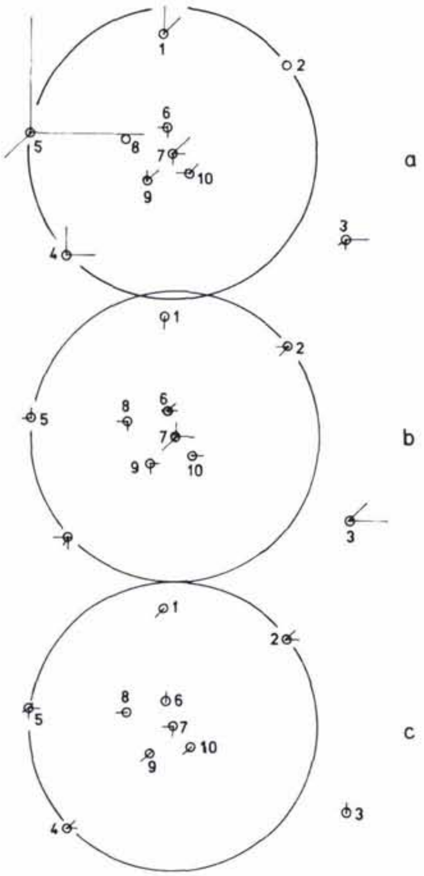


FIG. 7. Distribution of residual errors due to aperture size. Aperture sizes are 1.8 mm (a), 3.2 mm (b), and 4.0 mm (c). Experiments on AMR (right eye).

TABLE 1. SUMMARY OF ERRORS

Errors in Object Scale (micrometers)			Optimum Photographic Parameter	
Group*	*X-Y*	Z	Aperture Size (mm)	Magnification
A	±2	±10	Large (4.0)	Large (5×)
B	±3	±13	Large (4.8)	Large (6×)
C	±12	±19	Large (4.0)	Small (3×)

* A, average standard deviation of reference point observations (seven repetition); B, average standard deviation of the model coordinate in the group with the best parameter set; C, RMS error of the object coordinate with the best parameter set.

ture size (1.8 mm) was demonstrated with the large standard deviation of observations in Figure 2a. Aperture size of the camera had no apparent effect on the standard deviation of the model coordinate of each parameter group (Figure 3a).

Errors in the *X-Y*-dimensions and Z-dimension showed different characteristics. Errors in *X-Y*-dimensions were small in observations (± 2 μm) and in the model-coordinates of the same parameter set (± 3 μm), but errors were large in the object-coordinate (± 12 μm) (Table 1). This was caused by image distortions, and most of the systemic errors could be corrected if the characteristic of the error were known. Observation errors in Z-dimension (± 10 μm) were five times as large as observation errors in *X-Y*-dimensions. A large part of the observation errors in the Z-dimension were contributed by the geometry of the stereophotographs, such as base-distance ratio, which were partly pre-set by the small stereo-base (2.5 - 5.0 mm) of the Donaldson camera and the limited physical clearance between the cornea and the objective lens of the camera.

In the Z-dimension image distortions increased the errors of ± 13 μm of the model coordinate with the same parameter set to the errors of ± 19 μm in the object coordinate, but this effect was less than that in the *X-Y*-dimensions (Table 1). In Figure 4b and 5b, errors in the *X-Y* object coordinates were subject to image distortions more heavily than errors in the Z object coordinate.

Reproducibility of relative measurement was presented in RMS errors of the object coordinate, which is ± 12 μm in the *X-Y* object-coordinate and ± 19 μm in the Z object-coordinate. The results corresponded to the error range, ± 8.4 to 21.0 μm, which was estimated for the reproducibility of retinal stereophotogrammetry.[13] Errors in the Z-coordinate were compatible to the reported results[6] of digital processing of scanned images taken with the Donaldson Retinal Camera. In this study, standard deviations of depth (Z) measurements were ± 10 to ± 40 μm and standard deviations of width (*X-Y*) measurements were ± 40 to ± 130 μm. Errors in the *X-Y*-coordinate in our study were smaller.

In our recent study[14] of an analytical photogrammetric method applied to stereophotographs of a calibrated artificial object, taken by the same Donaldson Retinal Camera with a large magnification (5×) and a large aperture size (4.8 mm), better accuracy in the *X-Y* dimensions (± 4 μm) and larger errors in the Z-dimension (± 23 μm) were found. Image distortions were successfully compensated for in the process of coordinate transformation from image-coordinate to space-object-coordinate by Direct Linear Transformation method.[15] The better accuracy in the X-Y dimensions might be benefitted by the systemic error corrections.Further study using an analytical photogrammetric method on the optic disc instead of on an artificial object is clearly indicated.

Results of this study indicate a ± 1 percent error (± 12 μm) in the X-Y dimensions and a ± 3 percent error (± 19 μm) in the Z-dimension which enables us to detect cup changes of ± 2 percent in width and ± 6 percent in depth. Image distortions were the most significant errors, and the systemic part of the distortions should be corrected for precise measurement. Small magnification was preferred for the photographs, because only a small, central area of a film format was used, and less image distortions were found. Large aperture size was favorable to the results because of the limited amount of light for observation and the consequent low exposure level.

The results were very encouraging. With camera calibration for image distortion and a revised illumination system for observation, the relative measurement of the optic disc should be greatly improved.

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