Comparative reproducibility of the
digital photogrammetric procedure
utilizing three methods of
stereophotography

A. Ralph Rosenthal, Michael S. Kottler, David D. Donaldson, and
David G. Falconer

The reproducibility of digital photogrammetry of optic nervehead photographs taken with
the Zeiss fundus camera with Allen stereoseparator, the Donaldson fundus camera, and the
Zeiss fundus camera with twin-prism separator were evaluated. Reproducibility of the various
quantitative factors was significantly better when the two types of simultaneous stereophoto-
graphs were analyzed. The Donaldson fundus camera provided the best reproducibility of
the majority of geometric factors in varying-size optic cups. Larger percent errors were
encountered with shallower optic cups. Substantial improvements in parameter reproducibility
were obtained when finer sampling intervals were used during film digitization.

Key words: stereophotogrammetry, optic nervehead, reproducibility,
optic cup topography, stereophotography.

A digital stereophotogrammetric meth-
od capable of extracting quantitative pa-
rameters from conventional sequential

stereophotographs of the optic nervehead
was described in 1974. Prior study em-
ploying analog stereophotogrammetry of
the optic cup had demonstrated that if
simultaneous rather than sequential stereo-
photography was used, the results were
significantly more reproducible. Accurate
reproducibility is necessary in order to de-
tect small changes in quantitative analysis
of optic cup topography when following
individuals with ocular hypertension or
chronic glaucoma. This study was therefore
undertaken to determine which method of
stereophotography would provide the best
reproducibility when used in conjunction
with digital photogrammetry of the optic
nervehead. Three types of stereophoto-
graphs were compared.
Methods

One eye of each of three individuals (A. R. R., D. C. F., and D. M. M.) was studied. The subjects were chosen to include cups of different shapes and sizes. These eyes were dilated with 10 per cent phenylephrine (Neo-Synephrine) and 1 per cent tropicamide (Mydriacyl) on three different occasions. At each sitting, five to ten stereophotographs of the optic discs were taken with one of the following stereophotographic methods: (1) the Zeiss fundus camera with an Allen stereoseparator (conventional sequential stereophotography); (2) the Donaldson stereoscopic fundus camera (one method of simultaneous stereophotography); and (3) a twin-prism separator mounted externally to the Zeiss fundus camera (a second method of simultaneous stereophotography). The same photographer took the stereophotographs with cameras 1 and 3, and one of the authors (D. D. D.) took the photographs with the Donaldson camera. Stereobase and camera magnifications were calculated and are shown in Table I.

Each set of photographs was taken during a 1 to 2 hour sitting through a pupil which ranged between 7 and 9 mm. in diameter. The photographs were developed and subsequently electronically scanned and digitized. Previously defined quantitative parameters of (1) cup depth, (2) cup width, (3) profile area, and (4) cup volume were calculated for each of the three eyes with each type of photography.

For the purposes of this work, depth sensitivity or resolution was defined as the smallest change in cup depth which can be confidently detected by the contouring procedure. This distance is directly proportional to the sampling interval, i.e., the distance between density measurements taken on the fundus photograph by the film scanner. It also depends on the camera optics and stereobase. In the present study, the depth sensitivity ranged from 86 to 190 μ, depending on the fundus camera, stereoseparator, and sampling interval.

Results

The right eye of Subject A. R. R. had a very deep, cylindrically shaped cup. The geometric factors of this optic cup as determined by digital photogrammetry of each of the three types of stereophotographs are displayed in Table II. The depth sensitivity varied only slightly between the three photographic procedures. Table III compares the photographic error (reproducibility) for each of the parameters with each of the three methods of stereophotography. Both methods of simultaneous stereophotography perform better than the sequential stereophotographic technique for this eye.

The left eye of Subject D. G. F. had a moderately deep, irregularly shaped cup. The geometric factors of the optic cup of this eye as determined by digital photogrammetry of the three types of stereophotographs are shown in Table IV. The depth sensitivity obtained with the twin-prism stereoseparator photographs (86 μ) was much improved over those obtained with either of the other photographs (152 μ with the Allen stereoseparator and 143 μ with the Donaldson fundus camera). Also, the sampling intervals were considerably finer than those obtained with the previous eye. Table V compares the photographic error (reproducibility) for each of the parameters with each of the three photographic techniques. In general, both techniques of simultaneous stereophotography outperformed the sequential stereophotographic method for this eye.

Subject D. M. M.'s left eye had a fairly shallow, irregularly shaped cup. The geometric factors of the optic cup of this eye as determined by digital photogrammetry of the three types of stereophotographs are tabulated in Table VI. The depth sensitivities were similar to those used in Subject D. G. F.'s left eye and were considerably improved when compared to those used on Subject A. R. R.'s right eye. Table VII compares the photographic error (reproducibility) for each of the parameters with each of the three methods of photography. As with the previous two
Table II. Subject A. R. R.: right eye; refractive error: -0.25 +1.00 x100

<table>
<thead>
<tr>
<th></th>
<th>Allen stereo-</th>
<th>Donaldson fundus</th>
<th>Twin-prism</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>separator*</td>
<td>camera</td>
<td>separator</td>
</tr>
<tr>
<td>Depth sensitivity (μ)</td>
<td>195</td>
<td>181</td>
<td>192</td>
</tr>
<tr>
<td>Number of stereo pairs processed</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Cup parameter (mean value ± standard deviation):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (mm.)</td>
<td>0.98 ± 0.10</td>
<td>0.89 ± 0.03</td>
<td>0.92 ± 0.05</td>
</tr>
<tr>
<td>Width, horizontal (mm.)</td>
<td>0.98 ± 0.23</td>
<td>1.72 ± 0.05</td>
<td>1.31 ± 0.06</td>
</tr>
<tr>
<td>Width, vertical (mm.)</td>
<td>0.97 ± 0.22</td>
<td>1.58 ± 0.04</td>
<td>1.27 ± 0.04</td>
</tr>
<tr>
<td>Area, horizontal (mm.²)</td>
<td>1.03 ± 0.19</td>
<td>1.48 ± 0.02</td>
<td>1.21 ± 0.09</td>
</tr>
<tr>
<td>Area, vertical (mm.²)</td>
<td>0.87 ± 0.16</td>
<td>1.34 ± 0.08</td>
<td>1.13 ± 0.08</td>
</tr>
<tr>
<td>Volume (mm.³)</td>
<td>1.13 ± 0.23</td>
<td>1.98 ± 0.13</td>
<td>1.62 ± 0.14</td>
</tr>
</tbody>
</table>

*These data were reported in the initial description of the digital photogrammetric procedure.

Table III. Per cent error for Subject A. R. R., right eye

<table>
<thead>
<tr>
<th>Cup parameter</th>
<th>Allen stereo-separator*</th>
<th>Donaldson stereo fundus camera</th>
<th>Twin-prism separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (mm.)</td>
<td>10.6</td>
<td>3.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Width, horizontal (mm.)</td>
<td>23.5</td>
<td>3.0</td>
<td>4.6</td>
</tr>
<tr>
<td>Width, vertical (mm.)</td>
<td>22.9</td>
<td>2.8</td>
<td>3.1</td>
</tr>
<tr>
<td>Area, horizontal (mm.²)</td>
<td>18.9</td>
<td>4.9</td>
<td>7.3</td>
</tr>
<tr>
<td>Area, vertical (mm.²)</td>
<td>18.2</td>
<td>5.6</td>
<td>7.4</td>
</tr>
<tr>
<td>Volume (mm.³)</td>
<td>20.1</td>
<td>6.8</td>
<td>8.5</td>
</tr>
</tbody>
</table>

*These data were reported in the initial description of the digital photogrammetric procedure.

Table IV. Subject D. G. F.: left eye; refractive error: -8.75 +2.25 x85

<table>
<thead>
<tr>
<th></th>
<th>Allen stereo-</th>
<th>Donaldson fundus</th>
<th>Twin-prism</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>separator</td>
<td>camera</td>
<td>separator</td>
</tr>
<tr>
<td>Depth sensitivity (μ)</td>
<td>152</td>
<td>143</td>
<td>86</td>
</tr>
<tr>
<td>Number of stereo pairs processed</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Cup parameter (mean value ± standard deviation):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (mm.)</td>
<td>0.50 ± 0.05</td>
<td>0.48 ± 0.01</td>
<td>0.50 ± 0.05</td>
</tr>
<tr>
<td>Width, horizontal (mm.)</td>
<td>1.63 ± 0.35</td>
<td>1.59 ± 0.10</td>
<td>1.53 ± 0.07</td>
</tr>
<tr>
<td>Width, vertical (mm.)</td>
<td>1.53 ± 0.32</td>
<td>1.33 ± 0.09</td>
<td>1.59 ± 0.14</td>
</tr>
<tr>
<td>Area, horizontal (mm.²)</td>
<td>0.83 ± 0.33</td>
<td>0.84 ± 0.05</td>
<td>0.69 ± 0.08</td>
</tr>
<tr>
<td>Area, vertical (mm.²)</td>
<td>0.80 ± 0.19</td>
<td>0.64 ± 0.05</td>
<td>0.88 ± 0.19</td>
</tr>
<tr>
<td>Volume (mm.³)</td>
<td>0.85 ± 0.34</td>
<td>0.97 ± 0.08</td>
<td>1.09 ± 0.18</td>
</tr>
</tbody>
</table>

eyes, both techniques of simultaneous stereophotography outperformed the sequential stereophotographic method for this eye.

Generally, in the three eyes studied, the actual values for each of the geometric parameters obtained from the two types of simultaneous stereographs agreed well with each other (Tables II, IV, and VI). Some values obtained from the sequential stereographs were at variance with those obtained from the two types of simultaneous stereographs, whereas others were in quite good agreement (Tables II, IV, and VI). This result was expected because no attempt was made to calibrate the three methods of stereophotogrammetry in absolute distances.

Discussion

The present study has evaluated the reproducibility of digital photogrammetry utilizing the standard method of sequential stereophotography (i.e., the Zeiss fundus camera plus Allen stereoseparator) and two techniques of simultaneous stereophotography—the Donaldson fundus camera and a newly developed twin-prism separator mounted in front of the Zeiss fundus camera. In the three eyes studied, simul-
Table V. Per cent error for Subject D. G. F., left eye

<table>
<thead>
<tr>
<th>Cup parameter</th>
<th>Allen stereo separator</th>
<th>Donaldson stereo fundus camera</th>
<th>Twin-prism separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (mm.)</td>
<td>10.1</td>
<td>2.7</td>
<td>9.0</td>
</tr>
<tr>
<td>Width, horizontal (mm.)</td>
<td>21.2</td>
<td>6.1</td>
<td>4.5</td>
</tr>
<tr>
<td>Width, vertical (mm.)</td>
<td>20.8</td>
<td>7.0</td>
<td>8.7</td>
</tr>
<tr>
<td>Area, horizontal (mm.²)</td>
<td>39.1</td>
<td>6.1</td>
<td>12.2</td>
</tr>
<tr>
<td>Area, vertical (mm.²)</td>
<td>23.6</td>
<td>8.2</td>
<td>22.0</td>
</tr>
<tr>
<td>Volume (mm.³)</td>
<td>40.0</td>
<td>7.8</td>
<td>16.9</td>
</tr>
</tbody>
</table>

Table VI. Subject D. M. M.: left eye; refractive error: +0.50

<table>
<thead>
<tr>
<th>Cup parameter (mean value ± standard deviation):</th>
<th>Allen stereo separator</th>
<th>Donaldson fundus camera</th>
<th>Twin-prism separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (mm.)</td>
<td>0.31 ± 0.06</td>
<td>0.40 ± 0.04</td>
<td>0.34 ± 0.04</td>
</tr>
<tr>
<td>Width, horizontal (mm.)</td>
<td>1.05 ± 0.16</td>
<td>1.70 ± 0.12</td>
<td>1.37 ± 0.20</td>
</tr>
<tr>
<td>Width, vertical (mm.)</td>
<td>1.06 ± 0.13</td>
<td>1.26 ± 0.13</td>
<td>1.25 ± 0.10</td>
</tr>
<tr>
<td>Area, horizontal (mm.²)</td>
<td>0.30 ± 0.08</td>
<td>0.60 ± 0.09</td>
<td>0.45 ± 0.07</td>
</tr>
<tr>
<td>Area, vertical (mm.²)</td>
<td>0.32 ± 0.08</td>
<td>0.45 ± 0.06</td>
<td>0.44 ± 0.10</td>
</tr>
<tr>
<td>Volume (mm.³)</td>
<td>1.17 ± 0.31</td>
<td>0.76 ± 0.12</td>
<td>0.79 ± 0.13</td>
</tr>
</tbody>
</table>

Table VII. Per cent error for Subject D. M. M., left eye

<table>
<thead>
<tr>
<th>Cup parameter</th>
<th>Allen stereo separator</th>
<th>Donaldson stereo fundus camera</th>
<th>Twin-prism separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (mm.)</td>
<td>18.9</td>
<td>9.2</td>
<td>10.5</td>
</tr>
<tr>
<td>Width, horizontal (mm.)</td>
<td>15.6</td>
<td>7.0</td>
<td>14.5</td>
</tr>
<tr>
<td>Width, vertical (mm.)</td>
<td>12.0</td>
<td>10.3</td>
<td>7.8</td>
</tr>
<tr>
<td>Area, horizontal (mm.²)</td>
<td>27.9</td>
<td>14.8</td>
<td>15.1</td>
</tr>
<tr>
<td>Area, vertical (mm.²)</td>
<td>24.2</td>
<td>13.4</td>
<td>23.1</td>
</tr>
<tr>
<td>Volume (mm.³)</td>
<td>26.2</td>
<td>16.5</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Simultaneous stereophotography afforded significantly better reproducibility than sequential stereophotography (Tables III, V, and VII). In addition, the Donaldson fundus camera definitely outperformed the twin-prism separator for the majority of geometric factors analyzed. This difference in performance is related to the wider-angular field of the Donaldson camera (approximately half the horizontal field is lost with the twin-prism technique) and to higher optical distortion associated with the twin-prism device (the mounting angle of the twin-prism introduces a gentle slope in the stereophotography) This improvement in reproducibility with the Donaldson camera is particularly evident in individuals with shallow cups, such as Subjects D. G. F. and D. M. M. (Tables V and VII, respectively). In particular, the reproducibility of some parameters obtained from Donaldson stereophotographs from Subject D. G. F. was two to three times better than that observed in photographs taken with the twin-prism device. It is believed that the new Donaldson stereo camera currently in production will reduce the error due to distortion even further. In eyes where large, deep cups exist, e.g., Subject A. R. R., the two methods of simultaneous stereophotography provided similar reproducibility; hence with large, deep cups the photographic technique may not be as critical (Table III).

Additional problems exist with the twin-prism separator. The most serious problem...
arises when the separator prisms are less than 10.00 D. in strength. In this case the two disc images overlap (Fig. 1) and digital photogrammetry fails at the disc margin. The problem of overlapping imagery is reduced by increasing the prism strength to 12.00 D. or more. However, prisms stronger than 11.00 D. are difficult for the ophthalmic photographer to use, since the separator prisms come dangerously close to the patient's cornea. In addition, with higher-power prisms more care is needed to align the optical axes of the camera and eye to avoid vignetting of the optic disc imagery. Nevertheless the stereo imagery obtained with the 11.00 D. separator is clear and offers clinically reproducible impressions of the optic cup geometry.

A second problem with the twin-prism device results from the fact that the two prisms are set at a 15° angle with respect to the optical axis of the fundus camera. This angle causes the retinal surface to look sloped when stereopairs are subjected to digital photogrammetry. However, the image-slope problem appears to disappear with direct viewing of the stereoimagery, even though twin-prism stereophotographs provide a pseudoscopic (i.e., convex) rather than stereoscopic (i.e., concave) impression of the optic cup when viewed through a simple single-frame commercial viewer (Asahi Optical Company). Mirror systems have been devised which generate the desired stereoscopic effect. Hence for routine clinical impression and direct evaluations the twin-prism device is satisfactory.

The Donaldson fundus camera places its stereoimagery at nonstandard intervals on the photographic film, necessitating inconvenient and costly hand mounting. For
Table VIII. Per cent error at reduced depth sensitivity for Subject D. G. F., left eye

<table>
<thead>
<tr>
<th>Cup parameter:</th>
<th>Allen stereo separator</th>
<th>Donaldson fundus camera</th>
<th>Twin-prism separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth sensitivity (μ)</td>
<td>195</td>
<td>286</td>
<td>192</td>
</tr>
<tr>
<td>Number of stereo pairs processed</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Cup parameter:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (mm.)</td>
<td>11</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Width, horizontal (mm.)</td>
<td>53</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Width, vertical (mm.)</td>
<td>36</td>
<td>15</td>
<td>28</td>
</tr>
<tr>
<td>Area, horizontal (mm.²)</td>
<td>64</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>Area, vertical (mm.²)</td>
<td>33</td>
<td>18</td>
<td>42</td>
</tr>
<tr>
<td>Volume (mm.³)</td>
<td>45</td>
<td>32</td>
<td>30</td>
</tr>
</tbody>
</table>

Table IX. Per cent error at reduced depth sensitivity for Subject D. M. M., left eye

<table>
<thead>
<tr>
<th>Cup parameter:</th>
<th>Allen stereo separator</th>
<th>Donaldson fundus camera</th>
<th>Twin-prism separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth sensitivity (μ)</td>
<td>307</td>
<td>286</td>
<td>192</td>
</tr>
<tr>
<td>Number of stereo pairs processed</td>
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<td>5</td>
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<tr>
<td>Cup parameter:</td>
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<tr>
<td>Depth (mm.)</td>
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<td>Width, horizontal (mm.)</td>
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<td>28</td>
</tr>
<tr>
<td>Width, vertical (mm.)</td>
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<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Area, horizontal (mm.²)</td>
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<td>25</td>
<td>56</td>
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<td>Area, vertical (mm.²)</td>
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<tr>
<td>Volume (mm.³)</td>
<td>30</td>
<td>25</td>
<td>56</td>
</tr>
</tbody>
</table>

widespread clinical application, it would probably be necessary to develop a special mounting apparatus to handle large volumes of stereopairs recorded at Donaldson intervals. However, no special engineering problems would be involved in developing such an apparatus. Additional disadvantages of the Donaldson fundus camera are its current cost and lack of availability.

Utilization of finer sampling intervals during film digitization, thereby improving the depth sensitivity of the photogrammetric procedure, substantially improved the reproducibility of the contours of shallow cups. The tabulated results from Subjects D. G. F. and D. M. M. illustrate this point. The optic cup of Subject D. G. F. spanned approximately 3 to 5 sensitivity levels, utilizing the heightened sensitivity of 86 to 152 μ (Table IV). Comparison of parameter reproducibility at the improved sensitivities with those at sensitivities of 195 to 286 μ (Tables V and VIII, respectively) yielded improvements of 60 per cent with the Donaldson camera, 50 per cent with the twin-prism separator, and 20 per cent with the Allen stereoseparator at the higher resolution. The optic cup of Subject D. M. M. spanned approximately two sensitivity levels at the finer resolution intervals of 86 to 152 μ (Table VI). Comparison of parameter reproducibility at the higher resolution with those at reduced sensitivities of 192 to 307 μ (Tables VII and IX, respectively) indicated improvements of 40 per cent with the Donaldson camera and 40 to 60 per cent with the twin-prism separator. The Allen measurements showed no significant improvement.

This study supports the notion that larger per cent errors are encountered with shallower optic cups. The truncation error associated with the finite depth sensitivity of digital photogrammetry represents the chief systematic error for the small optic cups. In addition, reference-level variations
traceable to image shifts on the photographic film represents the chief statistical error for the smaller optic cups. Finer digitization of the stereomagery is necessary to remedy the above problems. Unfortunately, sampling the stereomagery at smaller intervals substantially increases computer costs.

Two points concerning the direct relationship of reproducibility to improvement in depth sensitivity should be addressed. (1) Will further narrowing of sampling intervals improve reproducibility and at what point does this relationship plateau? (2) What reproducibility is required to measure clinically distinguishable progression of cupping in patients with either ocular hypertension or chronic glaucoma? In other words, what percentage change must be detectable to alert the ophthalmologist that progressive glaucomatous cupping has occurred in a patient with chronic glaucoma or that the optic cup has enlarged in a patient with ocular hypertension? It does not appear unreasonable to aim at a 5 per cent error in reproducibility as an acceptable goal. In this circumstance a 10 per cent change must take place to be confidently detectable. We do not know if this magnitude of change is clinically recognizable or not. It appears that the final level of sensitivity required to obtain clinically useful per cent error depends on the size and depth of the cup. With the large, deep cup (e.g., Subject A. R. R.) we were able to achieve our goal of 5 per cent reproducibility with larger sampling intervals. With the smaller cups additional improvement in depth sensitivity will be required.

REFERENCES