Simultaneous stereoscopic fundus camera incorporating a single optical axis

David D. Donaldson, Rochelle Prescott,* and Stephen Kennedy

The method of stereoscopic fundus photography, where both photographs are taken simultaneously, yields the most consistent and reproducible record of depths in the fundus. However, all systems devised to date have had undesirable photographic aberrations. For the most part, this has resulted because the optical axis of each image is not the same as that of the objective lens. A single-axis system has now been devised to minimize distortions in the stereoscopic photographs, which therefore makes stereophotogrammetry relatively simple. This design also has other advantages such as simplified alignment procedures, the use of Barlow lenses for multiple magnifications, and various paired apertures for obtaining photographs especially adapted to unusual situations.

Key words: stereoscopic fundus photography, single optical axis, stereophotogrammetry, reproducibility, distortion, aberration, resolution, stereobase, absolute fundus photography, simultaneous fundus photography

The ability to assess small depth changes in abnormalities of the fundus can be critical in both investigative and clinical applications. In order to accomplish this, it is necessary to take "absolute" stereophotographs; that is, the two photographs must be taken simultaneously, with superior resolution and freedom from distortion. It is desirable, for wide application, that the quantitative analysis of stereophotographs be relatively simple and straightforward. To meet this last requirement, any differences in the two photographs, except those due to parallax, must be absent. This last requirement has not been met in previous systems. The convergence and/or the lateral displacement of the axes of the paired optics has resulted in a variation of scale across each photograph, so that the magnification was only equal in the two photographs for one lateral distance and had to be compensated for, thus greatly complicating the data reduction. In the present camera this problem has been removed by an optical arrangement in which the three optical axes, i.e., that of the aspheric lens and the pair for the two camera lenses, are not only parallel but also, optically, lie precisely along one line. The results of this arrangement are not only the elimination of the distortion but also a simplification of the construction and an increased precision of alignment of the camera.

Although stereoscopic fundus photographs were made as early as 1909 by Thorner,¹ they were not simultaneous photographs and therefore were entirely unsuitable for precise analysis of depth relationships. This was first demonstrated quantitatively by Saheb et al. in 1972.² Others have devised various methods of nonsimultaneous stereoscopic fundus photography, and some of these are more reliable but are still unsuitable for accurate ste-
Fig. 1. Simultaneous stereoscopic photographs of flat square grid with small circle in schematic eye taken through twin prisms. Note the elliptical distortion of the circle, trapezoidal distortion of grids, and the curvature of vertical lines.

Rephotogrammetry. A review of these earlier methods can be found in various publications such as Donaldson.\textsuperscript{3} Not until 1930, was the first simultaneous stereoscopic photographic equipment produced when Nordenson\textsuperscript{4} converted a Zeiss-Nordenson camera for this purpose. This system apparently had parallel axes but not a single optical axis, although this cannot be determined because of the lack of detailed information in the original article. Only two such cameras are believed to have been made, and the quality of the photographs was poor. Norton\textsuperscript{5, 6} in 1953 attached a Bausch & Lomb binocular ophthalmoscope to a 35 mm stereoscopic camera, and again the published photographs appeared to be poor in quality, due in part to the long exposure time required with this system. Drews,\textsuperscript{7} in 1957, published a method of taking simultaneous stereoscopic fundus photographs; however, again the published photographs were of poor quality, and the literature does not indicate that he ever refined his apparatus to obtain satisfactory pictures. In 1964, Donaldson\textsuperscript{3} published a description of a simultaneous stereoscopic fundus camera which was the first to give satisfactory results. However, the pictures did have distortion because the reflecting surfaces of the rhomboidal prisms were not parallel and the resulting convergence of the paired camera axes caused a keystone distortion in the photographs. In 1976, Kottler et al.\textsuperscript{8} and Falconer et al.\textsuperscript{9} reported on their twin-prism separator method of producing simultaneous stereoscopic photographs on a single 35 mm frame. Because the system involved wedge prisms, a distortion of a keystone type was also inherent in this system (Figs. 1 and 2). In 1977, Rosenthal et al.\textsuperscript{10} reported on the comparative reproducibility of their digital photogrammetry procedure using the Allen separator (a nonsimultaneous stereoscopic method), the twin-prism separator (which produced a serious distortion), and the earlier Donaldson simultaneous stereoscopic fundus camera. There was an appreciable advantage to the Donaldson camera in comparative reproducibility.

In these various instruments for simultaneous stereoscopic photographs, apparently none had a single optical axis, and therefore inherent in all were certain distortions which made them less adapted to accurate stereophotogrammetric analysis. In 1976, Donaldson\textsuperscript{11} published a brief clinical description of his new camera (Fig. 3) that involved the principle of a single optical axis, which resulted in minimal distortion. (It should be noted that some designs for binocular microscopes call for the use of a single axis by placing a beam splitter in back of a single objective. These designs then use off-axis portions of the exit pupils to obtain a stereoscopic effect.\textsuperscript{12}) In all previous stereoscopic fundus cameras, however, the optical axes were either convergent or parallel with the relay lenses off-axis from the aspheric lens. The two images were distorted, and the magnification changed steadily across the image so that the scale was the same only for the center of the two images. The single optical axis system described in the present communication allows for a simplified data reduction system due to the relative absence of distortion.
Fig. 2. Simultaneous stereoscopic photographs with same constants as those of Fig. 1 except that the twin prisms in front of the objective lens are replaced by rhomboidal prisms (Fig. 5). The result is that both halves of the stereopair have a single optical axis and also exhibit reduced distortion.

Fig. 3. Appearance of camera mounted on a table with the "joy-stick" for aligning the camera while focusing.
Fig. 4. Schematic representation of a simplified imaging system of a stereoscopic fundus camera to demonstrate how a single optical axis system will produce two superimposed images. The rays and optical elements are shown in red. The depth is indicated by the cupped disk where the light reflected from the fundus of the eye (A) passes through the pupil (B) and is focused by the aspheric lens (D) to form an aerial image of the fundus at F. The pupil of the eye is conjugate to the apertures (I and I'), which separate the light into two bundles represented by short and long lines, respectively. The relay lens (K) then images the aerial image (F) to the photographic image (P). The superimposed images are identical except for the parallax. This parallax, of course, is due to the different effective angles of each of the image-forming bundles of rays and the depth relationships within the fundus.
Fig. 5. Schematic representation of the introduction of rhomboid prisms (J) to make possible the taking of simultaneous stereoscopic photographs. The rhomboid prisms are used to separate the two bundles of light from the apertures (I and I') so that they pass through two matched relay lenses (K) in a manner which is optically identical to that of Fig. 4. Therefore there is still only one axis, but the two images are now separated laterally so that simultaneous stereoscopic photography is made practical.
Fig. 6. Schematic representation of the top view (above) and side view (below) of the camera, illustrating not only the optical pathways but also the illumination and viewing portions. A, Ocular fundus; B, pupil; C, small plus-spherical lens which brings the pupil into focus (used in the alignment procedure); D, aspheric ophthalmoscope lens; E, electronic flash tube (end-on type); F, inverted aerial image of fundus; G, fiber optic bundle (to relay light from flash tube to location in front of aperture plate); H, small right-angle prisms (for directing light from fiber optics); J, rhomboidal prisms; K, camera lens; L, Barlow lens (negative achromat); M, reflex mirror; N, focusing eyepieces; O, reticle in focusing eyepieces; P, image of fundus at film plane.

Description of equipment

The camera designed to eliminate the distortions inherent in previous cameras has a single optical axis. The principle in the simplest form can be visualized in a camera where a stop is placed at the image of the eye pupil formed by the aspheric lens (Fig. 4). This stop is composed of two apertures. The light is separated into two bundles of rays, and a single relay lens then focuses the rays to form a single image. When one of the apertures is obscured and a photograph is...
made, one half of the stereopair of photographs is produced. The other photograph is produced when the other aperture is obscured, thus producing the second half of the stereopair. It is obvious that this system certainly has a single optical axis, but no light can pass along this axis because this portion has been occluded by the opaque area of the two-hole diaphragm image at the eye pupil. There is only one optical axis involved in the system, yet it will produce a stereopair of photographs. If stationary objects were being photographed, such a system would be feasible although inconvenient. In the case of the eye, no such system would be practical because of the almost constant movement (including fixational movements) of the eye which would make reproducibility of the stereoscopic effect impossible, as is shown by the lack of reproducibility of data with the Allen separator. Therefore it is obvious that a method of simultaneous stereoscopic photographs using the same principle be devised. Two rhomboid prisms have been introduced into the system (Fig. 5). These prisms have been designed so that the lateral displacement of the image of the optical axis produced by each is precisely one-half the separation of the optical axes of the paired camera lenses. The two parallel reflecting surfaces of the prisms cause all rays in each of the two bundles to maintain their same angular relationship with the axial ray. Thus, after the bundles of rays pass through the matched relay lenses, stereopairs of fundus photographs are produced, which have minimal

![Fig. 7. Various types of apertures and their relationship to the pupillary size (see text). It must be realized that the pupil, when imaged at the aperture plane, is slightly more than doubled in size. The centroid-to-centroid distance becomes the stereobase when imaged at the pupil.](image-url)
aberration and furthermore are identical except for the parallax produced by the depth of the image and aberrations due to the crystalline lens itself.

Discussion

The development of a camera as described, with no appreciable distortions, allows the analysis of the photographs stereophotogrammetrically by a procedure which is relatively simple. When distortions are present, complicated and expensive equipment (originally used in aerial photography) which requires highly trained personnel and time-consuming corrections must be used for stereophotogrammetrical analysis. If the photographs themselves are free of distortion, photogrammetrical equipment can be simple and the procedure carried out by untrained individuals. As long as care is being taken to utilize the proper aperture openings to correspond with the size of the pupil, the data obtained in stereophotogrammetry will be precise and comparable. This results because in the present system the three optical axes (that of the aspheric lens and the two paired relay lenses of the system) not only are parallel but also optically lie precisely upon one another.

Other advantages accrue from the use of this simplified system. First, practical constructional advantages result from the simplified alignment system required in such a camera. This is due to the fact that the centers of curvature of all the elements lie along a single axis and therefore one can simply observe the reflections of a source on or near the optical axis and precisely align the elements in the system. Furthermore, since the rhomboidal prisms can be made with opposite sides precisely parallel, a slight rotation of the rhomboidal prisms around a vertical axis will not tilt the axis, and lateral displacement will vary only as a cosine function; for example, a rotation of 5° will cause a lateral displacement of only 0.1 mm in the axis but will cause a difference of almost 3 mm in the distance along the optical axis to the image. This allows a slight difference in the paired conjugates to be compensated for and the magnifications precisely adjusted. Moreover, rotation of the prism around a line parallel to the optical axis will move the axis vertically, again with a negligible lateral movement.

This system also allows a Barlow lens to be introduced into the optical paths to increase the magnifications (Fig. 6). The use of the rhomboid prisms also allows the introduction of various pairs of apertures at the points where the rays enter the rhomboid prisms. Various combinations of diameter of apertures and center-to-center distances can be utilized, depending on the size of the pupil, depth of field requirements, and illumination factors. Conventional round apertures can be used with good success, but D-shaped apertures have the distinct advantage that their images can be formed within the pupil and result in a greater stereobase than would be possible with round apertures of equal area (Fig. 7). Correlation of the pupil size with the outside diameter of the aperture mask is important; if the aperture mask when imaged at the pupil is actually larger than the pupil size, then the stereobase will be determined by the pupil instead of the aperture, and photogrammetric data will indicate a lesser depth than is actually present.

The limitation of the above system is primarily the eye itself. It is well known that the eye is afflicted with various aberrations, and these are generally a function of the radial distance of the rays from the optical axis of the eye. However, it is unavoidable that an eccentric portion of the lens be used in order to have parallax in the resulting stereoscopic pair of photographs; unfortunately, some slight loss of resolution may result. A second limitation to the accuracy is a result of the variation in the optical constants of the eye from individual to individual; these vary to such a degree that we should speak in terms of precision and reproducibility rather than accuracy. Thus an absolute measurement of the fundus has no accurate value, but precision and reproducibility have great importance in following morphological changes which may be related to pathological conditions.
REFERENCES