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acuity as the angular velocity of the test object is increased is similar not only when the test object is moved horizontally or vertically but also if the observer is rotated in a horizontal plane.

(2) The semiempirical equation $Y=a+bx^3$ describes satisfactorily the data obtained for horizontal and vertical movement of the test object as well as that obtained when the observer was rotated horizontally.

(3) An individual whose visual acuity is susceptible to increases in angular velocity in the horizontal plane will very likely be velocity susceptible in the vertical plane of pursuit.

(4) Although 5 to 10 ft-c is adequate illumination when the test object is stationary, visual acuity is substantially benefitted by increases up to and probably exceeding 125.00 ft-c when the observer is rotated in the horizontal plane. When the observer is stationary and the object is moved in a circle in a plane perpendicular to the line of sight visual acuity has been shown to be benefitted by an increase of illumination up to 500 ft-c. It therefore seems that the relationship is a general one which will also hold when the test object is moved relative to the observer's eye in any plane.

(5) The higher the relative angular velocity of the test object the greater must be the intensity of illumination in order to maintain a given visual acuity threshold.

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New Technique for the Measurement of Small Eye Movements*

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A technique has been developed for recording eye movements as large as three or four degrees, with a precision of about ten seconds of arc. The technique is not subject to artifacts when the head moves, or if the eye should shift in its socket, and no attachment to the eye is required. A very small spot of light is focused on the subject's retina and is made to scan repeatedly across the optic disk. Light reflected back out of the eye is projected on to a photomultiplier tube which drives the vertical amplifier of a cathode-ray oscilloscope. The horizontal sweep of the oscilloscope is triggered in synchrony with the scanning spot. In the optic disk, the blood vessels absorb considerably more light than their whitish background. Therefore, each time the scanning spot passes over a blood vessel, a vertical deflection is registered on the oscilloscope. The distance between the beginning of the scan and this vertical deflection measures the optical position of the retina with respect to any stationary external stimulus. Changes in this distance represent movements of the eye.

INTRODUCTION

Eye movements have been studied extensively in connection with reading disabilities, visual tracking and scanning, visual acuity, and many other aspects of vision. In essentially all of these cases the movements of the eyeballs themselves are not of primary interest. The factor that is important is the displacements, produced by eye movements, of the retinal image with respect to the retina. All of the techniques presently used to record displacements of the retinal image actually measure movements of the eyeball and the corresponding displacements of the retinal image must be inferred. In some cases this inference is very difficult or impossible.

One of the most commonly used methods for recording eye movements is the corneal reflection technique, as used, for example, in ophthalmographs. This technique has a severe limitation for the study of small retinal image displacements. When photographing the corneal reflection, very small lateral shifts of the eye which produce almost no shifts of the retinal image, are indistinguishable from rotary eye movements that produce relatively large shifts of the retinal image. For this reason, the corneal reflection technique is inadequate for measuring retinal image displacements to an accuracy of better than about one degree visual angle. Exactly the same limitations apply to techniques in which the front of the eye, or an object attached to the schlera, is tracked or photographed directly.

If two electrodes are placed on the skin on opposite sides of the eyeballs, eye movements produce changes in the voltage between them. Therefore, a record of these voltage changes is a record of eye movements. However, the noise level of records taken this way is such that movements cannot be recorded to an accuracy of better than about one-half a degree.[1]

To overcome the lateral movement artifacts of the corneal reflection technique and achieve very great sensitivity, Ratliff and Riggs developed a recording

* This work was supported by grants B-1280 and B-1337 from the National Institutes of Health, U. S. Public Health Service.

[1] T. Law and R. L. Devalois, Papers Mich. Acad. Sci. 43, 171 (1958). This electrical recording method was originated by Scholl [Deut. Arch. klin. Med. 140, 79 (1922)].

technique which makes use of the optical lever principle.[2] The subject wears a tight-fitting contact lens, in which a plane mirror is imbedded. Collimated light, reflected from this mirror, is imaged on a moving film. When the eye moves, the contact lens moves with it. However, only rotational components of the movements of the contact lens will produce deflections of the projected image, because lateral movements of a plane mirror in a columnated beam do not cause the reflected image to move.

With this method, the possibility exists that the contact lens will slip on the eye. There is good evidence that a properly designed and fitted contact lens will slip very little or none[3,4] but the fitting of such lenses is difficult. For this reason, it is expensive and time consuming to measure the eye movements of more than a very few subjects.

Using the method described here, a subject need not wear a contact lens. He can be fitted into the apparatus and tested, in less than an hour altogether. The present method is also free of artifacts due to lateral movements of the head and eyes, and so can be used to study very small eye movements.

In the methods mentioned previously, movements of the eye are measured, and displacements of the retinal image are deduced from these movements. In the method to be described here, displacements of the retinal image with respect to the retina, are measured directly, and movements of the eye, if they are of interest, must be deduced.

PRINCIPLES OF OPERATION

The retinal blood vessels of a subject's eye may be observed through an ophthalmoscope. When he moves his eye, the blood vessels appear to shift. Normally, the field of light projected into the eye by an ophthalmoscope is large and diffuse. But if this bright field were to be made small, and the subject's eye were focused on it, then the retinal image of the field could be observed directly, and when the subject made an eye movement, the retinal blood vessels could be seen to shift under that image. The present apparatus is designed to measure just such shifts.

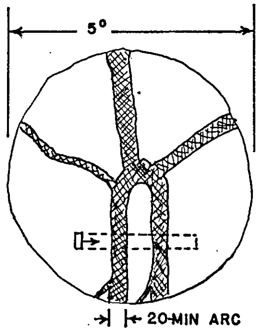

FIG. 1. Drawing of the optic disk, right eye, subject LS. The small rectangle is the scanning spot. The dashed lines indicate the locus of its path of movement.

[2] F. Ratliff and L. A. Riggs, J. Exptl. Psychol. 40, 687 (1950).
[3] Riggs, Armington, and Ratliff, J. Opt. Soc. Am. 44, 315 (1954).
[4] R. W. Ditchburn and B. L. Ginsborg, J. Physiol. 119, 1 (1953).

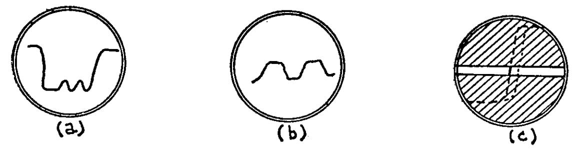

FIG. 2. Drawing of the oscilloscope trace during one scan: (a) shows the entire scan, (b) an enlarged portion of the scan, and (c) a further enlargement showing the leading edge of one blood vessel before and after a horizontal eye movement. The cross-hatched area is covered by an opaque mask during photography.

The subject looks at a fixation point and a beam of light is directed through his pupil to form an image of a bright rectangle on his blind spot, or optic disk. The subject's retina may be seen through an ophthalmoscopic system. Figure 1 is a drawing of the appearance of the optic disk of the subject whose eye movement records will be shown.

The disk itself is covered by myelinated nerve fibers. Since myelin reflects light relatively well, and there is no light-absorbing backing in this region of the retina, the disk looks relatively bright when illuminated. The dark bars across the disk are retinal blood vessels. Against the disk, these vessels are typically large, clearly defined, and dark. The small rectangle on this figure is the bright retinal image that is projected onto the disk. This spot of light is made to scan repeatedly across the disk along the path indicated on the drawing. When the scanning spot is falling on the disk it looks relatively bright through the ophthalmoscope, but when it falls on a blood vessel much of the light is absorbed by the blood and the spot is barely visible. In the actual apparatus, the light reflected back out of the eye falls on a photomultiplier tube and the output of the phototube is displayed on a cathode-ray oscilloscope. The oscilloscope sweep is synchronized with the scanning spot.

Figure 2(a) is a drawing of the shape of the oscilloscope trace, as the scanning spot makes one scan across the optic disk. An increase in light intensity drives the trace downward, so that the trace drops sharply as the scanning spot enters the eye. Two upward humps follow. Then the trace returns to its initial level when the scanning spot again leaves the eye. The two humps represent the two blood vessels in Fig. 1, since the blood vessels reflect less light than their background.

Figure 2(b) is essentially an enlargement of the two humps in Fig. 2(a). It is produced by increasing the vertical gain and sweep speed of the oscilloscope.

Figure 2(c) is a further enlargement of the trace, showing only the leading edge of one of the blood vessels. To obtain eye movement records the face of the cathode ray tube is masked off as shown in this figure so that only a small, almost vertical portion of the trace is exposed.

The oscilloscope sweep may be set so that it always begins at a particular horizontal position on the face of the cathode-ray tube. The sweep is triggered when the

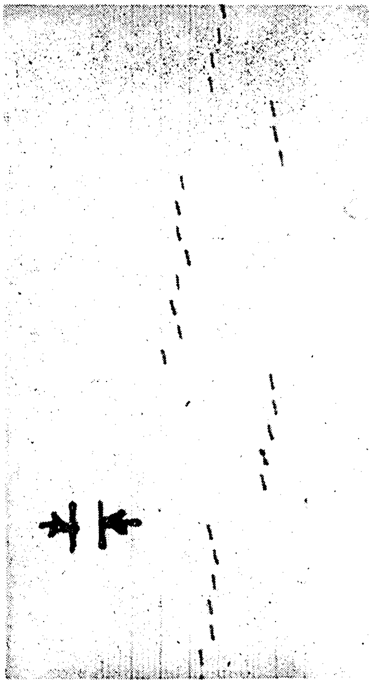

FIG. 3. A portion of an eye movement record. The distance between arrows represents 3 minutes of arc. The subject was fixating a point as steadily as possible during this record, so that the displacements of the trace represent involuntary eye movements.

scanning spot reaches a predetermined point in its travel. If the eye were to move horizontally, between one scan and the next, it would take a different time for the scanning spot to get from that predetermined point to the blood vessel. This would produce a corresponding shift in the position of the vertical trace on the cathode-ray tube. The dotted line in Fig. 2(c) indicates how the trace would be displaced if the eye were to move horizontally between scans. The actual duration of each scan is very short (less than 20 μsec), so that the eye cannot move appreciably during the scan itself. Therefore, any displacements of the trace must be attributed to movements that occurred between scans. This system registers all eye movement components perpendicular to the blood vessel.

An image of the masked face of the oscilloscope is formed on film that is moving continuously downward. Figure 3 shows a portion of an eye movement record taken in this manner. Each dash is produced by a single scan and in this record the scanning rate was ten per second. The subject was instructed to fixate as steadily as possible, so that the movements shown here are the so-called involuntary eye movements. The distance between arrows represents an excursion of three minutes of arc. The scanning rate may be easily increased to give more information per second and the noise level of this record, in terms of equivalent eye movements, is about ten seconds of arc.

This procedure actually records the relative position of the leading edge of a blood vessel. Changes in the diameter of the blood vessel, as with pulse, would therefore be indistinguishable from small eye movements (ten seconds of arc is on the order of one-thousandth of a millimeter on the retina). To the extent that pulse pressure expands the blood vessels symmetrically it would be preferable to record the position of the middle of the blood vessel rather than one edge. For this reason the following modifications were introduced into the system. The width of the scanning spot was increased until it was about the same as the width of the blood vessel. In this way, the wave form of the hump in the trace is made more sinusoidal with a maximum at the center of the blood vessel. This wave form is then differentiated, so that the point at which the output is zero volts represents the center of the blood vessel. The portion of the trace at zero voltage is then photographed in exactly the same way as was the leading edge in the above discussion.

DESCRIPTION OF THE APPARATUS

A schematic diagram of the apparatus is shown in Fig. 4. The light source is a 100-watt high-pressure Mercury arc lamp (OSRAM, HBO-107). The arc size is about 0.3 mm square, and the brightness 600 000 candles per square inch. Storage batteries supplied the power for the lamp.

A commercial dc power supply was originally purchased with the lamp. This supply had a large ripple which was faithfully reproduced in the lamp brightness. In addition, when the bulb was run from this supply, large, irregular, fluctuations in the dc component of the bulb brightness occurred, despite the ballast resistor in the power supply. Evidently this instability was produced by the supply ripple because the arc is remarkably stable when run from storage batteries with a small ballast resistor. The lamp is rated at 20±4 v, and it was run, through a ten ohm variable ballast resistor from a 48-v storage battery supply.

Light from the source is columnated by L_1, and lens L_2 forms a 2-mm square image of the arc in the pupil of the eye. This arc lamp produces a continuous as well as a line spectrum with considerable energy in the ultraviolet and infrared. To protect the eye all wavelengths shorter than about 400 mμ were filtered out and heat glass was used.

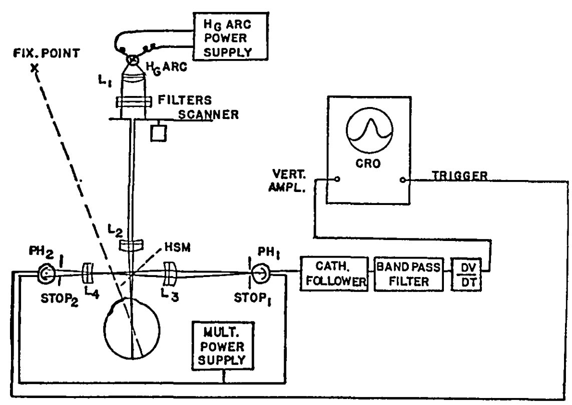

FIG. 4. Schematic diagram of the complete apparatus.

The scanner is a disk with a small rectangular aperture spun by a constant speed motor. The disk is placed at such a distance from L_2 that the image of the aperture is in sharp focus on the retina when the subject is accommodated for the fixation point. The position of the fixation point is adjusted so that the retinal image of the aperture falls on the subject's optic disk. When the scanning disk spins, the retinal image scans the optic disk.

Light reflected back out of the eye and from the half-silvered mirror, labled HSM, is collected by lens L_3 which forms an image of the pupil and the corneal reflection in the plane of $stop_1$. This stop has a circular aperture with a narrow, opaque bar running horizontally across it. The corneal reflection is imaged on this bar and the light getting past the stop falls on a photomultiplier tube. The bar prevents the relatively strong light in the corneal reflection from obscuring the light from the retina itself.

The output of this photomultiplier tube passes through a cathode-follower preamplifier, a band-pass filter to reduce noise, a differentiating circuit, and the resulting signal drives the vertical amplifier of a cathode-ray oscilloscope.

Light reflected to the left from the half-silvered mirror is collected by lens L_4, which forms an image of the scanning spot on $stop_2$. This stop has a rectangular aperture which may be shifted horizontally by very small steps. Light passing through the stop falls on a second photomultiplier tube, and the output of this phototube triggers the sweep of the oscilloscope in synchrony with the sweep of the scanning spot. Shifting the aperture in $stop_2$ changes the position of the scanning spot at which the oscilloscope is triggered. That is, the oscilloscope may be made to trigger at any desired point in the path of the scanning spot. This trigger point is usually adjusted so that the oscilloscope sweep begins just before the scanning spot crosses a retinal blood vessel.

This system measures, once for each scan, the distance between two particular locations. The first is the location of the retinal image of the scanning spot at the time when the oscilloscope sweep is triggered. This corresponds to the position of a retinal image of a particular point in space. The second location is the center of a retinal blood vessel. Thus, the distance between a retinal image and a particular point on the retina is measured once for each scan. Shifts in the position of the retinal image with respect to the retina may be recorded.

LIMITATIONS OF THE TECHNIQUE

This eye movement recording technique has two primary limitations. First, the noise level is such that movements on the order of 10 seconds of arc or smaller cannot be discriminated. Second, the scanning spot produces glare, which might interfere with certain types of viewing tasks. Since the image of the scanning spot falls on the blind spot it is only the scattered light that acts as glare, but the scattering is appreciable. There is not enough glare to cause difficulty in fixating a small point of light or to interfere with reading, but a measurement of visual acuity, for example, might be somewhat interfered with.

Large vertical eye movements would be indistinguishable from smaller horizontal ones if they were large enough so that the scanning spot began to pass over nonvertical parts of the blood vessel. For this reason subjects with a relatively long stretch of straight blood vessel must be selected. About half of the subjects we have screened have at least one degree of straight blood vessel.

The apparatus, as described here, may be used to record movements as large as three or four degrees, with a sensitivity of about ten seconds of arc. The optics may be changed to record considerably larger movements but with a corresponding decrease in sensitivity.

SUMMARY

A technique has been described to measure movements of the retinal image with respect to the retina. Movements may be recorded with a precision of 10 seconds of arc. There are no artifacts owing to lateral movements of the head or eye, and subjects need not be fitted with contact lenses.