VECTOR-ELECTRO-OCULOGRAPHY AND ITS CLINICAL APPLICATION*†

TWO-DIMENSIONAL RECORDING OF EYE MOVEMENTS

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EYE movements are one of the important physiological phenomena which occur when some visual information is obtained.

The examination of eye movements may be divided into two broad categories: subjective and objective. In the past observation was mostly subjective, but the recent development of electronic instruments has enabled us to record eye movements objectively by electro-oculography (E.O.G.). This procedure has been historically reviewed by Marg (1951), but its clinical application is of comparatively recent date. Mackensen (1957a, b, c) published three reports on the fixation and the saccadic movements of the amblyopic eye, Hiroishi (1958) studied strabismus, Lehnert and Thieme (1962) examined the pursuit movement of paralytic squint, and von Noorden and Mackensen (1962a, b, c) reported some notable findings regarding the pursuit movement and eccentric fixation of the amblyopic eye.

These studies all dealt with the one-dimensional recording of eye movements, but the actual movements usually observed are very complicated, taking every direction and varying in both amplitude and velocity. Law and DeValois (1958) proposed to attempt two-dimensional measurements and, on the basis of this two-dimensional recording, Ford, White, and Lichtenstein (1959) succeeded in measuring the reaction time for fixation.

The present authors have lately attempted two-dimensional recording of eye movements (Uenoyama, Uenoyama, and Iinuma, 1963) on the principle of the separation and summation of electrical vectors as adopted by Ford and others. This method is given the tentative name of vector-electro-oculography.

Principle of Vector-E.O.G.

The principle of E.O.G. is based on the bipolar body which the eye ball forms owing to its standing eye potential, which is nearly constant under a fixed adaptation, but as soon as eye movement starts, its bipolarity causes a change in the biophysical field of the peribulbar tissue. The change is picked up as the potential difference between the two electrodes placed on each side of the eye (Fig. 1, opposite).

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FIG. 1.—Basis of electro-oculography.

The principle of vector-E.O.G., on the other hand, is as follows:

Any two-dimensional eye movement is accompanied by the movement of projected electrical vector. With two pairs of electrodes placed on the upper and lower sides and on the right and left sides of the eye, the projection of electrical vector is picked up by separating it into two components, horizontal and vertical. These two kinds of electrical vector, *i.e.* potential differences, are separately amplified and fed into the X-axis and the Y-axis deflexion plates of a cathode ray tube. It is thus possible to observe on the cathode ray tube the summation of the two electrical vectors, the spot of which, in its movement, is proportionate, in both the direction of progress and the angles of rotation, with the actual eye movement examined. It is further possible to observe and record directly the velocity of eye movements, when the Z-axis (or brightness modulating circuit) is used with time markers of a fixed cycle superimposed (Fig. 2).

FIG. 2.—Principle of vector-electro-oculography.

Experimental Method

(1) Apparatus

Oscilloscope—a VC-7 type dual beam oscilloscope manufactured by the Nihon Kodenshō Kōgyō Co. Ltd.*

Two pre-amplifiers for the X-axis and Y-axis—Plug-in Unit AVB-2 type by the same company.

Time constant—0.3 sec., when saccadic eye movements are recorded and 2.0 sec. in other cases.

Calibration—200 μ V/cm. both horizontally and vertically, when saccadic movements are recorded and 400 μ V/cm. in other cases.

Highcut filters were employed in more than 30 c.p.s.

For the purpose of recording, photographs were taken in each case, and when necessary, 8 mm. ciné-film records were also obtained.

(2) **Target and Fixation of the Head.**—When saccadic eye movements were recorded, a target specially contrived for this experiment by the authors was employed. This target is so made that miniature bulbs light up at fixation points which can easily be adjusted. In the other cases of two-dimensional eye movements, a target set in motion was followed by the subject with his eye. In every case, the distance between the eye and the target was about 30 cm. The frequency of eye movement was about 2 c.p.s. in saccadic movements and 0.5 ~ 1.0 c.p.s. in other cases. A chin rest was used for fixing the head.

(3) **Electrodes and their Placement.**—Two pairs of silver dish electrodes for electroencephalography were employed as different electrodes on the pupillary line of the primary eye position with the horizontal axis placed on the inner canthus and about 1 cm. lateral from the outer canthus, and with the vertical axis on the upper and lower orbital edges. Electrode paste and cellophane tape were used for fixing the electrodes. An ear electrode for electroencephalography was employed as an indifferent electrode. The electrode resistance was kept in less than 10 K Ω in every case.

(4) **Output Leading.**—The output of the two pairs of electrodes was amplified with the horizontal output fed into the X-axis deflexion plates of the cathode ray tube and the vertical output into the Y-axis deflexion plates. Eye movements were so reproduced that they could be observed on the cathode ray tube in the same way as they were seen from the subject's side. This is because facility in making comparison with the routine examination of eye movements is aimed at.

(5) **Illumination.**—The room was illuminated by about 220 foot lamberts.

(6) **Shielding.**—The room was electrically shielded.

Results in Normal Subjects

Results were obtained from adult volunteers with normal visual acuity and eye position and no refractive errors or ocular disease. When saccadic movements were

* Nihon Kodenshō Kōgyō Co. Ltd., Nishi-Ochiai 2-514, Shinjuku, Tokyo, Japan.

examined, movements in five strokes were subjected to superimposed photography.

(1) Horizontal, vertical, and oblique (the last in the two directions of 45° and 135°) saccadic eye movements at the rotation angles of 20° , 40° , 60° , and 80° respectively (Fig. 3).

FIG. 3.—Vector-electro-oculograms of horizontal, vertical, and oblique (the last in the directions of 45° and 135°) saccades.

Calibration— $200\mu\text{v}/\text{cm}$. both horizontal and vertical.

Time constant— 0.3 sec.

Saccadic arc— 20° , 40° , 60° , and 80° .

(2) Eye movements in pursuit of several two-dimensional figures. Circular eye movements at the respective rotation angles of 20° , 40° , 60° , and 80° , and triangular and square eye movements (Fig. 4).

FIG. 4.—Vector-electro-oculograms of eye movements in pursuit of several two-dimensional figures.

Circular movements at the respective rotation angles of 20° , 40° , 60° , and 80° .

Calibration— $400\mu\text{v}/\text{cm}$. both horizontal and vertical.

Time constant— 2.0 sec.

(3) Recording of the velocities of eye movements by the superimposition of time marks on the spots. Saccadic, triangular, and square eye movements were examined (Fig. 5).

FIG. 5.—Vector-electro-oculograms with time marks superimposed. Time marks—100 c.p.s.

FIG. 6.—Standard method of vector-E.O.G. recording. 60° arc saccades through the primary eye position were examined at intervals of 15° in direction. Records were so taken that each saccade could be observed from the side of the subject. Frequency of movement—one stroke a second. Five strokes were subjected to superimposed photography.

Calibration—200 μ v/cm. both horizontal and vertical. Time constant—0.3 sec.

Standardization for Clinical Application

The eye movements to be examined by this method should be appropriate to the ocular disease under consideration. At present, the authors are experimenting on 60° arc saccades through the primary eye position at intervals of 15° in direction. Records thus obtained from normal subjects are shown in Fig. 6 (opposite). The frequency of eye movement adopted is generally 2 c.p.s., but when paralytic squint is examined, less than 2 c.p.s. is considered preferable. Although recording from the affected eye is a matter of course, fixation in this case has to depend upon uniocular vision with the unaffected eye. In cases of nystagmus, the right eye is examined generally, but invariably with regard to both binocular and uniocular vision. An electronystagmographic examination is also performed at the same time. In cases of amblyopia eye movements are recorded from the amblyopic eye, but comparison between uniocular vision with the amblyopic eye and binocular vision is important in this case too.

Clinical Findings by Vector-E.O.G.

(1) **Paralytic Squint.**—Records from cases of paralytic squint are shown in Fig. 7, and in Figs 8 and 9 (overleaf).

FIG. 7.—Paresis of left lateral rectus, showing restriction of lateral movements (left-side figure in 1st row) There is a tendency for the curving and the direction of movement seen in the middle figure in the first row and in the figure in the fourth row to become nearly vertical instead of taking different directions at intervals of 15° as in the normal cases shown in Fig. 6.

FIG. 8.—Paresis of right superior oblique, showing restriction of medial downward movements (lower left direction of middle figure in third row). There is curving in the figures in the third row.

Vector-E.O.G. generally reveals restricted eye movements in these patients. The restriction can be observed not only on the photographic records but also directly on the cathode ray tube, as it is reproduced there in peculiar forms, *i.e.* movements like those with a brake applied suddenly. Peculiar curves such as can be seen in some of the photographic records shown in Figs 7 and 8 and the tendency for saccadic movements to become almost vertical instead of taking directions at regular intervals of 15° (Fig. 7) can be better observed directly on the cathode ray tube. 8 mm. ciné-film records of some of these movements were also taken but cannot be shown here.

(2) **Nystagmus.**—Two cases of nystagmus are recorded in Figs 10 and 11 (overleaf, pp. 326 and 327). Fig. 10 shows horizontal jerky nystagmus in the middle part of the vertical eye movement, Fig. 11 shows nystagmus of the same kind at each end of the eye movement.

FIG. 9.—Total external ophthalmoplegia in the right eye, showing restricted movements in all directions. The upward movements in the figures in the second row are artefacts due to blinking.

(3) **Amblyopia.**—A case of amblyopia is recorded in Figs 12 and 13 (overleaf, pp. 328 and 329). Fig. 12 shows convergent strabismus with amblyopia before operation. After the operation, remarkably less disturbance was recorded in the traces of eye movements, but abnormal shifts presented themselves again in the oblique movements (Fig. 13).

Discussion

As regards eye movements, extensive theoretical and experimental studies have been made by German scholars, but their theories are too difficult to understand and their experimental methods of little use in clinical application. The methods currently used for examining the oculomotor functions are the Maddox rod test, the red-and-green test, the double-image test, and so on. Because these methods are subjective, the results are often confusing in diagnosis. Their common defect is that the examination is performed while the eyes are stationary.

FIG. 10.—Horizontal jerky nystagmus in the right eye. Nystagmic movements are seen in the middle part of the saccadic movements in nearly vertical directions.

E.O.G., which was formerly used for physiological studies of eye movements, has lately been given clinical application by Mackensen (1957a, b, c; 1958), Hiroishi (1958), Lehnert and Thieme (1962), and von Noorden and Mackensen (1962a, b, c), but all these clinical studies are based on one-dimensional recording. There have so far been very few reports of two-dimensional recording, even in the purely physiological studies of Law and DeValois (1958) and Ford and others (1959).

The authors (1963) have attempted the two-dimensional recording of eye movements with the aid of an X-Y oscilloscope, by using alternating amplifiers for the sake of stability. From its principle, this method is tentatively named vector-E.O.G. This method is still imperfect and the following points await further improvement:

(1) For recording swift saccadic movements, alternating amplifiers and silver-dish electrodes are adequate, but when slow movements are examined, direct-coupled amplifiers and unpolarizable electrodes have to be employed. The latter require further improvement of the stability of the baseline and the practicability of the electrodes.

FIG. 11.—Horizontal jerky nystagmus in the right eye. Nystagmic movements are seen at both ends of the saccadic movements in the figures in the second and third rows.

(2) The peribulbar tissues are never symmetrical but have individual variations, so that it is, therefore, practically impossible to place two pairs of electrodes with perfect symmetry. This is the chief reason why vector-E.O.G. still lacks accuracy as pointed out by Alpern (1963).

(3) The standing eye potential on which E.O.G. is based is constantly though slightly oscillating (Arden and Kelsey, 1962), and this must be taken into account as it is bound to cause slight errors in the results.

(4) Although rolling is one of the important eye movements, it cannot be directly recorded by vector-E.O.G. because of the principle of motion involved.

(5) Blinking, which usually produces a relatively large upward potential, is an irregular movement. In this sense, it is easily distinguishable from eye movements in general, but it sometimes introduces confusion into photographic records of eye movements. The injection of a local anaesthetic into the upper eyelid will eliminate this confusion but for a routine clinical examination such an injection is not considered desirable.

FIG. 12.—Amblyopia of the right eye with convergent strabismus. Unstable shifts peculiar to amblyopia can be seen in the figures in the third row.

(6) Unlike E.O.G. in the past, it is impossible for vector-E.O.G. to make the circuit for sweep serve as the time axis. The time relation of eye movements is, therefore, recorded by making use of the Z-axis of a cathode ray tube and the velocity of eye movements is then reproduced (Fig. 5). Mackensen (1958) made studies in this connexion by the routine method of E.O.G. but in future the recording of the velocity of eye movement by vector-E.O.G. will prove advantageous.

In spite of these defects, vector-E.O.G. has led to interesting clinical findings, and it is hoped that these first two-dimensional studies of eye movements will lead to further research to solve the technical problems in further studies of the physiology and pathology of ocular cybernetics.

Summary

Two-dimensional eye movements are reproducible on a cathode ray tube by vector-E.O.G. This method has been successfully employed in recording various two-dimensional movements in normal subjects. The recording is not yet perfectly accurate but the results so far obtained are encouraging.

Cases of paralytic squint, nystagmus, and amblyopia were examined with interesting results.

FIG. 13.—After operation for strabismus in the same case as is seen in Fig. 12. Disturbances of movement are decreased, but abnormal shifts are present in the figures in the second row.

Vector-E.O.G. is a new method studying the physiology and pathology of eye movements which allows them to be recorded dynamically, showing movement in more than one direction plotted against time.

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