COMMUNICATIONS

TORSIONAL MOTIONS OF THE EYEBALL*

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OF the many attempts which have been made in the past to record motions of the eyeball, the most successful investigations have used the corneal reflex method (Lord and Wright, 1948), photographic recording of the motions of a beam of light reflected from a plane mirror worked on a contact lens (Ratliff and Riggs, 1950; Ditchburn and Ginsborg, 1953), or photographic recording of the motion of the image of a bright source reflected in a globule of mercury pipetted on to the cornea (Barlow, 1952). These experiments have recorded at most the motions of the eyeball producing side-to-side and up-and-down motion of the visual axis when performing various visual tasks.

The motions described by previous authors may be summarized as follows:

- (a) Tremor of amplitude 5 to 15 sec. arc and frequency 30 to 80 c.p.s.
- (b) Flicks ranging from 1 to 20 min. arc in extent and occurring at intervals of 0.03 to 5.0 sec.
- (c) Slow drifts of up to 6 min. arc in an interflick period.

RECORDING OF TORSIONAL MOTIONS.—The eyeball is also capable of rotating about the visual axis, a motion generally called “torsion”; consider the eyeball to be a sphere, then if it rotates through a small angle about an axis lying in Listing’s plane and making some finite angle with the horizontal, the diameter which was originally vertical will sweep out the surface of a right cone about the axis of rotation and thus cease to lie in the vertical plane which passes through the centre of the sphere and the new direction of fixation. The angle between this diameter and the plane is called the angle of “normal torsion” (see Duke-Elder, 1938), and, if it is small, can be shown to be given by the expression:

$$t = \frac{\tan \alpha (1 - \cos \beta)}{1 + \tan^2 \alpha \cos \beta} \dots \dots \dots (1)$$

where t is the angle of normal torsion, α is the angle between the axis of rotation and the vertical direction, and β is the angle between the primary position and any fixation direction of the visual axis.

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This expression gives maximum values for torsion when $\alpha = 45^\circ$; substituting this value leads to:

$$t_{\max} = \frac{(1 - \cos \beta)}{(1 + \cos \beta)} \dots\dots\dots(2)$$

which further reduces to:

$$t_{\max} = 0.73 \times 10^{-4} \beta^2 \dots\dots\dots(3)$$

if t and β are small and measured in min. arc. Equation (3) shows that if $\beta = 2^\circ$, $t_{\max}$ is only 1 min. arc; it thus appears that, for small motions of the visual axis, normal torsion should be vanishingly small.

The existence of normal torsion during gross rotations of the visual axis from the primary position (more than 15°) can be demonstrated quite easily using either an after-image technique or a Maddox rod test; the experiment described below has been devised to see whether torsional motion persists for small motions of the visual axis.

Eye motions have been recorded using a contact lens method, essentially the same as that described by Ditchburn and Ginsborg (1953) but with this modification: instead of working an optical flat on a contact lens (which means that the normal to the plane surface cannot be parallel to the visual axis), a small stalk is stuck to a contact lens (Fig. 1) and a very small plane mirror (M_1) is attached to the end of this stalk; the normal to the mirror is adjusted to be parallel to the visual axis. A second mirror (M_2) is fixed to the temporal side of the stalk, so that the normal to M_2 lies in the horizontal plane and is perpendicular to the visual axis. The stalk is just long enough for these mirrors to be carried clear of the eyelids. Beams of light from a projector are reflected from these mirrors to the

FIG. 1.—Mirror attachment to contact lens enabling motions about three axes to be recorded.

moving film of a continuous recording camera; from the records obtained, the motion of the mirrors and hence of the eyeball can be calculated. M_1 will record both up-and-down and side-to-side motions of the visual axis but is insensitive to torsional motions, since rotation about the visual axis does not alter the plane of this mirror; M_2 records torsional motion and side-to-side motion but is insensitive to up-and-down motion. Using this apparatus, records have been obtained of the eye movements of two subjects when performing various visual tasks.

TORSIONAL MOTIONS WHEN FIXING.—Typical records of the eye movements when fixing are shown in Fig. 2 for two subjects, DHF and RMP. The fixation target was an illuminated pinhole subtending 1 min. arc at the eye. It will be seen that the side-to-side and up-and-down motions follow very closely the movements described by other observers, and that, in addition, a characteristic set of torsional motions exist despite the fact that the maximum excursion from the mean position of the visual axis in the records shown is less than 10 min. arc.

FIG. 2.—Records of torsional motions when fixing for two subjects: DHF (upper tracings), and RMP (lower tracings).

The torsional motions may be summarized as follows:

- (a) Tremor of maximum amplitude 45 sec. arc and frequency about 35 c.p.s.

This tremor is much more marked for DHF than for RMP in all three motions.

(b) Flicks, of small amplitude compared with the other motions, usually about 2 min. arc in extent.

(c) Slow drifts, irregular in nature, of up to 5 min. arc in an interflick period.

The torsional motion of the eyeball is of the same nature as the other motions and differs only in magnitude; this is in direct conflict with Listing's law, which implies that the effects of the extra-ocular muscles combine in such a way as to produce only "normal torsion" of the eyeball, and hence in this case should give no observable torsion.

It may be that the existence of small torsional motions is a natural consequence of the geometry of the muscle-planes of the extra-ocular muscles, for if it is assumed that the lateral and medial recti can produce rotation only about a vertical axis H (Fig. 3), whilst the superior and inferior recti act about the axis V_1-V_2 and the superior and inferior obliques about the axis T_1-T_2 , then a small rotation θ about the T_1-T_2 axis would produce a torsion ($\theta \sin 51^\circ$) about the primary position of the visual axis TT , and an upward rotation ($\theta \cos 51^\circ$) of the visual axis about a horizontal axis VV in

FIG. 3.—Muscle-planes of extra-ocular muscles (right eye from above).

Listing's plane. Similarly, a small rotation ϕ about the V_1 - V_2 axis would produce a torsion ($-\phi \sin 23^\circ$) about TT, and an upward rotation ($\phi \cos 23^\circ$) about VV. Thus we have:

$$\text{Total upward rotation} = \theta \cos 51^\circ + \phi \cos 23^\circ, \dots\dots\dots(4)$$

$$\text{Total torsion} = \theta \sin 51^\circ - \phi \sin 23^\circ \dots\dots\dots(5)$$

If Listing's law is to be obeyed in these circumstances, the torsion must be zero, thus:

$$\theta \sin 51^\circ = \phi \sin 23^\circ,$$

$$\text{or:} \quad 0.78 = 0.39 \phi.$$

$$\text{Thus:} \quad \phi = 2 \theta, \dots\dots\dots(6)$$

and hence the superior and inferior recti and the oblique muscles should be "geared together" to give rotations in the ratio of 2:1. This is obviously not the case, since the eye makes torsional motions.

Alternatively, the ratio between the action of these two sets of muscles might be constant, *i.e.*,

$$\phi = K \theta. \dots\dots\dots(7)$$

K is thus a measure of the relative actions of the superior and inferior recti and the oblique muscles.

In this case we have:

$$\text{Upward rotation} = \theta (0.63 + 0.92 K)$$

$$\text{Torsion} = \theta (0.78 - 0.39 K)$$

and the ratio of these two motions is given by:

$$\frac{\text{Upward rotation}}{\text{Torsion}} = \frac{0.63 + 0.92 K}{0.78 - 0.39 K} \dots\dots\dots(8)$$

Thus, if K is a constant, a graph of upward rotation against torsion should be a straight line.

The deflection from the mean position of the traces representing vertical motion and torsion were calculated at many points throughout a typical record obtained whilst fixing; the results are shown in Fig. 4 (overleaf). A straight line of slope -3.2 can be drawn among the points, but the correlation coefficient is only 0.58, and this is not significant if the normal test (coefficient greater than $3 \div \sqrt{\text{number of observations}}$) is accepted.

Similar results are obtained for the second subject, and thus it must be concluded that the torsional motion of the eye when fixing is mainly random.

TORSIONAL MOTION WHEN PERFORMING A DYNAMIC TASK.—It is more likely that any correlation between the action of the various extra-ocular muscles will appear when the eye is active than when it is nominally at rest; accordingly, records were taken of the eye motions when following a fixation target sweeping to and fro in cyclic fashion along a line inclined at 45° to the

FIG. 4.—Values obtained for torsion and vertical motion when subject is fixing.

horizontal in a vertical plane. The total excursion of the target subtended 52 min. arc at the eye, whereas the mean excursion of the visual axis was only 30 min. arc—such a phenomenon has been noted by other observers (Lord and Wright, 1949); a typical record is given in Fig. 5.

The eye movements were measured at corresponding points in many cycles and the mean values calculated; any random elements in the motion should be reduced by this process, but once again, a plot of the mean vertical motion against the mean torsional motion shows a correlation coefficient of only 0.02, indicating that the tor-

FIG. 5.—Record of torsional motions when subject is performing a dynamic task.

sional motion is random even in this case.

Finally, the amplitude of the vertical and torsional flicks occurring during this motion were compared; the results are shown in Fig. 6, and a correlation coefficient of 0.93 exists between the vertical and torsional motions, the

slope of the "best fit" line being (-2.48 ± 0.18) . If, however, a graph of the ratio $\left\{ \frac{\text{upward rotation}}{\text{torsion}} \right\}$ against the value of K is constructed from Equation (8) (Fig. 7, overleaf) and the range of slopes found above is plotted on it,

FIG. 6.—Values obtained for torsion and upward rotation when subject is performing a dynamic task.

between the vertical motion of the visual axis and the torsion of the eyeball should be present in all cases, only when the eyeball performs a large involuntary motion, *i.e.* a flick, does the correlation have any significance; but the value then obtained for the ratio $\left\{ \frac{\text{upward rotation}}{\text{torsion}} \right\}$ leads to the conclusion that the vertical motion of the visual axis during a flick is produced almost entirely by the superior and inferior recti, and that the oblique muscles are not used to correct the resulting torsion. During interflick periods, however, it would appear that the elevation or depression of the visual axis is produced by the effects of the superior and inferior recti and the oblique muscles combined in random proportions, and that this gives rise to random values of torsion of the eyeball.

Finally it should be noted that any recording technique which uses a reflecting surface with its normal not parallel to the visual axis will record a component of torsional motion confused with the other motions.

then it will be seen that Equation (8) is satisfied by all values of K except those lying within the range $+23$ to -125 . It appears therefore that this correlation between the vertical motion of the visual axis and the torsion of the eyeball is purely fortuitous, the relation between the two motions being one which can be produced with fair accuracy by any action of the superior and inferior recti which is large compared with that of the oblique muscles.

CONCLUSIONS

It has been demonstrated that torsional motions of the eyeball occur for small excursions of the visual axis from the primary position, excursions so small that normal torsion should not take place. The existence of torsional motion is in opposition to Listing's law, which requires the superior and inferior recti and the oblique muscles to combine in action so as to produce normal torsion only.

Although the geometry of the muscle planes would suggest that a correlation between the vertical motion of the visual axis and the torsion of the eyeball should be present in all cases, only when the eyeball performs a large involuntary motion, *i.e.* a flick, does the correlation have any significance; but the value then obtained for the ratio $\left\{ \frac{\text{upward rotation}}{\text{torsion}} \right\}$ leads to the conclusion that the vertical motion of the visual axis during a flick is produced almost entirely by the superior and inferior recti, and that the oblique muscles are not used to correct the resulting torsion. During interflick periods, however, it would appear that the elevation or depression of the visual axis is produced by the effects of the superior and inferior recti and the oblique muscles combined in random proportions, and that this gives rise to random values of torsion of the eyeball.

Finally it should be noted that any recording technique which uses a reflecting surface with its normal not parallel to the visual axis will record a component of torsional motion confused with the other motions.

FIG. 7.—Graph showing range of values of K obtained when subject is performing a dynamic task.

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