

Ocular Torsion during Voluntary Blinks in Humans

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PURPOSE. Most studies on blink-induced eye movements have been restricted to rotations about the horizontal and vertical axes. By additionally measuring rotation about the torsional axis, the authors investigated whether the three-dimensional rotation of the eye during the early phase of eyelid closure could be assigned to the action of a single extraocular muscle.

METHODS. In five healthy human subjects, eye movements about all principal axes of rotation (horizontal, vertical, and torsional) were recorded during voluntary blinks of different durations (as short as possible, 0.83 seconds, and 1.67 seconds) in straight-ahead gaze. Original dual search coils frequently rotate about the line of sight, because the upper eyelid touches the nasally exiting wire leads. Therefore, the search coils were modified so that the wires left the silicon annulus from its inner border at 6 o'clock.

RESULTS. The earliest eye movement during blinks consisted of a pulselike trajectory in a direction that was always extorsional, downward, and inward, regardless of the duration of eyelid closure. The beginning of all three movement components preceded the beginning of eyelid movement; thus, a coil artifact is unlikely. On eyelid opening, a consistent pulselike movement in the intorsional, upward, and outward direction occurred.

CONCLUSIONS. During the initial phase of voluntary eyelid closure, the eyes move in a three-dimensional direction that is consistent with a pulselike innervation of the inferior rectus muscle. To obtain reliable measurement of torsional eye movements with dual search coils during blinks, modification of the annulus is indispensable. (*Invest Ophthalmol Vis Sci.* 2002;43:3438-3443)

Two phases of eye movements associated with blinking can be distinguished: an initial dynamic ocular rotation that occurs with every blink and a subsequent sustained phase¹ that occurs only when closure of the eyelid is prolonged. Using the search coil technique, Collewijn et al.² described the horizontal and vertical trajectories of the human eye during the entire period of voluntary and reflexive blinks. The initial eye movement, which emerged before the eye was closed, was found to

be nasal- and downward. Bour et al.³ measured horizontal and vertical eye movements during blinks at different gaze positions within 10° from straight-ahead gaze. Based on the gaze-dependent pattern of trajectories, they concluded that the combined action of the inferior and superior recti muscles is sufficient to explain ocular rotation during short blinks.

Eye movements during blinks are associated with a co-contraction of most of the extraocular muscles,³⁻⁷ which in turn leads to a retraction of the eyeball. In the rabbit, Evinger and Manning⁸ recorded electromyograms (EMGs) of all six extraocular muscles during light-evoked and air-puff-evoked blinks. With the exception of the superior oblique muscle, all extraocular muscles were activated. Judging from the published figure (Fig. 1 in Ref. 8), the inferior rectus muscle showed the most brisk activation of all muscles at the beginning of the eyelid movement. Therefore, we hypothesized that a transient net force along the pulling direction of this muscle could explain why the initial movement of the eyeball is downward and nasalward. Despite the possibility that mechanical properties of the orbital tissue would divert this initial trajectory from the exact pulling direction of the inferior rectus muscle, we expected that at least the sign of the torsional component of the trajectory would agree with our prediction. In other words, the initial net force in the direction of the inferior rectus muscle would transiently extort the ocular globe.

To investigate the three-dimensional ocular kinematics during the initial phase of blinks, we recorded eye movements in healthy human subjects with dual search coils that were modified to exclude torsional artifacts. Using a miniature search coil on the eyelid, we were able to describe the time course between eyelid and eyeball movements and to differentiate among the eye movements during the initial (more dynamic) and the sustained phases of eyelid closure and the eye-reopening phase.

METHODS

Subjects

Five healthy human subjects (two women, three men; 32-55 years) gave consent and participated in this study after being informed of the experimental procedures. Protocols adhered to the Declaration of Helsinki for research involving human subjects and were approved by the local ethics committee.

Setup

Ocular rotations of both eyes about all three principal axes (x -axis: torsional movements; y -axis: vertical movements; z -axis: horizontal movements) were simultaneously recorded with dual search coils (manufactured by Skalar, Delft, The Netherlands), which combine two coils: one is oriented in the frontal plane; the other, wound in a figure-eight fashion, has its effective area approximately along the line of sight.⁹ Both coils are embedded in a self-adhering silicone annulus placed around the cornea.¹⁰ In addition, the movement of the right upper eyelid was measured with two serially connected miniature search coils (Fig. 1, left side) that were attached to the skin above the tarsus with an adhesive.

The magnetic field system consists of a cubic coil frame (side length: 1.4 m) of welded aluminum that produces three orthogonal

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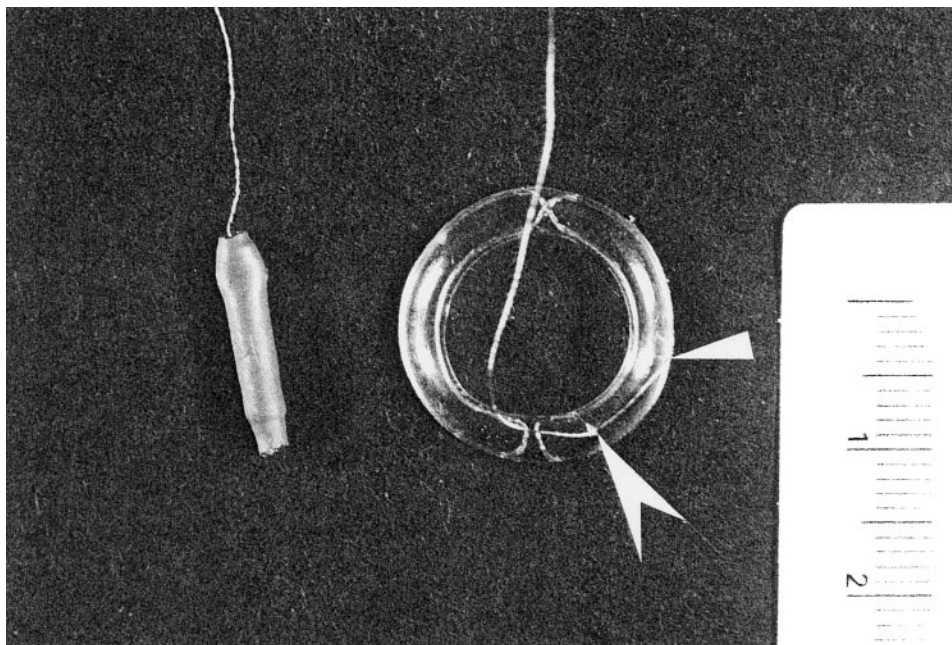
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FIGURE 1. Photographs of search coils. *Left:* Two-dimensional eyelid search coil. *Right:* Modified dual eye search coil. The original annulus was modified so that the wire leads exited the inner border of the search coil annulus at 6 o'clock. *Nontailed arrowhead:* original location of wire exiting from the annulus and the first stitch that gives the initial direction (clockwise, right eye coil; counterclockwise, left eye coil). *Two-tailed arrowhead:* second stitch that gives the wire the correct direction when exiting the annulus.



magnetic fields with frequencies of 55.5, 83.3, and 41.6 kHz and intensities of 0.088 Gauss. Amplitude-modulated signals were extracted by synchronous detection (modification of a Remmel-type system¹¹ by Adrian G. Lasker, Baltimore, MD). The bandwidth of the system is 0 to 90 Hz. Peak-to-peak noise signals in all three principal directions after calibration, as measured by a dual search coil placed in the center of the magnetic frame, were approximately 0.1° to 0.2° .

Coils were calibrated in vitro on a gimbal system. During the experiments, voltages related to the orientation of the eye coils in the magnetic coil frame were digitized with a 16-bit analog-to-digital converter at 1000 Hz and written to a hard disk. The data were analyzed off-line by computer (Matlab, ver. 5.3; The MathWorks, Natick, MA). Details of the calibration procedure and off-line analysis are described elsewhere.¹²

Eye positions were expressed in rotation vectors. A rotation vector is oriented parallel to the axis of rotation that moves the eye from the reference position to the current position. The length of a rotation vector is $r = \tan(\phi/2)$, where ϕ is the amount of rotation. For the convenience of the reader, the three components of rotation vectors are given in degrees. Because rotation vectors obey the right-hand rule, the signs of the horizontal and vertical components had to be inverted to make them consistent with the clinical definition of directions. Thus, in the following sections, rightward, upward, and clockwise rotations of the ocular globe, as seen by the subject, are positive.

Modification of the Search Coil Annulus

We were concerned that, during blinks, the upper eyelid touches the nasally exiting wire leads of the search coils and thus produces an intorsional slippage of the annulus on the conjunctiva or, alternatively, a similar movement of the conjunctiva on the sclera. Also the movement of the lower eyelid in the nasal direction during closing of the eyelids¹³ could interfere with the wire leads. We therefore made the following modifications to the search coil annuli under a microscope (Fig. 1, right side): (1) The small silicon tube at the insertion of the wire leads to the annulus was removed; and (2) to guide the wire to a position at the inner border of the annulus at 6 o'clock, two stitches were applied. The arrowheads in Figure 1 show the position of the stitches on a modified right eye coil: The nontailed arrowhead indicates the first stitch, which gives the initial direction to the wire (clockwise for the right eye and counterclockwise for the left eye annuli). The double-tailed arrowhead shows the position of the second stitch from which the wire leaves the inner border of the annulus.

Paradigms

Subjects were seated inside the coil frame. Search coils were mounted on both eyes and the right upper eyelid. The subject had to fix the two eyes on a red dot straight ahead (diameter: 3 mm) on a tangent screen at a distance of 1.24 m. Subjects were instructed to close both eyes according to an acoustic signal given by a metronome beating 72 times per minute. Thus, the interval between two beats was 0.83 seconds. Three temporal patterns were tested:

Paradigm 1. Eyes closed as briefly as possible on every second beat (short-as-possible blink).

Paradigm 2. Eyes closed during one interval (0.83 seconds) and open during two intervals (1.67 seconds).

Paradigm 3. Eyes closed during two intervals and open during two intervals.

RESULTS

First, we compared the trajectories of blink-induced eye movements recorded with the original and the modified dual search coil annuli. Figure 2 shows an example (subject DS) of upper lid movements and three-dimensional rotations of the right eye. Two measurements were performed with the original annulus: one with the wire leads exiting nasally and one with the wire leads exiting temporally.

Eyelid movements were similar in all three conditions. Eye movements, however, differed in torsional components. With the original annulus and the wire lead exiting nasally, torsional eye traces appeared pulslike in the extorsional direction. Then, after the zero line was crossed, an intorsional plateau was reached and maintained until the beginning of eye opening. With the wire leads exiting temporally, the torsional traces moved quickly to a large extorsional plateau, which was kept until the beginning of eye opening. The torsional traces recorded with the modified annulus resembled the torsional traces from the original annulus and the nasally exiting wire leads, but there was no negative torsional offset with the eyes closed. The intorsional offset during lid closure measured with the original coil, and the nasally exiting wire leads was probably due to the force exerted by the upper eyelid on the wire lead, because after the eyes had opened again, the torsional

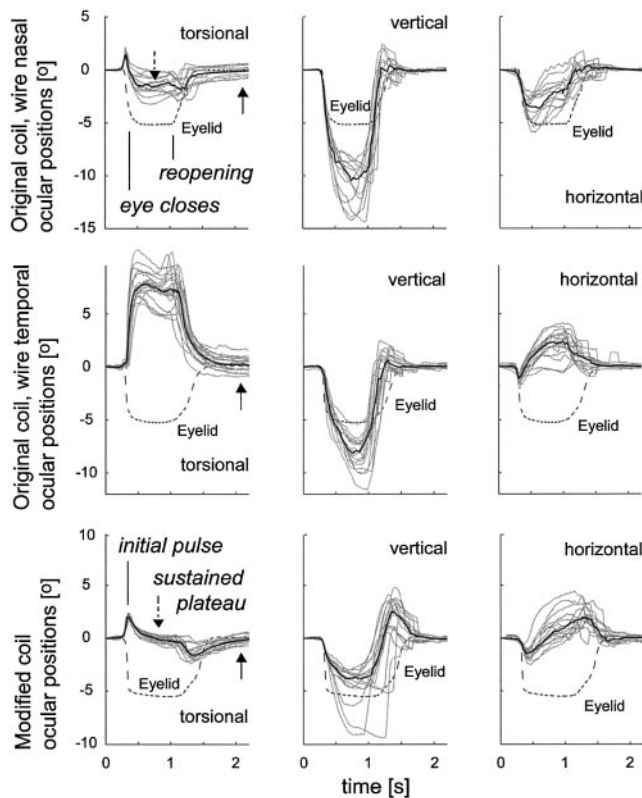


FIGURE 2. Comparison of blink-induced three-dimensional eye movements between measurements with the original and the modified search coil annulus in the right eye in a single subject. Each measurement consisted of 15 to 20 trials. *Left column:* torsional; *middle column:* vertical; and *right column:* horizontal components of ocular position (*dashed lines:* upper eyelid movement; *solid lines:* median eye position tracings). The eyelid traces represent only a raw, non-calibrated signal, whereas ocular movements are expressed in degrees. *Top row:* original coil with the wire leads exiting nasally; *second row:* original coil with the wire leads exiting temporally; *third row:* modified annulus. *Solid arrows:* scattering of the torsional eye position after eye reopening (see statistical analysis in Table 1). *Dashed arrow:* torsional eye position during the sustained phase of eyelid closure at crossing of the zero line in the torsional tracings with the original coil.

offset became close to zero again. In the position with the wire leads exiting temporally, they had even less room to move in the lateral angle of the eyelids, which is probably the reason that the torsional artifact of the annulus was larger in this position. In all measurements, the horizontal and vertical components showed less scatter after the reopening of the eyes than did the torsional component. Analysis of variance showed that the torsional scatter of intraindividual traces was much less with the modified coil (solid arrows, see also Table 1, $P < 0.01$). A torsional build-up existed due to slippage of the coils. After 20 blinks, the absolute torsional offset was approximately

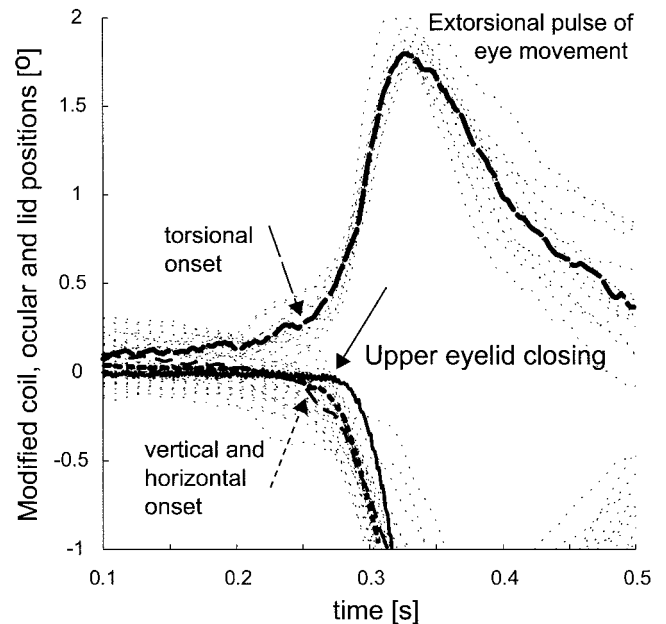


FIGURE 3. All three components of eye movement (modified search coil annulus) preceded upper eyelid closure during the beginning of a blink. *Dashed arrows:* the exact deflections of the eye-movement traces from zero (onset) were not precisely determined, because of the gradually increasing acceleration. *Solid arrow:* onset of the downward movement of the eyelid.

nine times more in the intorsional direction with the original coil and the wire exiting nasally than with the modified coil. The original coil with the wire exiting temporally showed an absolute offset of approximately 1.5° in the extorsional direction.

Theoretically, the extorsional pulslike movement measured with the modified annulus could still be due to eyelid-induced torsional annulus slippage. Figure 3 shows evidence that this was not the case. All components of eye movement measured with the modified search coil (dashed arrows) clearly preceded the downward movement of the eyelid (solid arrow). This agrees with previous photographic findings that the horizontal and vertical eye movement components begin before the eyelid movement.¹⁴ The exact deflections of the median eye movement traces from zero (onset) were not determined due to the gradually increasing acceleration. Therefore, the delay of the eyelid could only be estimated.

Because the improved torsional quality of the modified dual search coil was statistically confirmed (see Table 1), we used this annulus for further experiments.

Movements of the eyes and eyelids were further analyzed using the median traces of 45 to 60 consecutive trials. Figure 4 shows data collected at different durations of eye closure (subject DS). Independent of the duration of eyelid closure, there was a consistent initial pulslike movement of eye posi-

TABLE 1. Statistical Analysis of the Intraindividual Torsional Scatter and Torsional Offset Introduced by Eye Closure

	Mean of Scatter	Minimum Scatter	Maximum Scatter	Torsional Offset after Each Blink	Absolute Torsional Offset after ~20 Blinks
Original coil, wire nasally ($n = 3$)	0.397	0.325	0.458	-0.113	-2.69
Original coil, wire temporally ($n = 3$)	0.601	0.379	0.768	0.080	1.51
Modified coil, wire inferior ($n = 5$)	0.248	0.199	0.294	-0.013	-0.31
P (analysis of variance)	0.008			0.027	

Degree of torsion was obtained at 700 ms after lid reopening. Incyclorotation is represented by negative values. Data are expressed in degrees.

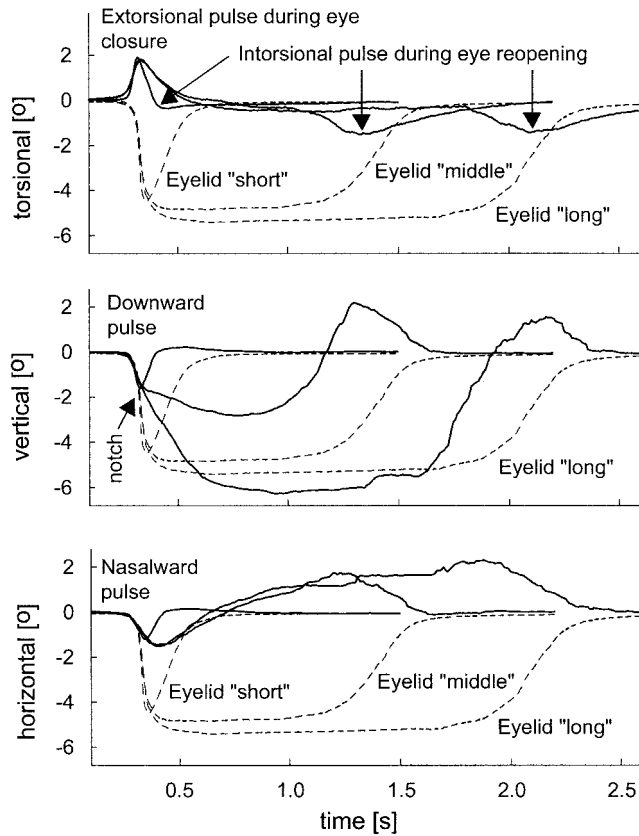


FIGURE 4. Overlay of three different durations of eyelid closure (as short as possible, short blink; 0.83 seconds, middle blink; 1.67 seconds, long blink) for the torsional, vertical, and horizontal eye position tracings (solid lines). For temporal comparison, the corresponding median traces of eyelid movements are also given (uncalibrated raw voltages, dashed lines). The amount of the extorsional eye movement is independent of the duration of eyelid closure, but this is not so of the intorsional component during the eye opening phase, when the amount of intorsion is bigger during the middle and long lid closure compared with the short-as-possible blink.

tion in the extorsional, nasalward, and downward directions. The vertical traces during eye closure lasting 0.83 or 1.67 seconds did not return to zero during the sustained phase, but showed a slight notch or directly continued in the same direction without interruption.

During reopening of the eyes, a pulse of three dimensional eye movements occurred in the intorsional, upward, and outward directions. For the short-as-possible blink, during which no sustained phase was observed, the initial pulse quickly merged into the pulse after eye opening, which resulted in a double saccadic pulse—that is, two consecutive saccadic pulses without steps. Also, at the end of prolonged eye closure, there was a pulse of the eye position in the intorsional and upward directions. As soon as the eyelid did not cover the line of sight, a correcting saccade occurred to foveate the target straight ahead. The exponential decay of torsional eye position after eyelid opening outlasted the saccadic horizontal-vertical refixation.

Figure 5 depicts the same three-dimensional eye movement trajectories as in the Figure 4 in three different orthogonal views. We plotted the three components of eye movements against each other as rotation vectors with signs defined by the right-hand rule. Traces from the beginning of the blink to the maximal eccentric position of the initial movement were relatively straight and pointed in the same three-dimensional

direction during all three paradigms (solid traces). Thereafter, the trajectories were vastly curved and irregular (dashed traces).

Figure 6 summarizes the median three-dimensional eye position trajectories and the median uncalibrated eyelid movements in all five subjects, with their eyes closed for 0.83 seconds. The initial phase of the horizontal, vertical, and torsional components was consistent among all subjects—that is, the pulselike trajectories pointed extorsional, downward, and inward. Whereas the vertical component was conjugate, both the torsional and horizontal components were symmetrically disconjugate, leading to a horizontal-torsional vergence movement (divergent and excycloergent). The sustained phase of ocular positions during eyelid closure, however, was more variable, both among subjects and between the two eyes of individual subjects. Only two of the five subjects showed the classic Bell's phenomenon.

It was our hypothesis that the net force along the inferior rectus muscle predominantly influences the eye movements during the earliest phase of eyelid closure. This was tested by comparing the three-dimensional direction of the initial eye movement with the moment vector of the inferior rectus muscle computed from the anatomic data published by Robinson.¹⁵ In Figure 7, we fitted the least-square linear regression through the median peak amplitudes of the initial phase in the five subjects (solid symbols) and compared the orientation of this best-fit line with the orientation of the anatomic moment vector of the inferior rectus muscle. The linear fit was well established among all subjects (see linear regression coefficient, R^2 , of the linear regression in figure legend). In the torsional-vertical plane (Figs. 7A-C), the best-fitted line (dashed) pointed in the approximate direction of the moment vector of the inferior rectus muscle (solid line), independent of the duration of eyelid closure, but there was a consistent small deviation in the extorsional direction. In the horizontal-vertical plane (Figs. 7D-F), the deviations between the anatomic

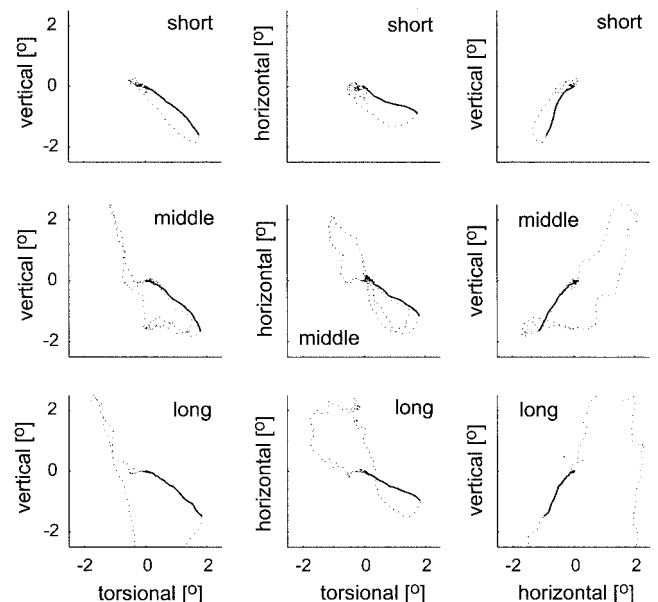


FIGURE 5. The median traces of the torsional, vertical, and horizontal eye positions are plotted against each other. Solid traces: the trajectories (relatively straight) from the beginning of the eyelid closure to the peak position of the initial phase pointed to the same direction independent of the duration of the eyelid closure: short (top row), middle (middle row), long (bottom row). Dashed traces: the trajectories (vastly curved) from the peak position of the initial phase to the end of eyelid closure were irregular.

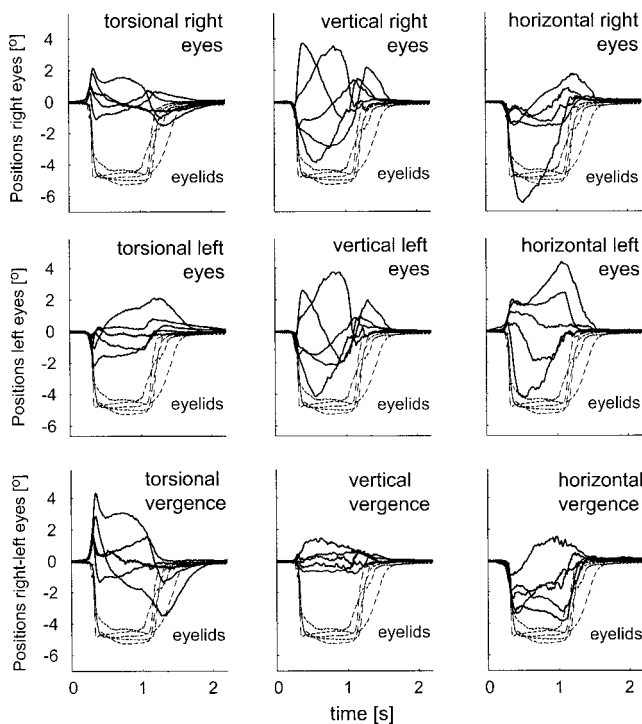


FIGURE 6. Overlay of all subjects' torsional (*left column*), vertical (*middle column*), and horizontal (*right column*) eye position (median traces of 45–60 trials) during eyelid closure lasting 0.83 seconds. Data of both the right and the left eye as well as vergence (right eye minus left eye) are plotted. Initial phases among all subjects were very consistent (extorsional, downward, and inward pulslike trajectories). Vertical components were conjugate; horizontal and torsional components symmetrically disconjugate (divergent and exocycloergent). However, the ocular positions during the sustained phase of eyelid closure were variable. Only two subjects showed a classic Bell's phenomenon.

and eye movement data were small. The position of maximal eye eccentricity during the sustained phase of eyelid closure (open symbols) changed with the duration of the closure and was highly variable among the subjects.

DISCUSSION

In healthy human subjects, we recorded eye movements about all principal axes of rotation (horizontal, vertical, and torsional) during voluntary blinks at straight-ahead gaze. We used dual search coils that were modified so that the exiting wire lead did not mechanically alter the torsional component. The initial eye movement associated with closing the eyes consisted of a pulslike movement in a direction that consistently was extorsional, downward, and inward, regardless of the duration of lid closure. Eye positions during the later phase, however, varied extensively among the subjects. After eyelid opening, a consistent pulslike movement in the intorsional, upward, and outward direction occurred.

Despite our modification of the search coil, it is still possible that the eyelids artificially influenced eye position during blinks. The fact, however, that all three components of eye movements, including torsion, preceded the beginning of the upper eyelid movement in synchrony speaks against a mechanical explanation for the recorded trajectories (Fig. 3). For the vertical and horizontal components, the beginning of the eye movement before the upper lid movement has already been shown in previous studies, both with search coils² and optical methods.^{14,16}

Theoretically, a further source of eye movement artifact could be cross-coupling of translation into rotation. A translation of the dual search coil by 0.2 m in our large magnetic frame (side length: 1.4 m) led to a change in angular position of less than 10%. The translation of the ocular globe induced by co-contracting eye muscles during blinks is only on the order of 1.0 to 1.5 mm.¹⁷ Therefore, we are confident that the rotations measured in this study were not due to the translational movement of the coil associated with the retraction of the eye.

Compared with the original dual search coil annulus that is commercially sold, the modified annulus, with the wire lead exiting on the inner rim at 6 o'clock, showed novel aspects of torsional eye movements during blinks. First, the initial torsional movement was clearly monophasic when measured with the modified annulus, not dysphasic. This, of course, changes theoretical considerations on the origin of the initial blink-evoked eye rotation. Second, the torsional scatter of eye positions was similar before and after blinks, when measured with the modified annulus. Thus, previous search coil studies on the validity of Listing's law probably have underestimated how strictly this law actually is obeyed in humans.¹⁸ With the modified annulus, the thickness of Listing's plane seems as small as in rhesus monkeys,¹⁹ in which three-dimensional ocular rotations are measured with search coils that were surgically attached to the sclera.

We hypothesized that the co-contraction of extraocular muscles associated with eyelid closure is not perfectly synchronous, because the eyes continue to move after eyelid closure is initiated. The inferior rectus muscle is the only muscle that pulls in the extorsional, downward, and inward directions. If there is indeed a stereotyped sequence of eye muscle forces operating on the ocular globe, we expected that the earliest pulslike eye movement would reflect the pulling direction of this primarily activated extraocular muscle. Two previous stud-

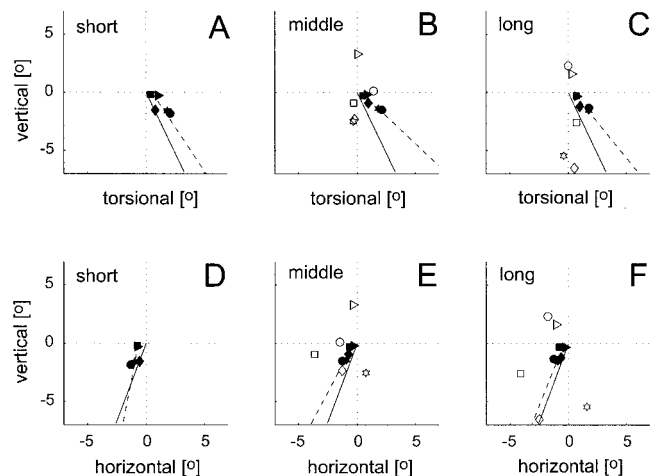


FIGURE 7. Eye position at the peak amplitude of the initial (*solid symbols*; median of 45–60 blinks) and sustained (*open symbols*) phase of eyelid closure in all subjects ($n = 5$). *Dashed line*: linear fit through the initial peak eye positions. *Solid line*: pulling direction of inferior rectus muscle published by Robinson. Eyelid closure (A, D) short as possible, (B, E) 0.83 seconds, and (C, F) 1.67 seconds. (A–C) Torsional versus torsional eye position. (D–F) Horizontal versus vertical eye position. Deviation of eye position from the anatomic pulling direction in the torsional-vertical plane (torsional bias, correlation coefficient of linear fit): (A) 8.1° , $R^2 = 0.55$; (B) 21.3° , $R^2 = 0.87$; and (C) 13.6° , $R^2 = 0.77$. Deviation of eye position from the anatomic pulling direction in the horizontal-vertical plane (horizontal bias, correlation coefficient of linear fit): (D) -9.7° , $R^2 = 0.27$; (E) 7.2° , $R^2 = 0.80$; and (F) 1.1° , $R^2 = 0.40$. Data for pulling direction (*solid lines*) adapted, with permission, from Robinson DA. A quantitative analysis of extraocular muscle cooperation and squint. *Invest Ophthalmol.* 1975;14:801–825.

ies indirectly corroborate this conjecture: Evinger and Manning⁸ published electromyographic recordings of all extraocular muscles during blinks. There was no activity of the superior oblique muscle, and the inferior rectus muscle showed the brisk activity of the remaining five muscles at the beginning of eyelid closure. Bour et al.³ investigated blink-induced eye movements in two dimensions (horizontal, vertical) at different gaze directions and found that the amplitude of the eye displacement during short, voluntary blinks was minimal in adduction and downward gaze. At this gaze direction, the inferior rectus is already activated, and therefore additional blink-evoked activation leads to a minimal further displacement of the ocular globe.

The three-dimensional trajectories of the eye associated with eyelid closure deviated slightly from the anatomic pulling direction of the inferior rectus muscle measured by Robinson (see Fig. 7).¹⁵ Considering that Robinson defined a pulling direction by simply computing a straight line between the points of origin and insertion, a small deviation is not surprising. Anisotropic mechanical properties of the eye plant²⁰ are certainly able to modify action directions of eye muscles. Not an additional secondary pulling of the superior rectus muscle, but the pulling of the inferior oblique muscle could explain the observed small deviation, because this muscle additionally pulls in an extorsional direction.

What could be the neurophysiological basis for an early pulse-like activation of the inferior rectus muscle? At the beginning of eyelid closure, the levator palpebrae motoneurons receive an inhibitory burst signal that causes the firing rate of these neurons to drop immediately to zero (inhibitory cutoff). Simultaneously, the inferior rectus may receive an excitatory burst signal. Such reciprocal muscle synergy is possible, because the upper eyelid moves downward with downward saccades.²¹

Our analysis also covered the three-dimensional trajectories of the eye after eyelid reopening and showed that a consistent pulsatile movement in the intorsional, upward, and outward directions occurred. Because the baseline from which the eye movement started at the beginning of eyelid opening was different in each subject, depending on the respective tonic co-contraction during the sustained phase of eyelid closure (Bell's or inverse Bell's phenomenon), the eye movement kinematics during eyelid opening could not be quantitatively analyzed. We can only assume that the rectus superior muscle receives a phasic burst during eye opening. This would be in agreement with the synergistic behavior, with the levator palpebrae muscle that is activated causing the upper eyelid to open the eye.

The co-contraction of the extraocular muscles during reflex blinks³⁻⁷ is most commonly considered to be a protective reflex only in some remnant neural system, because the eyes are retracted because of blinking. However, blink-induced eye movements cause substantial changes in the dynamic properties of saccades,²² and, under pathologic conditions, may facilitate saccades.^{23,24} For the short-as-possible blink, we found double pulsatile trajectories in all three components (horizontal, vertical, torsional) as coordinated pattern of extraocular muscle innervation.

In conclusion, we studied extorsional eye movement during the first phase of eyelid closure, with the results suggesting that the inferior rectus muscle is earlier or more briskly activated than the remaining extraocular muscles during their co-contraction. Torsional eye movements can only reliably be measured with dual search coil annuli that are modified to prevent torsional artifacts. Future studies should be designed to combine three-dimensional eye movement measurements with simultaneous electromyographic recordings of extraocular muscles.

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