The Absence of So-called Compensatory Ocular Countertorsion

The Response of the Eyes to Head Tilt

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Objectives: To show that so-called compensatory ocular countertorsion (static ocular counterrolling) does not exist and to describe the torsional eye movements that occur while the head is tilting.

Methods: Two miniature video cameras, a fiberoptic light source, and a fixation target were suspended from a headband. The cameras, fixation target, and light source moved in synchrony with the head. One camera videorecorded iris and conjunctival landmarks, and the other recorded head movement and position. The video frames were digitized and analyzed using computer algorithms.

Results: The eyes showed no compensatory ocular countertorsion in any stabilized head tilt position. During head tilt, periodic torsional eye movements occurred. These movements included a tonic counterlag followed by a saccadic forward torsion that rotated the eyes prior to the head; this was followed by a saccadic countertorsion that realigned and synchronized the eyes with the head, bringing the eyes and head into equilibrium.

Conclusions: Compensatory ocular countertorsion does not exist. Torsion occurs only during head tilt. The eyes are oriented to the brain and not to the horizon. When the head stabilizes in any tilted position, the retinas assume the same dynamic state of equilibrium with the brain that they assume in every other position. The main function of the oblique muscles is to stabilize the retinas in relation to the brain in all held head positions and directions of gaze. During head tilt, the oblique muscles produce involuntary torsional movements of small amplitude (up to approximately 10°) that appear to anticipate the final head position and prepare the eyes for obtaining retinal correspondence. These torsional movements may protect the retinas by dampening the effect of the head movement on this sensitive tissue.

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It is generally believed that the eyes manifest compensatory ocular countertorsion (COCT) (also known as static ocular counterrolling) around the visual line when an earthbound person tilts his or her head and holds it at a steady angle to the shoulder or terrestrial horizon. For example, when the head is held in a tilted position at about 50°, the eyes undergo countertorsion around an anterior-posterior axis that is variable but always less than 50°. Compensatory ocular countertorsion is believed to be caused by the gravitational and inertial stimulation of the hair cells in the otolith organs of the vestibular apparatus. Hypothetically, otolith function could be evaluated by measuring COCT, which may be diminished in a state of weightlessness. These measurements might also yield information concerning vestibular physiologic characteristics, the cause of space motion sickness, and the mechanisms of ocular and neurological abnormalities.1-11

Compensatory ocular countertorsion has been accepted as a foundation or variable in many scientific studies on vestibular and ocular motor physiologic characteristics and as a precept in the interpretation of clinical ocular motor defects.12-26 The existence of COCT is so universally accepted that there is even a published history of this phenomenon.27 The Nagel1 law states that any degree of sideways tilt of the head toward the shoulder produces a torsional rotation of both eyes in the opposite direction, equal to approximately one sixth of the degree of head tilt. Although subsequent investigators have demonstrated that COCT is highly variable and asymmetrical in every position of head tilt, all agree that its magnitude is directly related to the magnitude of the head tilt.1-26

There are logical reasons to believe in the existence of ocular torsion as a normal compensatory mechanism for head tilt. Orbital dissection shows that the eyes move within lubricated ball-and-socket joints and therefore seem capable of 3 de-
degrees of freedom of motion: horizontal, vertical, and torsional. This belief is reinforced by the anatomical locations of the insertions of the oblique extraocular muscles, whose primary function would appear to be torsion. An area for the so-called neural integration and control of torsional and vertical movements has been identified in the midbrain nucleus of Cajal.

Experimental methods with natural and artificial ocular surface landmarks, astigmatic axes, after images, the blind spot, digital tracking, and cinematography have been used to demonstrate COCT. In recent studies, the measurement of COCT varied between 7° and 14° depending on the subject and whether or not astigmatic axes, Maddox rod images, or cinematography was used to confirm the existence of this phenomenon. The scleral induction coil method has shown the existence of this phenomenon.

The stored digitized video files were copied to Adobe Photoshop 5.5 software (Adobe Systems Inc, San Jose, Calif) for analysis. The Photoshop layering tool was used to organize the frames in sequence. The first frame was selected and displayed as the background layer. The second frame in the sequence was selected and copied. The first frame was then reselected, and the second frame was pasted as layer 1 on top of the background layer. The procedure was repeated until all of the frames were contained in a numbered sequence in a single graphics-layered document. Empty layers were added at the end of the sequence, on which various landmarks from the background frame were traced. These layers could be moved independently and superimposed onto the other frames of the sequence.

MEASUREMENTS

The eye measurements used in our study were, for practical purposes, schematic (Table). Like all biological measurements, they encompass a physiological range and vary from time to time and according to subject. The angular tilt and velocity of the head were measured from the captured frames at 30-millisecond intervals using the rectangular bars that contained the alternating black-and-white stripes. The measuring tool of Adobe Photoshop 5.5 was used for obtaining measurements. This versatile tool can measure an angle to 0.1° (6 minutes of arc) and a linear distance between pixels of 0.16° (10 minutes of arc).
The number of pixels in an iris image was related to its magnification and ranged from 360 to 480 pixels. Thus, each pixel was between 7.5 and 10 arc minutes in length. The iris was about one sixth of the circumference of the globe, or approximately 60°. If the number of pixels in the diameter of the iris was 360 and the iris diameter was 12 mm, each pixel was approximately 0.16° or 10 arc minutes.

To measure velocity and change in position, the limbus was bracketed using guidelines selected from the view menu of Adobe Photoshop 5.5. Guidelines appear to float over the entire image and can be moved independently from frame to frame. They were used to measure in pixels the amount of eye movement that occurred in 30-millisecond intervals.

LANDMARKS

The anterior surface of the eye has iris, limbal, and conjunctival landmarks. At first, 2% pilocarpine hydrochloride was instilled to control iris movement. This proved unnecessary because iris landmarks are displaced radially and limbal landmarks are not displaced at all by iris movement. In addition, because the light source moved with the head, the iris was evenly illuminated, which also minimized iris movement. Conjunctival vessels proved to be suitable landmarks. Even though the conjunctiva is fixed at the limbus and loose over the scleral surface, there was no distortion of the conjunctival vessels during eye movement.

SUBJECTS

The eye and head movements of 15 subjects (7 men and 8 women) were recorded. All were healthy adults who ranged in age from 21 to 74 years. Visual acuity in all subjects was 20/25 OU or better without correction, with contact lenses, or following refractive surgery. All had clinically normal-appearing conjunctivas, irises, and retinas and clinically normal eye and head movements. All subjects gave informed consent for this study, which was approved by the Human Investigation Review Committee of Wayne State University School of Medicine (Detroit, Mich).

RESULTS

EYE ORIENTATION WITH THE HEAD HELD STEADY AT DIFFERENT ANGLES OF HEAD TILT

Six landmarks were traced on images of a greatly magnified (approximately ×144) segment of the iris (Figure 2A). The landmarks were traced using the Adobe Photoshop 5.5 pencil tool with a line 1 pixel thick. Each landmark was drawn in a separate layer using the Photoshop layering tool. The tracings could be moved independently of each other or merged in varying combinations and were shifted away from the landmarks to show their configurations. Iris segments were further enlarged to show details (Figure 2B and C). The tracings could be moved to outline the landmarks with a precision greater than 10 arc minutes.

The head was tilted to the left shoulder from 0° to 90° and held for about 5 seconds at randomly selected angles (Figure 3). The magnitude and velocity of the head tilt were measured from the alternating black-and-white stripes. Eye frames were obtained from the video clips for analysis at 3°, 12°, 33°, 46°, 60°, and 90°. The outlines of the tracings of the selected iris landmarks were superimposed individually in each frame. The superimposed tracings were precise and identical in each frame. If COCT was present, it was less than 10 arc minutes.

Two other methods were used to determine eye orientation in different positions of head tilt (Figure 4). A rectangular segment of the conjunctiva containing conspicuous blood vessels was selected from the initial frame and placed in its own layer. Its opacity was then reduced to 60%. Thus, when this layer was superimposed, the conjunctival vessels in the frame were seen through the rectangular conjunctival segment (Figure 4B). Insets of the segment of conjunctiva were placed on top of the striped bar that indicated the angle of head tilt. Although the conjunctiva adheres relatively loosely to the sclera, the superimposition of the tracings was precise in different head tilt positions. No COCT was measured.

Iris areas were selected based on the similarity in color of adjacent pixels using the Adobe Photoshop magic wand tool (Figure 4C). The iris collarette of this subject

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<td>Iris diameter, mm</td>
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*Indicates approximate measurements.
†Varies with the magnification of the iris.
‡The measurement used in the experiments was 10 arc minutes.
is shown in detail. The collarette layer was superimposed onto each frame. No COCT was measured.

The left eye of this subject is focused upward and slightly outward (Figure 5A). The configuration of conjunctival vessels near the limbus remained the same at head tilts of 3° to 80°. The superimposition of the layer of conjunctival vessels was precise in all frames. No COCT was measured. All 15 subjects had the same findings as described previously.

**Figure 3.** Six video frames of the iris with the head held tilted to the shoulder and horizon from 3° to 90°. Superimposition was precise and identical in all frames. There was no compensatory ocular countertorsion. Striped bars indicate the degree of head tilt.

**EYE MOVEMENTS DURING HEAD TILT WITH THE FIXATION TARGET MOVING WITH THE HEAD**

During head tilt, the eyes underwent involuntary, unconscious movements around an anterior-posterior axis. These periodic eye movements had 3 phases. The first was a small-amplitude tonic countertorsional movement. The second was a forward-torsional sac-
cade that accelerated prior to the head. The third was a counter-decelerating saccade that allowed the head to catch up to the eye. The cycle repeated itself until the eyes and the head came to rest and achieved a dynamic equilibrium that was devoid of torsion.

Although the amplitude of the eye movement varied from subject to subject, the pattern of alternating

Figure 4. Six video frames of the iris with the head held tilted to the shoulder from 6° to 57°. B, Conjunctival vessel tracing proved adequate for measuring eye orientation. C, Pixel color values also provided a means of measuring eye orientation. Striped bars indicate the degree of head tilt.
tonic and saccadic movements was consistent. The amplitude of the saccade was directly related to the velocity of the head movement (Figure 6 and Figure 7). Active (attentive) fixation caused a decrease in the amplitude of the movement (ie, a blurred target produced visible eye movements of relatively large amplitude), and a clear target produced small-amplitude movements (Figure 7B).

The location of the anterior-posterior axis usually did not correspond with the visual line. Head tilt generally was not “pure” but was associated with a vertical (pitch) and/or horizontal (yaw) rotation of the head. These rotations caused a shift of the anterior-posterior rotational axis away from the visual line. Rotation around such an eccentric axis added a vertical and/or horizontal component to the head tilt.28

When the head moved slowly (<10°/s) and the subject held fixation, the magnitude of these movements was minimal. When the head tilted rapidly (>10°/s), the torsional eye movements were visible, but in no instance did the magnitude of the torsional saccades exceed approximately 12°.

POSSIBLE CAUSES OF ARTIFICIAL COCT

It is difficult to produce pure head tilt and prevent small-scale lateral and vertical head movements. A slight amount of head movement may cause a significant shift of the eye in the orbit or a shift of the head from a stable frontal plane. For example, a vertical or horizontal head movement of only 1 mm may cause a 1-mm shift of the eye in the orbit. This small shift could produce an angular error of 5° (1 mm on the retinal surface is about 5° or 900 µm). When projected onto a flat surface and recorded on photographic film or videotape, these shifts cause the landmarks to show a measurable angular deviation, which may be interpreted as COCT. In addition, the fixation target, if not in a constant location relative to the head tilt, may cause an eye shift in the orbit (Figure 8 and Figure 9).34

To prevent horizontal and vertical rotation of the head during tilt, researchers have used fitted plastic head and body shells and casts, alginate dental material, straps, and the so-called human disorientation device. However, the scalp is moveable over the underlying skull, and even when a plastic cast or headband is tightened to the point of discomfort, slippage of the device is possible. Despite restraint with a mechanical device, the head tends to make small lateral and/or vertical movements when tilted. Bite bars, which may be slightly askew, limit the head movement to the axis of the bar. They are generally uncomfortable, and when the head is tilted, slight slippage is possible no matter how carefully the bite bar is fitted.

The failure to distinguish between what happens during head tilt and what happens when the head is held steady may be a source of artifact. The intermittent torsional movements that occur during head tilt may be interpreted as COCT. The scleral induction coil technique has the sensitivity to record these movements.29-32,35,36 Other possible causes are the nonuniform illumination of iris crypts and folds, which cast shadows of varying depths and sizes, and the displacement of fixation targets. Artifact may also be caused by the slippage of contact lenses, variations in intraocular pressure, or ocular pulsations and blinking.

COMMENT

STEADY HEAD TILT

When the head is held steady in any position tilted to the horizon or shoulder, healthy subjects affected by earthbound gravity show no COCT. The gravitational force on the extraocular muscles, supposedly mediated by impulses from the otolith apparatus, is counterbalanced by impulses that probably arise from the reticular activating system of the brain stem, the contralateral otoliths, the visual cortex (possibly the fusion reflex), or all 3. The
eye weighs between 7 and 8 g, and the head weighs about
2800 g. Thus, the head weighs approximately 360 times
more than the eye. The headband and suspended cam-
eras add an additional 700 g to the head. Despite this ex-
tra weight, which should add increased inertial and gravi-
tational stimulation to the otoliths, no COCT results. We
conclude that the eyes (retinas) are oriented to the head
(brain) and not to the terrestrial horizon and that the ef-
fects of gravity are neutralized by the tonus in the extra-
ocular muscles.

Figure 6. The measurement of ocular torsion during head tilt (indicated by
the striped bars). The head was tilted to the left shoulder at about 30°/s.
Three frames of the left eye were obtained at 30-millisecond intervals and
were captured between 32° and 34° of head tilt. A, The eye lags behind the
head. B, The eye makes a saccade in the direction of the head tilt in less than
30 milliseconds, as shown by the blurriness of the frame. The sampling rate
was not fast enough to record the saccade in detail. C, The eye has moved
prior to the head. D, The angle of saccadic torsion was 4° at about 34°
of head tilt. Circle indicates initial position of iris; X, center of pupil; and E,
rotation of iris after 30 milliseconds. Together they form the angle of forward
rotation of approximately 4°.

Figure 7. A, The eye lags behind the head and periodically makes a saccade
to catch up to the head. When the head ceases tilting and holds its position,
the eye and head are in synchrony. B, The amplitude of the saccade is
determined by the velocity of the head tilt.

DURING HEAD TILT

During head tilt, the eyes undergo intermittent, invol-
untary torsional tonic and saccadic movements that are
not conscious. These torsional movements take place
around an anterior-posterior axis that is determined by
the complexity of the head movement (ie, whether the
head while tilting also has a horizontal and/or vertical
component). When the axis of rotation does not corre-
spond to the visual line, the anterior pole of the axis (the
index point for all eye movement) transcribes a small circle
of latitude that adds vertical and horizontal movements
to the torsional movement (an eccentric torsion, a skew-
like deviation).37-42

The torsional movements have alternating, inter-
mittent tonic and saccadic phases. In the tonic phase, the
eyes appear to lag behind the head. In the saccadic phase,
the eyes accelerate prior to the head and then deceler-
ate, allowing the head to catch up to the eyes. The move-
ments have the same amplitude and duration in both eyes.
The amplitude of the saccades increases and their num-
ber decreases as the head tilts faster. When the head tilts
rapidly or the image is blurred, the saccades are visible
without magnification. When the head tilts slowly, the
torsional movements are of small amplitude and may re-
quire magnification to be seen. Conscious attention to a
fixation target decreases the amplitude of the torsional
movements. The peak velocity and duration of the sac-
cades depend on their amplitudes. Torsional saccades have
been measured from about 2° for sharply focused images to about 12° for indistinct images.37-42

**OBLIQUE MUSCLES**

The consensus is that the functions of the oblique muscles are to produce torsion, to provide COCT to compensate for head tilt, to produce vertical eye movements in synergy with the vertical rectus muscles, and by co-contraction, to supplement the abduction produced by the lateral rectus muscle. The absence of COCT suggests that the principal function of the oblique muscles is to provide a servomechanism for the inhibition of ocular torsion, thus allowing ocular stability in all held head positions in space and in all gaze directions. A secondary function is to produce the torsional movements during head tilt that compensate for the inertia of the head. (The head weighs at least 360 times more than the eye.) The magnitude of these involuntary torsional movements is directly related to the velocity and amplitude of the head movements, but they rarely exceed 10°. In vertical and oblique movements, the oblique muscles act synergically with the rectus muscles to prevent torsion.43 Thus, a constant equilibrium between the retinas and the brain is maintained, and retinal correspondence is preserved in all head positions in space.

**OTOLITHS**

Otolith ablation in cats causes alterations in the extensor muscle tonus of both the homolateral limbs and contralateral cervical musculature. The head-righting reflex is diminished, and there is a loss of the compensatory eye movements that result from the alteration of head positions in space. Experimental evidence suggests that the otoliths detect changes in gravitational and inertial forces and are responsible for the orientation of the head and body in space and for the nystagmus produced by linear acceleration; however, an extensive literature search found no experimental evidence to support the general belief that the otoliths are responsible for COCT.44

Electrical stimulation of the cat’s otolith apparatus and utricular nerve produced torsional movements, smooth vertical or horizontal movements, and horizontal nystagmus.45 Stimulation of the utricle produced horizontal eye movements, whereas stimulation of the saccule caused vertical eye movements. In these experiments, the eye movements could not be correlated with those of the head. An alternative interpretation of these findings is that the eye movements resulting from unilateral utricular stimulation are part of a stabilizing mechanism that keeps the eyes and head in equilibrium in all positions of head tilt. The midbrain’s so-called neural integrator for torsional movements may also have an inhibiting and stabilizing function rather than an excitatory function.29

**CONCLUSIONS**

The function of the intermittent torsional movements is probably to dampen the possible harmful effects of head movement on the retinas, thereby allowing the retinas to rapidly and precisely orient to new head positions. When head or body tilt causes the fixation object to be out of view, the saccades anticipate a new orbital position and fixation object.47
Torsional eye movements have the same characteristics as movements induced by rotation of the head around a horizontal or vertical axis. The difference is that torsional movements take place around an anterior-posterior axis. They are probably caused by stimulation of the semicircular canals and not the otoliths. The otoliths may counteract the effects of gravity and contribute to the stability of the eyes and head in space. In any sequence of head movement, the vestibular apparatus acts as integrated wholes. When the head comes to rest in any position tilted to the shoulder or horizon on earth, the eyes and head establish a dynamic equilibrium in which there is no COCT. In this state of equilibrium, the large-scale, visible (macroscopic) eye movements are absent. Although the eyes do not appear to be moving during fixation, they are moving microscopically back and forth across the foveae in flicks, drifts, and tremors. This dynamic equilibrium between the retina and the brain is the same in all positions of steady head tilt (and in all steady head positions). Imagine the computational burden placed on the brain if for each position of the brain in space, there were varying retinal correspondence. The absence of static COCT provides additional evidence for the validity of the Donders law.

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