We analyzed pursuit racking eye movements from selected neurological patients and compared them to the responses of 20 normal subjects. The patients/subjects tracked a small spot of light moving sinusoidally in the horizontal plane at a frequency of 0.4 Hz and a peak-to-peak amplitude of 40 °. The eye-movement responses were separated into a smooth-pursuit component and a saccadic component. We calculated the asymmetry as well as the gain and phase response of the smooth-pursuit component. The saccadic component was quantified by calculating the percentage of the total tracking movement contributed by the saccadic system. The patients with smooth-pursuit impairment exhibited a higher percentage of saccadic tracking and a lower smooth pursuit gain compared to the normal subjects. One patient with a unilateral lesion exhibited significant asymmetry in the smooth-pursuit component. In this case, the direction of the asymmetry indicated the side of the lesion.
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The Application of Smooth Pursuit Eye Movement Analysis to Clinical Medicine

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Pursuit tracking eye movements were analyzed from selected patients with neurological injuries and compared to the responses of 20 normal subjects. The patients/subjects tracked a small spot of light moving sinusoidally in the horizontal plane at a frequency of 0.4 Hz and a peak-to-peak amplitude of 40°. Eye-movement responses were separated into a smooth-pursuit component and a saccadic component. The smooth-pursuit component was analyzed by calculating the gain, phase, and asymmetry. The saccadic component was quantified by calculating the percentage of the total tracking movement contributed by the saccadic system. The patients with smooth-pursuit impairment exhibited a higher percentage of saccadic tracking and a lower smooth pursuit gain compared to the normal subjects. One patient with a unilateral lesion exhibited significant asymmetry in the smooth-pursuit component. In this case, the direction of the asymmetry indicated the side of the lesion.

The smooth pursuit (SP) eye-movement system operates in concert with the saccadic system to allow visual acquisition and tracking of moving targets (Fig. 1). Saccades are rapid eye movements of refixation that enable one to quickly place the image of a target on the fovea. SP movements are generated to maintain the image on the fovea as the target moves. Saccades are high velocity (up to 800°/s), short duration (20-120 ms) eye movements during which vision is suppressed. SP movements have a maximum velocity of about 50 to 80°/s, but visual acuity is maintained during SP. Normally, tracking a target moving smoothly at a modest velocity generates predominately SP eye movements interspersed with a few “catch-up” saccades. If the SP system becomes impaired, the saccadic system is called into action more often as the SP system fails to keep pace with the target motion. Complete failure of the SP system results in “staircase tracking” consisting of a continuous sequence of pure saccadic eye movements.

A number of clinical tests of the SP system have been reported over the last 20-25 years (1-3,10-12). The early tests consisted of having patients track a swinging pendulum and recording eye movements using standard electrooculography (EOG). The recordings were analyzed by visual inspection. Increased saccadic tracking was taken as an indicator SP dysfunction, and unilateral lesions were often found to cause impairedSP tracking toward the side of the lesion (2,3). Later, computer driven displays and computer analysis of the recordings were developed. We began to explore computerized SP testing at the Armstrong Laboratory in the late 1970's (4,13). In 1989 we replaced our EOG eye-movement recording system with an infrared reflectance system, and upgraded our data analysis procedures (7). Since that time we have developed new, more powerful methods to analyze eye movements using nonlinear adaptive digital filters (8,9). These new analysis methods, originally developed for the analysis of nystagmus, have enabled us to implement a new, more sensitive test of the SP eye-movement system. We are now able to accurately separate the eye-movement responses into an SP component and a saccadic component and analyze each component separately.

METHODS

Subjects

We tested 20 normal subjects ranging in age from 21 to 38; median age was 29. There were 13 men and 7 women. Subjects were all active duty military personnel with no history of disease or injury that might affect tracking performance. All subjects were briefed as to the purpose of the research and the testing procedures to be used. The voluntary, fully informed consent of the subjects used in this research was obtained as required by Air Force Regulation 169-6. In addition to the normal subjects, a number of selected patients with neurological problems were tested to assess the effect of known lesions on SP tracking.
Fig. 1. Simplified block diagram of the pursuit tracking system. Differences between the target and eye position signals produce a delayed error signal, e(t). If e(t) exceeds a certain threshold, the saccadic system is activated causing a refixation of the eye movement to reduce the error to near zero. As the target moves, the SP system will act to match the eye velocity to the target velocity. If the target motion is smooth and the SP system is successful in keeping e(t) small, few saccades will be produced. Failure of the SP system to keep e(t) small results in more frequent activation of the saccadic system. In this simplified model, the combined tracking response (eye position signal) is the sum of the saccadic system and SP system outputs.

Data Analysis

Subjects/patients were instructed to track a small spot (628 nm) of red light moving sinusoidally in the horizontal plane while the movements of both eyes were recorded. The target was generated by a 1-mW He-Ne laser. A General Scanning G-300DP scanner and a General Scanning CCX-650 controller provided the target motion. The target was projected onto a curved screen located 2 m in front of the subject. Target motion was sinusoidal, with a peak-to-peak amplitude of 40° and a frequency of 0.4 Hz. Peak target velocity was 50.3°/s. The subject’s head was stabilized by means of a bite bar. Eye movements were recorded using a modified version of the infrared reflectance device previously described by Engelken et al. (6). A Compaq DeskPro 386/33 computer equipped with an Analog Devices RTI-802-8 digital-to-analog converter and an RTI-800-A analog-to-digital converter were used to generate driving signals for the scanner and digitize the eye-movement responses. The eye-movement signals were digitized to a resolution of 12 bits at a rate of 125 Hz. The eye-movement signals and the target position were stored in files on the hard disk for later analysis.

Apparatus

Subjects/patients were instructed to track a small spot (628 nm) of red light moving sinusoidally in the horizontal plane while the movements of both eyes were recorded. The target was generated by a 1-mW He-Ne laser. A General Scanning G-300DP scanner and a General Scanning CCX-650 controller provided the target motion. The target was projected onto a curved screen located 2 m in front of the subject. Target motion was sinusoidal, with a peak-to-peak amplitude of 40° and a frequency of 0.4 Hz. Peak target velocity was 50.3°/s. The subject’s head was stabilized by means of a bite bar. Eye movements were recorded using a modified version of the infrared reflectance device previously described by Engelken et al. (6). A Compaq DeskPro 386/33 computer equipped with an Analog Devices RTI-802-8 digital-to-analog converter and an RTI-800-A analog-to-digital converter were used to generate driving signals for the scanner and digitize the eye-movement responses. The eye-movement signals were digitized to a resolution of 12 bits at a rate of 125 Hz. The eye-movement signals and the target position were stored in files on the hard disk for later analysis.

The combined tracking performance includes contributions by both the SP and saccadic systems. We quantified combined tracking by calculating the gain and phase response using the target signal as the system input and the eye position signal as the system output. In order to quantify the relative contributions of the SP and saccadic systems to the combined performance, we calculated a parameter called Percent Saccadic Tracking (PST). PST was defined as:

\[
PST = \frac{\int_{0}^{T} |\text{SAC VEL}| \ dt}{\int_{0}^{T} |\text{EYE VEL}| \ dt} \times 100\%
\]

where SAC VEL is the saccadic velocity signal (Fig. 2, trace 5) and EYE VEL is the eye-velocity signal (Fig. 2, trace 3). The integrations were carried out over the 8 cycles (20 s) of tracking. PST represents the percentage of the tracking eye movements contributed by the saccadic system. A PST of 10 indicates that 10% of the combined tracking response is due to saccadic tracking.
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The SP tracking component was analyzed separately. SP was quantified by calculating the gain and phase response of the SP component using target velocity as the input and SP velocity as the output. In addition, we calculated the asymmetry of the SP component. Smooth Pursuit Asymmetry (SPA) was defined as:

$$SPA = \frac{\int_0^{t_0} SP \ VEL \ dt}{\int_0^t |SP \ VEL| \ dt} \times 100\%$$

where SP VEL is the SP eye-velocity signal (Fig. 2, trace 4). These parameters were computed for all 20 subjects and statistically analyzed to determine the mean values and the 95% confidence limits for future measurements. We also tested the parameters for right-eye, left-eye differences.

RESULTS

The results of the statistical analysis of our normal data are summarized in Tables I and II. Table I presents the analysis of the combined tracking performance; Table II, the analysis for the SP component. No significant differences between right and left eye responses were found. The results presented in the Tables represent pooled responses from both eyes. The combined tracking response includes the contribution of the saccadic component and yields higher gain than the SP component, as expected.

CASE REPORTS

In addition to the 20 normal subjects, we also tested several patients with known or suspected neurological problems. The following case reports represent typical findings.

Case Report 1

A 23-year-old foreign pilot trainee suffered a minor head trauma in a motor vehicle accident. He received a head CT scan for the head trauma and an incidental, 6-cm left temporal subarachnoid cyst was discovered. He denied headaches, hearing loss, tinnitus, otalgia, vertigo, imbalance, and facial nerve dysfunction. Although his left anterior ventricle was mildly effaced, he suffered no hydrocephalic symptoms. Otolaryngologic and neurologic examinations were normal.

Complete audiogram and auditory brain stem responses (ABR) were normal. Electronystagmography and EquiTest® dynamic platform posturography were normal. Smooth pursuit eye tracking (Fig. 3B) was normal with SP gain of 0.97 (normal 0.825 to 1.05) and a PST of 7 (normal 1 to 20).

Neurosurgical and neurology consultants recommended that surgical resection or shunting was not indicated at this time for a probable congenital, slowly enlarging subarachnoid cyst. He was not recommended for flight duties.

Case Report 2

A 28-year-old active duty bomber pilot with a 3-year history of gradual left-sided hearing loss and tinnitus presented to his flight surgeon in 1989 with headaches that occurred when he jumped, sat down hard, or laughed. Otolaryngology examination was normal except for a left hearing loss. Head CT scan revealed a 5 × 6 cm left acoustic neuroma.

Surgical resection required two stages, approximately 6 months apart. After the first surgery he developed an E. coli meningitis that was treated with intravenous and intrathecal gentamicin. His facial nerve was stretched by the primary tumor and became dysfunctional after the first surgery. He later underwent a VII–XII nerve anastomosis with minimal improvement in facial motor function. He slowly regained his balance.

Examination at the Aeromedical Consultation Service 2 years after his last surgery demonstrated a total hearing loss on the left, House grade III of VI facial motor function (tone at rest, decreased motor function with synkinesis and 7-mm lid lag), a normal Romberg but an abnormal tandem Romberg.

Audiovestibular testing revealed normal right audiogram and ABR, with anacusis on the left. EquiTest® dynamic platform posturography was abnormal in the sensory organization test conditions 5 and 6. Rotary chair testing of his vestibulo-ocular reflex revealed the expected low-frequency phase shift and decreased gain. His rotary chair response demonstrated normal symmetry, suggesting compensation for his unilateral vestibular loss. His SP tracking was severely impaired (Fig. 3C), especially when tracking to the left. SP gain was 0.45 (normal 0.825 to 1.05), PST was 57 (normal 1 to 20), and SPA was 53% (normal -7 to +7). He was not returned to flight duties.

DISCUSSION

Our analysis of pursuit tracking is based upon separating the tracking eye movements into SP and saccadic components. A normal subject (or patient with an intact SP system) should rely principally on SP eye movements to track the target used in our test. Low SP gain, increased PST and SPA are the chief indicators of pursuit tracking dysfunction. In Case Report 1, a patient is presented with a large subarachnoid cyst that did not compromise his SP tracking performance. The tracking test results complement the physical examination and the pathophysiologic characteristics of the lesion; i.e., a slowly enlarging nondestructive cyst.

The patient discussed in Case Report 2 presents...
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Fig. 3. Tracking record of a normal subject is shown in (A); tracking records for the patients discussed in Cases 1 and 2 are presented in (B) and (C), respectively. The eye position trace represents the combined tracking response and is the sum of the SP and saccadic components. Units of measurement are degrees of movement.

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