HEAD AND EYE TRACKING FOR STUDY OF THE VOR DURING NATURAL HEAD MOTION

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Abstract- Rotational testing of the vestibulo-ocular reflex (VOR) does not always correlate with patients' symptoms. One possible reason is that conventional testing is performed at low frequencies and relatively low velocities that do not correspond to the high frequency perturbations encountered during locomotion. We present a combined head-eye tracking system suitable for use with free head movement during natural activities. The system was used to study the response to rapid passive head turns in normal subjects and patients with unilateral lesions. The patients have marked, persistent VOR deficits for rotation toward the side of lesion. The implications of these results on the organization of the normal VOR and the process of VOR compensation are discussed.

Introduction- The vestibulo-ocular reflex (VOR) generates compensatory eye movements in response to head motion sensed by the vestibular sense organs in the inner ear. To maintain stable gaze (eye position in space) during head rotation, the VOR should generate eye rotation of equal magnitude (unity gain) and opposite direction (by convention, 0° phase). In normal subjects the VOR comes very close to this ideal for the frequency range of natural head motion [1].

Laboratory tests of the VOR are important in the diagnosis of dizziness, ataxia, vertigo and hearing loss. Testing is performed at low frequencies (e.g., 0.1 Hz) of rotation in a horizontal plane. However, the VOR is physiologically relevant during activities such as locomotion where the predominant head perturbations are between 0.5 and 5 Hz and mainly in pitch [1]. Patients who show recovery to low frequency testing often complain of poor vision and oscillopsia during locomotion. The ability to study the VOR under natural conditions with free head motion could allow development of tests that correlate well with symptoms.

The standard clinical method of recording eye movements, electro-oculography, suffers from low resolution, drift, noise, poor vertical measurements, and motion and EMG artifacts that limit its use during locomotion and other natural activities [2]. The standard research technique, magnetic scleral search coil [2], is limited in a clinical setting due to discomfort, limited recording time and risk of corneal abrasion or lead breakage. The requirement to stay in the center of the magnetic field precludes the use of search coils during many natural activities.

To address these concerns we have developed a head and eye tracking system for use during free head movement. The utility of this new system is demonstrated by repeating and extending Halmagyi's [3] test for determining the side of unilateral peripheral lesions. This high frequency, high velocity step test can complement the information obtained from low frequency caloric tests. In this test, the patient's head is turned rapidly to one side while the eyes are observed. If VOR gain is adequate the eye will move opposite to the head and maintain stable gaze. If inadequate, the eye will not move enough and several visible catch-up saccades (quick refixation movements) will be required to maintain gaze. In patients with total unilateral vestibular loss, the gain quickly recovers for rotation away from the side of lesion but remains significantly depressed for rotation towards the lesion. These results have implications for understanding and modeling of the normal VOR, its adaptive capabilities and the mechanisms of compensation to a vestibular lesion.

Methods- We have developed a combined head and eye tracking device based upon an infrared Video eye Tracking System (VTS, EL-MAR Inc. 2020) and a magnetic head tracking system (Flock of Birds, Ascension Technology Corp.). The VTS provides real time (120 Hz) estimates of vertical and horizontal positions of both eyes as well as pupil size. The VTS is based upon estimation of the distance of multiple corneal reflections to the center of the pupil [2] and has system noise with standard deviation of less than 0.05° and a linear range of ±40° (±30° vertically) [2]. To track head movements, a small receiver mounted on the VTS goggle frame senses a pulsed magnetic field transmitted from a larger, earth fixed unit. The head tracker transduces head position (x, y, z) and orientation (azimuth, elevation, roll) in 3 dimensions. The head tracker has system noise of 0.1° RMS and a 180° linear range.

We calculated the point of regard in 3-D during steady fixation under a variety of head movement conditions. In the light, the VOR (enhanced by vision) is nearly ideal [1]. Thus the ability of the combined system to provide line of sight estimates that were within ±1° of ideal demonstrates that the dynamics and delays of the eye and head tracker were properly matched. During head oscillation the eye and head velocities were highly correlated ($r > 0.98$) and calculated VOR gain and phase were consistent with reported values [1].

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Using the integrated system we studied the response to rapid head movements in normal subjects (N=4) and patients (N=4) after compensation from therapeutic unilateral vestibular ablation (by vestibular neurectomy). Rapid, passive, horizontal head turns [3] (10-20°, > 150 °/s peak velocity, > 1500 $°/s^2$ peak acceleration) were delivered manually while the subject fixated an LED at 1.2 m. Timing and direction of the passive head movements were randomized to eliminate prediction. Data contaminated with blinks, saccades or artifact were identified and removed from the analysis. Head and eye data were low pass filtered at 20 Hz and digitally differentiated. To eliminate visual contributions only the first 100ms of the response to the head turn was considered (visual tracking has a latency > 100ms).

Results- In normal subjects the eye velocity is highly correlated (r > .98) to the head velocity and no nonlinearities can be seen. Gain is symmetrical for both directions of head motion (see figure 1) and is always close to or above unity (range .89-1.36).

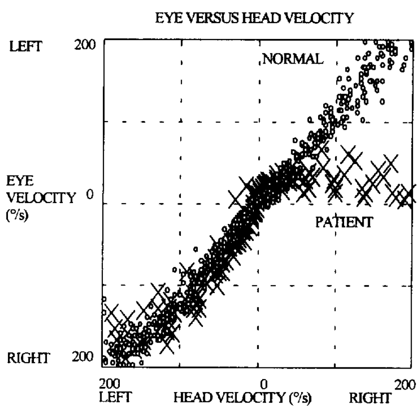

Figure 1: Eye versus head velocity during first 100 ms of the rapid head turn. Data from a normal subject (o) and a patient (x) with a right lesion are shown.

As in Halmagyi's work the neurectomy patients show a marked reduction in gain (range .04-0.68) during rotation towards the side of lesion. Compensatory eye movements are very small and catch-up saccades (quick refixation movements) are typically required. This reduction in gain is apparent at even low head velocity (see figure 1). Rotation towards the intact side elicits eye movements with a normal or slightly reduced gain (0.62-1.38).

Discussion- Head rotation is sensed by the three semicircular canals located in the inner ear. The lateral canals in each ear are arranged so that they sense horizontal rotational velocity. The canals operate in a complementary fashion so that the neural response from one canal increases when the other decreases. Central addition of the response from both ears occurs in the brainstem and drives the compensatory eye movements in a push-pull manner. This helps to linearize the response and adds redundancy to the system.

Primary sensory afferent neurons have a resting firing rate which is increased for ipsilateral rotation (towards the side of the canal) and decrease firing for contralateral rotation [1]. During contralateral head rotation the afferent firing rate reduces to zero and saturates at a velocity of approximately 180°/s. Halmagyi [3] suggested that this phenomenon could explain the deficit seen in unilateral patients during rapid head turns. Quantitative analysis of models of the VOR and afferent firing patterns has demonstrated that this explanation is not sufficient to explain the degree asymmetry at velocities well below 180°/s.

We will present a model which can explain the deficits to rapid head turns in patients with unilateral lesions. This model considers two groups of primary afferents: one with a regular and one with an irregular resting firing rate[4]. Irregularly firing afferents exhibit a high frequency gain enhancement and phase lead indicating an acceleration sensitivity. The regular afferents are much less frequency sensitive. The regulars have the largest anatomic projection to VOR interneurons and evidence suggests that the irregulars make no functional contribution to the normal VOR [4]. In this model, we propose that the irregular afferents play an important role in the adaptive VOR pathways. We will discuss the implications of this model on the organization of the normal VOR and the mechanisms of vestibular compensation.

Acknowledgments- To NSERC (Canada) for a fellowship to R.Allison. To MRC for grant MT-11339 to M.Eizenman.

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