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OFF-LINE COMPUTING OF SLOW-PHASE EYE VELOCITY PROFILES EVOKED BY VELOCITY STEPS OR CALORIC STIMULATION

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We describe a method to compute the slow-phase eye velocity profile without explicit removal of quick phases. It can be used for off-line analysis of eye movements evoked by angular head velocity steps or caloric stimulation. Zero-crossings of eye velocity from negative to positive values divide the velocity trace into intervals of different length. In each interval, the velocity data points are sorted in an ascending order. The value at the least slope (mode value) is taken as the representative slow-phase velocity for the processed interval. Spline interpolation between the representative points of all intervals results in an envelope that gives an accurate description of the slow-phase velocity over time and is used to determine parameters such as peak slow-phase velocity, time constant etc. The method can easily be implemented on a computer.

Keywords: Eye movements; Nystagmus; Vestibulo-ocular reflex; Caloric tests; Computer analysis; Software

Introduction

A number of methods to digitally process slow eye movements evoked by velocity steps or caloric stimulation have been proposed (e.g. Refs. 1–3). Most procedures are based on the removal of quick phases. However, this can only be achieved interactively since no algorithm proves reliable enough to automatically remove all eye movements which are not slow phases (quick phases, saccades, blinks). The interactive elimination of such eye movements is time-consuming. Therefore it is desirable to have a method at hand which does not depend on an explicit identification of fast eye movements, but still produces an accurate outline of the slow-phase eye velocity as a function of time. In this paper we propose a method which fulfils this requirement and can easily be implemented on a computer.

Methods and Results

The different procedural steps of our algorithm are illustrated on a sample of horizontal nystagmus obtained from a juvenile rhesus monkey (Fig. 1A). The

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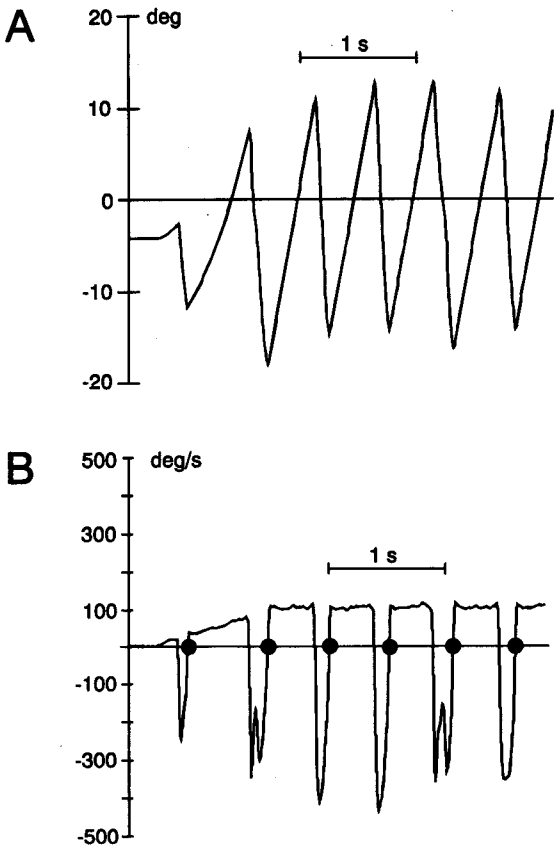

Fig. 1. Beginning of horizontal nystagmus. A monkey in upright position is accelerated in the dark from 0 to 120 °/s with 100 °/s^2. (A) Digitized and calibrated eye position trace (sampling rate 833 Hz). (B) Corresponding velocity signal. Note that the slow-phase plateau shows some normal physiological fluctuation. Taking the maximum slow-phase velocity as a representative value for each nystagmic cycle would yield considerable velocity noise between cycles. The marks divide the velocity data into intervals of different length. A mark is set where the trace crosses the zero line from negative to positive values.

animal, seated in a primate chair, was accelerated in the dark from 0–120 °/s with 100 °/s^2 about an earth-vertical axis. The animal's head was fixed to the chair with chronically implanted head bolts, whereby the stereotaxic horizontal plane (defined by the lower orbital rims and the interaural axis) was tilted 15° in the nose-down direction to position the lateral vestibular canal planes perpendicular relative to the rotation axis. Eye movements were recorded with the search coil technique [4] (Type 3000 Eye Position Meter manufactured by Skalar Instruments, Delft, Netherlands). Technical details and surgical procedures are described elsewhere [5]. For calibration, the animal was trained to fixate light dots on a screen. During experiments, analog coil signals were digitized with a sampling frequency of 833 Hz using a 12 bit A/D converter (Cambridge Electronics Device 1401) and stored on the hard disk of a personal computer.

Each step of the procedure is implemented in a separate program (written in *ANSI C* computer language). The programs are consecutively run in batch mode without interaction with an operator. On an IBM PS/2 Model 80, equipped with a floating-point co-processor, the analysis of a file containing 100 s of horizontal eye position traces takes around 400 s.

Step 1

The data of the entire experimental run is filtered and differentiated using a digital polynomial filter [6]. A window with a length of 31 data points, corresponding to 37.2 ms at the given sample frequency, is moved over the signal; the data points are least-square fitted, the resulting function is differentiated and solved for the central window point (Fig. 2A).

Step 2

The computer determines each zero crossing of eye velocity from negative to positive values and places a mark (Fig. 1B). In the example presented, 121 marks are set, which results in 120 intervals of different length. Only intervals with a time length of more than 100 ms, in our example 113 intervals, are further processed.

Step 3

All velocity data points within each separate interval are sorted in an ascending order (Fig. 3). The arrangement of the sorted data is always similar; quick-phase data are in much steeper sections than slow-phase data. Using a window with a size of 10 points, the location of the smallest slope is determined; the corresponding value is accepted as the representative slow-phase velocity for the given interval. In other words, we select the central value of the region with the highest velocity density (mode value). The duration from the beginning of the experimental run to the middle of a given interval yields the corresponding time stretch (Fig. 4).

Step 4

Cubic spline interpolation between the computed points [7] produces the slow-phase velocity envelope, which is then slightly filtered (running average over 1 s) (Fig. 2B). Parameters such as maximal slow-phase velocity and time constant can now easily be determined.

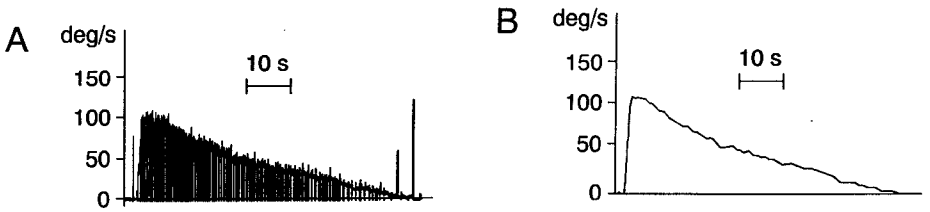

Fig. 2. Eye velocity data of the entire step response. (A) Horizontal velocity trace. The position data have been differentiated by a least-square procedure. For this figure, as the nystagmus direction was known and did not change, fast phases are clipped at an arbitrary level near zero velocity. The envelope of the slow-phase velocity can roughly be estimated by eye. (B) Corresponding slow-phase velocity envelope.

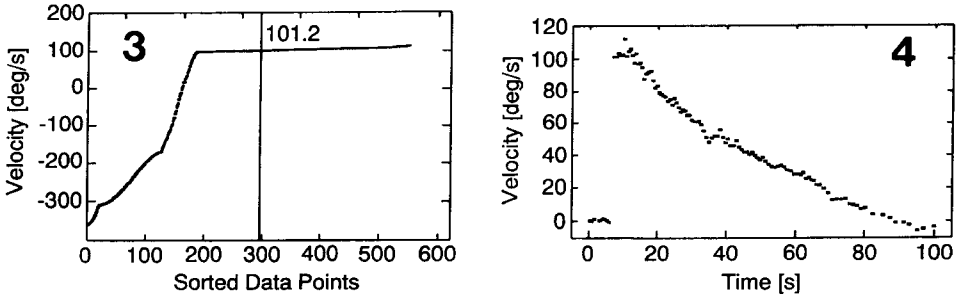

Fig. 3. Sorted velocity data points of the second interval in Fig. 1B. A window with a size of 10 points is moved over the data to determine the location of the smallest slope, indicated by the vertical line. The value at this location is taken as the representative velocity for the nystagmic slow phase (mode value). Since movements with sudden velocity changes, like quick phases, saccades and blinks, will always yield data points with lesser density than slow phases, this procedure proves to be very robust.

Fig. 4. The representative velocity values of all nystagmus slow phases are plotted over time. These data points can now be splined (see Fig. 2B).

Our method also gives adequate results for data obtained by caloric stimulation (Fig. 5A,B). The monkey, placed in the supine position, was irrigated with 10 ml of cold water (temperature 20°C).

Discussion

A practical method for obtaining the slow-phase velocity profile of digitized eye position traces has been described. The procedural steps were demonstrated for a vestibular velocity step. The method is also suited for the analysis of caloric nystagmus. It proves to be very robust against disturbances, like eye blinks or forward saccades, and does not rely on an explicit identification and removal of quick phases. As a consequence, it is not depending on interactions with a human operator; this greatly speeds up data analysis. Compared to interactive procedures [e.g. 3] our method leads to velocity profiles of similar accuracy with respect to the original unprocessed velocity signal. The algorithm is simple, and only a few

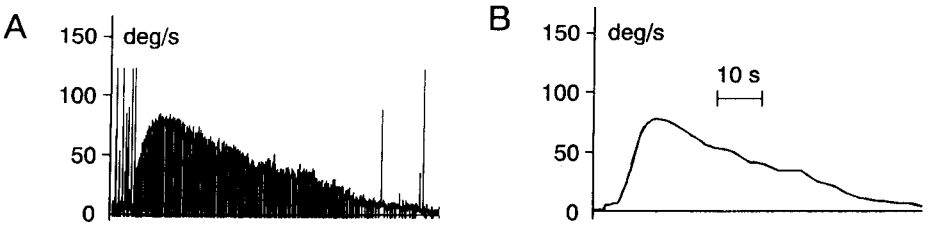

Fig. 5. Caloric stimulation with cold water (10 ml, 20°C) of a monkey in supine position. Eye movements were recorded in the dark. (A) Horizontal velocity trace. (B) Corresponding slow-phase velocity profile.

parameters have to be adjusted according to particular noise levels and sampling frequencies. It should be noted that, as in other procedures, the sampling frequency of A/D conversion must be high enough [8]. Our algorithm will underestimate slow-phase velocities if there is not a sufficient amount of data points to determine the mode value of an interval using a reasonable window size.

The described method can be applied whenever velocity changes during single slow phases are not critical for the analysis. In the case of sinusoidal vestibular stimulations, more sophisticated procedures with precise separation of fast and slow eye movements are appropriate [9]. Our algorithm implicitly follows the rules of visual inspection. Using hand analysis, one identifies a valid slow phase by its constant velocity and then measures the velocity over that part where it changes minimally (i.e. the mode value in our algorithm). Such single velocity values from all slow phases then form the profile for further analysis.

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