On Signal Analysis of Three-dimensional Nystagmus

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Introduction

There are three semicircular canals in the inner ear. They are located perpendicularly to each other. Disorders in their function cause balance problems such as vertigo.
Nystagmus is a repeated, bias, "saw-tooth" eye movement. It is reflexive, for example stimulated by injecting cool or warm air or water (37±7 °C) to a subject’s ear canal. For otoneurological patients nystagmus may **spontaneously** be induced by a disorder of a semicircular canal located in the inner ear.
Video-oculography with small videocameras directed at each eye has become a promising way to measure three-dimensional (3D) eye movements. It includes 1D horizontal, vertical and torsional (rotational) components.

Measurements are gaze angles [°] in three separate 1D signals. To consider nystagmus, we computed angular velocity curves (approximated first derivatives) from horizontal, vertical and torsional signals. The average angular velocity ($spv$) of the slow phase of each nystagmus beat was computed with linear regression. The mean of the $spv$ values of a signal was used.
Spontaneous nystagmus of 30 s: The blue curves are the horizontal signals, the green curves are the vertical signals, and the red curves (with noisy spikes for the right eye) are the torsional signals. A nystagmus beat includes a slow phase (down in the figure) followed by the fast phase in the opposite direction.
We also studied a hypothesis called J.R. Ewald’s first law originally from 1892: *the trajectory of nystagmus induced by a semicircular canal ought to reflect the anatomic orientation of that semicircular canal*. This had remained a hypothesis since, e.g., the positions of the canals of living subjects had not obviously been studied earlier than a few years ago.

Nystagmus induced by a horizontal semicircular canal is mostly horizontal. Nystagmus from anterior or posterior semicircular canals is assumed to be mixed torsional and vertical, since these canals are oriented diagonally.
Recordings were performed with small videocameras embedded in a mask (3D VOG Video-Oculography, Sensomotoric Instruments, Berlin, Germany). The subject was not allowed to move his head while recording. Sampling frequency was 50 Hz.
Before a 30 s recording, the calibration was made by asking a subject to alternately look at nine points located symmetrically on the wall. After the calibration the amplitude resolution is better (<) than 1°.
The eyes were covered and a subject was in a dim room, since spontaneous nystagmus (if any) of a patient then appears as it largest. Every measurement included 30 s (1500 samples).
The torsional quality signals given by the recording device were used successively to choose a better 2 s segment from two signal triples (better "eye"): the greater the average quality, the better torsional signal. There were spikes in the torsional signal of the right eye. Thus its quality was mostly poorer.
At first, the head of a subject is rotated 10° up round the vertical axis to set the horizontal semicircular canals equal to the gravity coordinate space. Thus the "anatomic" space is similar to that of video-oculography.
(1) Choose the better mean of 2 s torsional quality signal segments (the "better" eye). This is usually better than 0.5 (from [0,1.0]). This is repeated for all consecutive 2 s segments of the signals measured.

(2) Using linear regression (its slope) compute angular velocity curves for all three signals of each eye.

(3) Compute the direction of the slow phases of a nystagmus signal by counting whether the majority of velocity values are either positive or negative. We obtain the directions: horizontal right or left, vertical up or down, and rotational clockwise or counterclockwise.
(4) Using the "better" eye compute nystagmus beats of each 2 s segment by searching for pairs of the consecutive minimum and maximum from each velocity curve. Reject such that include poor torsional average quality values (lower than approximately 0.4).

(5) Using linear regression compute average angular velocities of all slow phases.

(6) Reject as probable outliers: if one or more of the components (horizontal, vertical or torsional) of a single nystagmus beat are, according to normal distribution, among the smallest or greatest of 5 % of all velocity values. Outliers are possible for the sake of noisy peaks or other artifacts in eye movement signals. Thus, at most $2 \cdot (5+5+5) = 30 \%$ of slow phase values are pruned.
(7) Compute three-dimensional directional unit vectors from the velocity components of the nystagmus beats.

(8) Draw a unit sphere to (functionally, not anatomically) model the head for the slow phase velocities \( spv. \) The horizontal rotation corresponds to the vertical axis, the torsional axis is pointed by the nose, and the vertical axis comes out from the left ear. (This is the subject’s gaze, not that of the spectator.)

(9) Set the normal vectors (C. C. Della Santina et al., Journal of the Association for Research in Otolaryngology, 6: 191-206, 2005) of the planes of the semicircular canals onto the sphere.
(10) Set the unit velocity vectors on the sphere and compute their mean.

(11) Compute angles between the mean vector and the normal vectors of the semicircular canals.

(12) The least angle or nearest normal vector predicts which semicircular canal can be the source of a balance disorder.
Example

The blue dots are the unit velocity vectors. The black line shows their mean vector. The green lines indicate the normal vectors of the planes of the semicircular canals. RH is the nearest with 4° angle (L=left and R=right inner ear; A=anterior, P=posterior and H=horizontal semicircular canal; SPV=slow phase velocity [°/s]).
Results

Recording and analysing signals of 28 patients we obtained the following results. Such patients were selected that were known to have a unilateral peripheral balance disorder.

Table 1. Means and standard deviations of the slow phases of the nystagmus beats recognized when three velocity values were computed from the accepted beats.

<table>
<thead>
<tr>
<th>Number of nystagmus beats before pruning</th>
<th>Number of nystagmus beats after pruning</th>
<th>Horizontal velocity [°/s]</th>
<th>Vertical velocity [°/s]</th>
<th>Torsional velocity [°/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>45.9±17.3</td>
<td>33.0±13.4</td>
<td>7.6±5.1</td>
<td>2.4±2.3</td>
<td>3.4±2.7</td>
</tr>
</tbody>
</table>
Table 2 includes average angles between the mean unit vectors of the nystagmus beats accepted and their nearest normal unit vectors. These results denote the planes of the horizontal semicircular canals.

Table 2. Means and standard deviations of the angles between the mean vectors and the nearest normal vectors representing the six semicircular canals.

<table>
<thead>
<tr>
<th>Normal</th>
<th>Left anterior</th>
<th>Left horizontal</th>
<th>Left posterior</th>
<th>Right anterior</th>
<th>Right horizontal</th>
<th>Right posterior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>Angle [°]</td>
<td>-</td>
<td>19.6±8.8</td>
<td>-</td>
<td>-</td>
<td>16.5±10.2</td>
<td>-</td>
</tr>
</tbody>
</table>
Conclusion

The results support Ewald’s first law.

The method can be used as a means to reveal unilateral disorders of semicircular canals. In unilateral weakness, the normal side drives the nystagmus, but in unilateral stimulation, the stimulated (over-exited) side determines the vector orientation.