A novel haploscopic viewing apparatus with a three-axis eye tracker

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PURPOSE To validate the accuracy and precision of a novel haploscope for use in investigating the mechanisms underlying normal eye control as well as the mechanisms of cyclovertical strabismus in pediatric and adult subjects. The accuracy and precision represent the device's ability to reproducibly measure true eye positions.

METHODS A novel haploscope was developed that allows the measurement of eye positions and movements under specified conditions of vergence, head tilting, and cover testing. Equipped with video oculography, the haploscope can aid in the objective assessment of binocular and adaptive mechanisms that maintain oculomotor alignment. The device's accuracy and precision were assessed using a model eye with 3 axes of rotation. The device was then used to measure ocular torsion during the well-documented phenomenon of ocular counter-roll with head tilt. The eye movements of 6 normal subjects were measured as each subject fixated binocularly on the center of radially symmetric targets during head tilting.

RESULTS The device yielded Pearson correlations with the model eye of $R = 1.0$, with residual error (*re*), a measure of accuracy, about all 3 ocular axes peaking at $re = 19 \pm 5$ arcmin. For human subjects, average positional error was $re = 21 \pm 9$ arcmin. Ocular counter-roll averaged $5.7 \pm 0.9°$ for left and right eyes.

CONCLUSIONS These results validate the accuracy and precision of this novel haploscope. They support its use in future investigations of the mechanisms of oculomotor control and alignment. (J AAPOS 2008;12:498-503)

Sensory heterotropia is a well-recognized phenomenon, although the mechanism underlying its development, proposed by Guyton in 1994,[1] has not yet been proved or widely accepted. In this proposed mechanism, sensory heterotropias develop when one eye loses vision to the extent that normal fusional reflexes to retinal image disparity are interrupted. This disruption causes the nonfixing eye to move to a fusion-free position and, over time, that eye may deviate farther and develop a sensory deviation, so named because of the lack of effective sensory input to maintain alignment. Horizontally, the most common sensory deviation is an exotropia.[2] Cyclovertical sensory misalignments of the eyes have proven more difficult to assess because of difficulty with objective, accurate, and precise clinical measures of ocular torsion and because of the contribution of multiple muscles to cyclovertical movements.

Several techniques offer objective measures of eye position and/or movement, including fundus photography, electro-oculography, and scleral search coils. Of these methods, scleral search coils are the most precise and accurate, producing measurements with best repeatability and closest to the true eye position, but they have limitations: the experimental apparatus is relatively elaborate, subjects must be extremely cooperative, and the awkward scleral coils preclude their use in children or in the general clinical setting. Because an extorted or intorted eye does not tort to right itself when viewing monocularly,[3] torsional deviations cannot be measured with the cover test. Hatamian and Anderson[4] exploited iris signatures in images to extract torsional information from video oculography. Van der Geest and Frens[5] found video oculography to compare well with measurements from scleral search coils. Using manual video oculography to measure the torsion accompanying vertical fusional vergence of the eyes, Enright[6] made key observations regarding cyclovertical muscle control that emphasized the importance of the superior oblique muscle in vertical fusional vergence.

With the aim of understanding the mechanisms involved in both binocular fusion and ocular misalignment, we designed and built a novel research haploscope. This device can measure simultaneous horizontal, vertical, and torsional eye movements binocularly with video oculogra-

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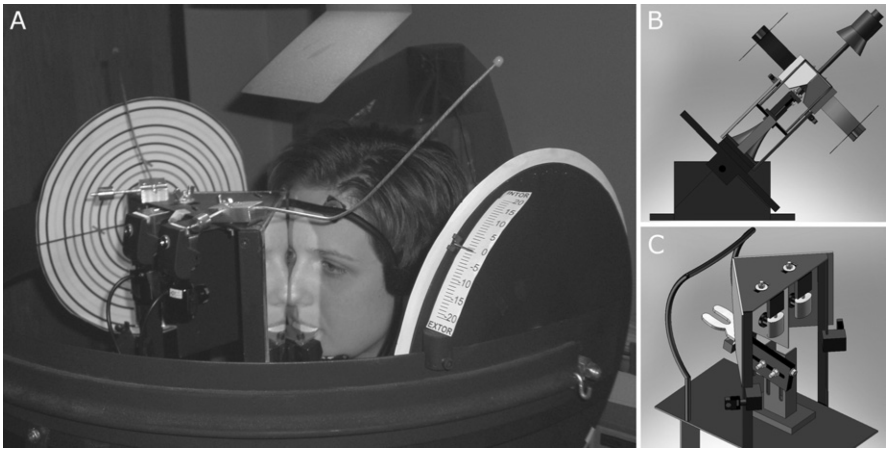

FIG 1. Haploscope. The device fully illustrated in 3 views. (A) Photograph with subject viewing. Note the angled mirror configuration, overhead lamp, bite bar, left and right cameras, and opposed viewing targets. These near targets at a 33 cm viewing distance each provide a field of view greater than 50°. (B) Illustrated front view, tilted right. Note the overall device design with wide base, capable of tilting 45° to the subject's left and right. (C) Illustrated oblique view, close-up. Note the configuration of the infrared cameras, which are mounted facing the subject, behind the angled mirrors.

phy. It also enables subjects to modify extraocular muscle forces ("vergence adaptation") by adapting to introduced amounts of binocular disparity. In sum, the haploscope enables the study of eye muscle behavior in various states of reproducibly induced vergence, fusion, or dissociation and head tilt in normal subjects and in patients with horizontal and cyclovertical strabismus. It is validated with a model eye under conditions identical to those used in human trials. We also examined ocular counter-roll, the tendency for both eyes to right themselves torsionally when the head is tilted to the right or left, to test the device's ability to measure this well-documented phenomenon.

Methods

Haploscope Design

The design specifications for the haploscope included the capability of measuring 3 dimensions of vergence—horizontal, vertical, and torsional. In addition, cover testing and head tilting had to be possible, as these are central to the routine evaluation of patients with cyclovertical deviations. A video presentation is available at jaapos.org (Video 1).

In general, a haploscope presents a different image, a viewed target, to each eye of the subject. The haploscope described here was modified from a discarded arc perimeter from the 1930s (Bausch and Lomb; Rochester, NY). A photograph and accurate schematic (Autodesk; San Rafael, CA) of the haploscope are provided in Figure 1. The subject's head was positioned at the device's façade. Directly in front of the subject's eyes were 2 cold mirrors (>90% visible light reflectance and >80% near infrared light transmission at an incidence angle of 45°; Edmund Optics; Barrington, NJ) mounted at 45° from the midsagittal plane. Target patterns for viewing were mounted 25 cm from either side of the subject's head, directly affixed to the arc perimeter's arms. Optically, they were approximately 33 cm from the respective eyes. The targets' reflections in the cold mirrors passed to each viewing eye separately, offering greater than a 50° field of view to each eye. Near infrared illumination was provided by 2 infrared-emitting diodes (OD-50L, 880 nm; Opto Diode Corp., Inc., Newbury Park, CA) mounted at the respective inferotemporal corners of the 2 mirrors. Two infrared-sensitive cameras (see below) were mounted just behind the cold mirrors to record the subject's eye positions and movements. The subject had to remain in a fixed viewing position and orientation with respect to the cameras. To achieve this constraint, the haploscope was outfitted with forehead mounts and an adjustable and lockable rigid bite bar. Each bite bar dental impression was custom-made using Kerr type I impression compound on an aluminum support plate (Kerr; Romulus, MI).

The target patterns were mounted on the ends of the perimeter's semicircular arc, which could be rotated from the fused horizontal position to different meridians, moving one target upward and the other one downward, inducing vertical disparity. The perimeter arc could be rotated about 20° in the roll plane (resulting in 40° of vertical disparity) before the 50° target began to fall outside the mirror reflection zone. The entire perimeter arc was mounted on a translating slide, allowing the targets to be moved fore and aft of the subject, providing precise adjustment of horizontal vergence. Finally, the entire haploscope, including the bite-bar-stabilized subject, could be tilted 45° to the left or right, maintaining the subject in a fixed viewing position across a variety of head orientations. The targets were 30 cm diameter discs displaying concentric rings of varied colors (3 mm line width, separated by 1 cm), centered on a solid dot (6 mm diameter), all on a white background.

Eye Tracking Apparatus and Data Acquisition

The eye tracking apparatus used video oculography, comprising 2 USB PC cameras: 4 SN9C120, 240 × 320 pixel resolution (Web Digital Camera; Hong Kong), equipped with Edmund Optics 12 mm fixed-focal-length lenses. These cameras interfaced with a Pentium 4, 2.99 Ghz desktop computer with 1.0 GB