Chapter 5

Electrooculography: technical standards and applications

W. Heide\textsuperscript{a,\*}, E. Koenig\textsuperscript{b}, P. Trillenberg\textsuperscript{a, c}, D. Kömpf\textsuperscript{a} and D.S. Zee\textsuperscript{c}

\textsuperscript{a}Department of Neurology, Medical University at Lübeck, Ratzeburger Allee 160, D-23538 Lübeck (Germany)
\textsuperscript{b}Department of Neurology, Neurological Hospital, Kolberger Strasse 72, D-83043 Bad Aibling (Germany)
\textsuperscript{c}Department of Neurology, Johns Hopkins Hospital, Pathology 2-210, 600 North Wolfe Street, Baltimore, MD 21287 (USA)

General description, physiological background, and comparison of different oculographic techniques

The term electronystagmography (ENG) refers to the recording of eye movements and nystagmus during fixation and in response to vestibular, visual, caloric, rotational, or positional stimulation. Typically, electrooculography (EOG) is the method used to record eye movements during ENG, with the exception that the classical EOG uses DC (direct current coupling) amplification, whereas ENG in clinical routine often uses condenser-coupled AC (alternating current coupling) amplification with a time constant of 5 or 10 s, resulting in a high pass filtered signal, in which slow baseline drifts are damped. Other methods for recording eye movements, especially when used to record ocular nystagmus, also have been labeled as ‘electronystagmography’, such as the term ‘video-ENG’ for computer-aided video-based eye movement recording systems.

Eye movement recording has been in use since the beginning of this century. Up to the 19th century, eye movements could only be monitored by an experimenter who was sitting closely to one side of the subject and watching his eyes (review: Carpenter 1988). Alternatively, subjects traced their own eye movements according to the path of a moving afterimage. Some of the first mechanical recording methods that required the suture of a lever system to the sclera are only of historical interest. Optical methods using a small mirror system attached to the sclera were more precise, but were also uncomfortable for the subjects and thus were also abandoned. Direct photographic recording is hardly used, because the evaluation procedure is time consuming and is presently replaced by computer assisted analysis of video images. A breakthrough was achieved in 1922 when the potential difference between the cornea and the retina, known as the corneo-retinal potential, was used for the recording of ocular nystagmus. This technique, called electrooculography (EOG), was introduced for diagnostic purposes in neurology and otology in the 1930s by R. Jung and others, and it is still the most widely applied technique for eye movement recording in clinical routine, used by otorhinologists and neurologists alike (review: Jung and Kornhuber 1964). Since the late 1950s, other techniques have been developed: infrared reflection oculography, photoelectric methods, the magnetic scleral search coil technique, and videoculography. All these eye movement recording techniques are still in use.

\* Correspondence to: Dr. Wolfgang Heide, Klinik für Neurologie, Medizinische Universität, Ratzeburger Allee 160, D-23538 Lübeck (Germany).
indicating that none of these methods is optimal for all recording purposes. The basic properties, applications, advantages, and disadvantages of the different techniques will be outlined in the following sections, whereas the second part of this paper (pp. 228–240) will deal only with EOG/ENG as the standard for clinical routine (Rottach and Heide 1997).

**Electrooculography (EOG)**

The technical principle of EOG and ENG is based on the fact that the eye acts as an electrical dipole between the positive potential of the cornea and the negative potential of the retina, maintained by means of active ion transport within its pigmented layer. This corneo-retinal potential difference ranges between 0.4 and 1.0 mV and is oriented along the line of sight (electrical axis), thus moving with the eye. In relation to a remote location, a skin electrode placed in the vicinity of the eye becomes more positive when the eye rotates towards it and less positive when it rotates in the opposite direction. For binocular horizontal EOG or ENG recordings, two silver-silver chloride electrodes are attached to the outer canthi of the eyes, for monocular horizontal recordings at the outer and inner canthi of each eye, for vertical recordings above and below one eye. The corneo-retinal potential leads to a potential difference between these two skin electrodes that directly depends on eye position and can be measured by means of a differential amplifier (Jung and Kornhuber 1964; Carpenter 1988). The potential is proportional to the sine of the angle between the electrical axes of current eye position and of primary eye position, showing an approximately linear relationship for angles up to 30° and amounting to about 15 to 20 μV per degree of eye rotation (for review see Baloh and Honrubia 1990).

**Advantages.** Application of surface electrodes is easy, noninvasive, without discomfort for the patient, and does not limit the field of view. In contrast to most other methods, EOG can be used with the subject wearing glasses and is applicable to children, poorly cooperative patients, or patients with ophthalmic disease. Further, it is possible to record eye movements with eyes closed, or during free head movements, and EOG permits accurate recording of a large range of horizontal movements (±40°), with a resolution of about 1–2°. Except for the costs of the equipment (preamplifiers, amplifiers), additional costs for each recording session are low (electrodes, electrode cream). Up to now, it is the most practical clinical method to record eye movements, whereas for many scientific purposes, more accurate methods are needed.

**Disadvantages.** The amplitude of the corneo-retinal potential changes with the amount of ambient light, so illumination has to be kept constant as much as possible. Further EOG and ENG is often contaminated by electrical, electroencephalographic, and electromyographic artifacts, by lid and blink artifacts, and by slow baseline drifts, caused by changes of skin resistance (see pp. 229–230).

Bitemporal recordings are sometimes taken, using electrodes attached to the outer canthi of the eyes, thus collecting a compound potential difference resulting from both eyes, i.e. from an imaginary ‘cyclopean eye’. However, despite the advantage of increasing the signal-to-noise ratio, these bitemporal recordings have the disadvantage of camouflaging disconjugate eye movements and conversely are unreliable in the presence of disconjugacy. For monocular recordings of horizontal eye movements, the lateral tilt of each eye’s recording axis may lead to a false appearance of dissociated eye movements such as dissociated gaze-evoked nystagmus on extreme lateral gaze (see p. 230). Also the vergence angle cannot be determined exactly with EOG because of these problems. Finally, EOG shows differences in the speed of abducting versus adducting saccades (abducting saccades appear slower) that do not appear with other methods (in fact abducting saccades are faster).

Furthermore, EOG recordings of vertical eye movements are unreliable and require special configurations for quantitative analysis (Peng et al. 1994). They are often contaminated by large lid artifacts. EOG does not allow the determination of the amplitude and direction of vertical eye movements associated with lid closure, as each blink or eyelid closure leads to a large upward deflection of
the vertical EOG signal, due to the eyelid movement (see p. 230). To record torsional eye movements (around the line of sight) is practically not possible by EOG, as eye rotations around its electrical axis do not influence the potential difference along the horizontal or vertical recording axes.

Infrared reflection oculography (IROG) and photoelectric techniques

These methods rely on the fact that the white sclera reflects more light than the pupil and the iris. When the eye moves to one side, less infrared light is reflected back to the detector on one side of the eye than on the other. Visual boundaries between the different ocular structures are used for tracking, such as the limbus (border between iris and sclera) or the edges of the pupil. To avoid blinding, constriction of the pupils, or perceptual interference with stationary light sources, most systems use invisible infrared light to illuminate the eye. Three different approaches have been developed. First, focused illumination of the eye with infrared light and a wide-angle photodetector measuring the reflected light; second, diffuse illumination of the eye with infrared light and a photodetector with a narrow receiver angle; third, wide-angle illumination combined with wide-angle photo detection. The latter methods were improved by using two light sources for each eye and two separate photodetectors equally spaced on either side of the iris, and by differential amplification, resulting in an extended linear range (15° in either horizontal direction from primary position). Further improvements were achieved by miniaturizing the detectors, in order to keep the obstruction of the field of view at minimum, and by introducing a circuit for blink control and the chopped emission of infrared light. Equipment with multiple photodetectors has a larger linear range (±20°) and permit the recording of vertical eye movements within a limited range of ±5–10° at maximum (Katz et al. 1987; Reulen et al. 1988). As the distance between the reflective surface of the eye and the sensors is critical for recording and has to be kept exactly constant, most systems are head-mounted, e.g. on a spectacle frame, thus positioning light sources and sensors close to the eye and permitting free head movements. Alternatively, table-mounted devices are in use as well (Katz et al. 1987).

Advantages. The resolution for small horizontal eye movements is very good (0.1–0.5°) because of the high signal-to-noise ratio. The baseline is usually stable, except for some fluctuations elicited by tears. Both eyes are recorded separately, so that a comparison of movements between the eyes is possible. Except for the equipment, the recording is free of costs. The application is noninvasive, without discomfort for the patient, except for the fact that in head-mounted systems the spectacle frame has to be fixed tightly to the head and might exert some pressure.

Disadvantages. The recording device is within the visual field of the subject and therefore obstructs the view. Recording is usually restricted to the horizontal plane, whereas recording of torsional movements is impossible and recording of vertical eye movements is limited to ±5° or 8°. Horizontal eye movements are linear up to an eccentricity of at least ±15°, some systems up to ±30°. Recording with corrective spectacles or contact lenses or with closed eyes is not possible, so spontaneous nystagmus has to be recorded with eyes open in darkness (which is the best technique anyway). Blinks of the lids cause large artifacts. Furthermore, the position between the eye and the device has to be kept constant, requiring exact positioning of the detectors by a skilled person. This is a time consuming procedure and only possible in cooperative patients. Head movements must be prevented in table-mounted systems. In head-mounted systems, the device may slip down during the recording session, because of its own weight. This might cause not only baseline drifts, but also influence the amplitude of the eye position signal. Tears, partial closure of the eyelids, or an altered infrared content of the ambient light may change the calibration factor. DC lighting should be used during the recordings, as the photodetectors may pick up the 50/60 Hz of AC lighting.

Videooculography and Purkinje eye-trackers

In contrast to IROG, video-based oculography (VOG) uses head-mounted miniaturized video cameras to track the image of the pupil (pupillo-
graphic method) or of the light reflexes (Purkinje images 1, 2, 3, and 4) generated by the anterior and posterior surfaces of the cornea (corneal reflex method) and of the lens, or a combination of both methods. The most prominent is the first Purkinje image on the anterior surface of the cornea, it can be detected easily by photographic or video-based camera systems. Each horizontal or vertical eye movement causes displacement of this image in relation to the limbus, the pupil and to the other Purkinje images, as the center of curvature of the corneal bulge differs from the center of rotation of the eye globe. However, in systems that measure eye rotation by tracking only corneal reflections or only the pupil, movements of the transducer relative to the subject’s head will be interpreted as eye rotations, thus causing large errors of eye position, by about 5° or 10° per 1 mm of lateral motion (Young and Sheena 1975). To overcome this problem, some video systems measure movement of reflected light from one surface of the eye (e.g. the corneal image) in conjunction with another (e.g. the center of the pupil, or the fourth Purkinje image reflected from the posterior surface of the lens). As these two images move relative to each other only during eye rotation, but not during translation, lateral shifts of the eye with respect to the transducer will not influence the measurement (DiScenna et al. 1995). Nevertheless, most systems require a rigid coupling between head, infrared light source, and camera. There are lightweight systems that are head-mounted and contain a video camera for each eye. In addition, some of them measure head movements, either passively, e.g. with an ultrasound device, or actively by monitoring the visual scene or at least the position of the visual stimulus generator using a third head-mounted camera. In other systems a remote camera is able to track the pupil thus compensating for small head movements so that a rigid coupling of light source, head and camera is avoided.

Infrared light is usually used for illumination of the eye. The video picture is analyzed either on-line or off-line by digital image processing. The sampling rate depends on the frame rate of the video camera, amounting to 30 to 60 Hz in conventional systems, but up to 250 or even 400 Hz in modern systems. Most systems do not analyze torsional eye movements. Recently, however, systems have been developed that perform a computerized analysis (pattern recognition) of the whole video image, instead of tracking only the pupil or corneal light reflexes. These systems can additionally measure ocular torsion in terms of shifts in the radial structure of the iris (Scherer et al. 1991).

Advantages. In addition to quantitative eye position records in two or three dimensions, video records provide a overall visual impression of a patient’s eye movements, thus being superior for teaching purposes and for the clinical observation of eye movement disorders. Further, 3D-VOG is the only noninvasive method allowing a three dimensional analysis of eye movements. Even in 2D systems, the linear range for the measurement of horizontal (up to ±40°) and vertical (up to ±30°) eye positions is much larger than with IROG, and the spatial resolution is almost comparable (about 0.5°). In contrast to IROG, most video systems are easy to handle, and many of them allow head-free or even fully remote recording.

Disadvantages. In early video systems the camera obstructed the view of the subject. This was partially avoided by the use of a semi-translucent mirror in the line of sight or in the periphery. Recording with closed eyes is not possible, and most systems cannot measure eye torsion. As most conventional video systems use frame rates of 30 or 60 pictures per second, the velocity and latency of saccadic eye movements can not be analyzed exactly with these systems. Purkinje-eye-tracking systems are influenced by lens motion artifacts which in particular distort saccade waveforms. Head-mounted systems have to be fixed tightly, thus being quite uncomfortable to wear for more than 30 min, and may change the inertia of the head so that studies of active head movements are not feasible. Fast head movements may cause a slip of the headband and consequently recording artifacts and a loss of calibration. Finally, video systems are rather expensive, particularly 3D-systems, systems with high sampling rates, and those with active on-line compensation of head movements. The search-coil technique
(Section 1.4) is superior to VOG in most respects, though it is invasive and does not allow for visualization of the eye. Nevertheless, video systems are being improved constantly and might gain increasing importance in the near future.

**Search coil technique**

This technique is based on Faraday’s law of electro-magnetic induction: a voltage is induced in a moving electric conductor that is oriented perpendicular to a magnetic field. Robinson (1963) introduced this method for measuring eye movements, embedding a small coil of wire (search coil) in a contact lens and fixing it on the surface of the eye by suction. The subject’s head is placed in the center of two oscillating magnetic fields, oriented perpendicular to each other, elicited by large surrounding coils (Helmholtz coils) that may either be head-mounted (with a diameter of 30 or 40 cm) or may fill the whole room (diameter of 180 cm). These two magnetic fields are alternated with a high frequency, ranging between 50 and 100 kHz, and with a phase shift of 90° between the horizontal and the vertical field. They induce an electric voltage in the small search coil during each horizontal or vertical eye movement. The amplitude of the induced voltage is proportional to the sine of the angle between the axes of the search coil and the magnetic field. A thin wire connects the eye coil to phase detectors that assign the induced voltages to horizontal or vertical eye rotations, depending on the phase of the signal, thus determining eye position with the respect to the Helmholtz coils (amplitude detection method). Alternatively, the inducing horizontal magnetic field may be rotating so that each horizontal eye rotation leads to a phase shift between the signal induced in the eye coil and the signal induced in a stationary reference coil (phase detection method). This phase shift reflects horizontal eye rotation, it is linear even for very large gaze shifts. Further improvements of the method were achieved by embedding the search coil in a flexible silicone ring self-adhering to the corneal limbus (Collewijn et al. 1975) and by integrating a second search coil wound in the sagittal plane for the recording of ocular torsion (torsion coil) (Ferman et al. 1987).

**Advantages.** The search coil technique with torsion coils allows precise three-dimensional recording of eye movements without baseline drift or restrictions in sampling frequency (thus being able to register fast eye movements accurately), yet with an excellent signal-to-noise ratio and a high resolution (in the order of 1 or 2 min of arc), without obstruction of the visual field. The linear range is ±30° or 40° in each dimension with amplitude detection and unlimited with phase detection. Calibration of the signal can be performed in vitro, prior to the recording session, when the eye coil is mounted on a calibration (gimbal) device, placed at the same position as the eye of the subject. Head-free recording is possible within the central portion of the magnetic field where it is still homogenous; its size depends on the size of the Helmholtz coils. On the other hand, larger Helmholtz coils are disadvantageous because the homogeneity of the field may be affected by nearby metal objects.

**Disadvantages.** In general the application of the search coil technique requires special technical knowledge, and the examiner has to develop some skill for the semi-invasive procedure of mounting the silicone ring on the anesthetized eye and removing it at the end. Recording duration is limited to an hour at maximum, but preferably to 30 min, then the silicone ring must be removed. Irritation or erosion of the cornea and corneal edema (inducing blurred vision) can occur with long recording sessions, but frequent application of artificial tears and encouraging blinking prevents these complications. These possible side effects limit the application of this method for clinical testing, excluding patients with glaucoma or other ophthalmic disease, young children, and possibly patients with cardiac pacemakers. As an additional disadvantage, the Helmholtz coils may obstruct the visual field and interfere with the projection of visual stimuli. Further, the thin wires connecting the search coil with the detection circuit break easily so that a coil usually works properly for only three or four recording sessions, even if the coils are handled carefully. Finally, there may be some slippage of the coil on the eye, which may interfere with measures of torsion. As coils and especially torsion coils are rather expensive, this
causes relatively high costs for each recording session, additionally to the costs of the equipment.

In conclusion, because of its superior recording properties the search coil technique is the gold standard in experimental eye movement research. It should be applied in patients only when other recording techniques are not appropriate to address the specific question.

**Technical requirements**

*Basic technology and recording equipment*

The following sections will concentrate exclusively on EOG as the standard technique for clinical electroneystagmography. EOG requires equipment for the recording and the preprocessing of the physiological signal.

For recording, surface silver-silver chloride electrodes available from different companies may be used. First the skin has to be cleaned with alcohol. According to our experience it is not necessary to rub off the superficial layers of the skin. Then rings of self-adhesive tape are attached to the outer rim of the cup electrodes and the cup electrodes are filled with electrode gel. The electrodes are attached laterally of the outer canthi of both eyes for binocular horizontal recording of an imaginary ‘cyclopean eye’ and above and below one eye for vertical recording. Placing the horizontal EOG electrodes more posteriorly toward the temples can help to reduce artifacts from muscle activity (Young and Sheena 1975). A ground electrode is placed on the center of the forehead or on the auricle. For monocular horizontal recordings, electrodes may be attached to the lateral aspect of the nose at eye level, thus more anteriorly than the temporal electrodes. The resulting lateral tilt of the monocular recording axes causes some distortion of the signal (see p. 230), further these recordings are often affected by lid or muscle artifacts. Nevertheless, monocular horizontal recordings are needed to record disconjugate eye movements. Only if disconjugacy or misalignment has been excluded, can the bitemporal binocular horizontal EOG with its better signal-to-noise ratio be used for analysis. After the electrodes have been attached, a few minutes should be allowed for the electrode cream to soak into the skin until the baseline is fairly steady.

For preprocessing an amplifier is needed which is switchable for DC recording (direct current coupling) or AC recording (alternate current coupling; with time constants of 5 or 10 s). In the DC mode, some amount of drift of the baseline is inevitable, so the amplifier should have the option of an automatic or manual DC reset, if the drift exceeds a certain voltage. If possible, the horizontal EOG should be performed in the DC mode in order to provide a better record of actual eye position, whereas for the vertical EOG with its multiple artifacts the AC mode may be sufficient in clinical routine use. To reduce interference with EMG signals, high-frequency filtering should be possible at different frequencies. A high-frequency filter with the −3 dB point at 300 Hz does not interfere with fast eye movements. When the patient is not relaxed, and thus subject to stronger EMG interference, or with electronic artifacts around 50 Hz, it may be necessary to use 100 Hz, 70 Hz, or 30 Hz filtering. But high-frequency filtering affects the velocity signal of fast eye movements (saccades, fast phases of nystagmus) by reducing its peak velocity. In general, 30 Hz filtering is regarded as sufficient for clinical routine ENG. The amplifier should have at least two channels, one for recording horizontal eye movements across both eyes (electrode placement at the outer canthi of both eyes), and one for the vertical EOG of one eye (electrodes placed above and below). The latter is used mainly for identifying lid artifacts during blinks or eye closure. Additional channels may be used to record the monocular horizontal EOG from each eye separately, or the vertical EOG from the second eye, and it is advisable to register the visual or vestibular stimulus on a separate channel. If EOG recording is used in combination with a rotating chair it is advisable to use a preamplifier mounted at the chair to increase the amplitude of the signal, for achieving a better signal-to-noise ratio before the signal is fed into the slip rings. It is, however, also possible to mount the main amplifier to the chair, particularly if it has a remote control of the base line signal, permitting on-line corrections of base line drifts while the chair is rotating.
The EOG signals can be recorded by a pen recorder on a paper trace, with a paper speed of 50 or 100 mm/s for saccades and of 10 mm/s for the remaining ENG. Alternatively, the EOG can be digitized by an analog-to-digital converter and analyzed with interactive computer programs (Balogh and Honrubia 1990). By convention, eye movements to the right are displayed so that they produce an upward deflection of the horizontal EOG trace and those to the left produce a downward deflection. For vertical recordings, upward and downward eye movements produce upward and downward deflections, respectively.

Stimulation equipment and conditions

Preparation and recording should be done in a dimly lit room, and patients should be allowed to adapt to the light conditions for 15 min to achieve a steady corneo-retinal potential. Ideally, electronystagmography should be performed in a light proof chamber so that vestibularly-induced eye movements (spontaneous nystagmus, vestibular nystagmus) can be recorded in total darkness with eyes open, as EOG recordings with closed eyelids are often distorted by artifacts. Further, a head-rest is required to stabilize the head during testing, in order to prevent interfering eye movements compensatory to head movements.

The calibration procedure and the recording of fixation, saccades, and smooth pursuit eye movements require a small visual target (preferably a laser target, with a diameter of 0.5°) that can be presented at various positions on the horizontal and vertical meridians of the visual field and can be moved with constant or sinusoidally modulated velocity profiles up to 60°/s. The light or laser spot may be projected onto a screen by means of a mirror that can be driven by a galvanometer, preferably in two dimensions. Alternatively, fixed light-emitting diodes may be used as visual targets for calibration and saccades. For the recording of optokinetic nystagmus (OKN), a coherently moving stimulus covering a large portion of the visual field (preferably the whole visual field) is required, such as a drum covered with a random black and white pattern rotating around the patient, or moving light dots projected onto the inner surface of a globe, thus covering the patient’s visual field. Alternatively, the patient can be rotated with constant chair velocity while viewing the stationary surround. In this case, the initial 40–60 s of the record contain a vestibular component to the nystagmus, but subsequently, the stimulus is predominant visual. Testing of the vestibulo-ocular reflex (VOR) requires a chair that can be rotated at velocities of at least 90°/s, preferably up to 200°/s. For caloric irrigation, a thermostat-controlled heating device should be used, with a water pump that provides a constant flow rate. A large syringe (containing 200 to 300 ml) may also suffice (in this case the syringe should be immersed into the water used for irrigation at the desired temperature so that the water does not immediately change temperature once it is filled into the syringe). The right and the left external auditory canals are alternately irrigated for a fixed duration (30 or 40 s) with water of 44°C, and with water of 30°C, respectively. Details of the procedure are outlined on p. 235.

Factors affecting the quality of the investigation

Both technical and biological factors influence the quality of EOG recording.

Electronic artifacts in the frequency range of 50 Hz can be abolished by using a filter with a high-frequency cut-off above 30 Hz. If there are electrostatic artifacts, the grounding should be improved.

The amplitude of the corneo-retinal potential changes up to 50% with dark adaptation (Henn 1993). Thus repeated calibrations are necessary after changes of illumination.

The baseline may drift as a result of changes in skin resistance, especially when the subject is sweating, which frequently accompanies nausea and vertigo. Baseline drifts may be reduced by using condenser-coupled AC recording. The time constant, however, should be as long as possible to minimize the distortion of slow eye movements. According to our experience a time constant of 5 s is a good compromise to reduce base line drifts without severely affecting the eye movement signal.

Surface electrodes pick up other undesired biopotentials, such as the ECG, the EEG from
frontal brain regions, and the EMG from the temporal and the orbicularis oculi muscles. This reduces the resolution of the method for small eye movements which is typically 1–2°. High-frequency filtering (30 Hz) reduces these problems, but may affect the velocity profile of saccades (see p. 228). Immediately (4–12 ms) before large amplitude saccades a negative potential (presaccadic spike potential) may be picked up, which is assumed to be due to extraocular muscle activity.

The vertical EOG is often contaminated by muscle and eyelid artifacts, making an exact quantitative analysis almost impossible. Eye blinks are easily identified because of their peaked waveform and their short duration; in the horizontal EOG, however, they can mimic saccades or even nystagmus (Balogh and Honrubia 1990). Some patients show a constant lid flutter with closed eyes that resembles nystagmus in both the horizontal and vertical channels. They should be recorded with eyes open in darkness. Constant eyelid closure leads to a large tonic upward deflection of the vertical EOG signal, which is caused by the eyelid movement, whereas a large upward eye rotation does not occur during normal lid closure. Search coil recordings have shown that lid closure is associated with only small vertical eye deviations either upwards or downwards.

Also monocular horizontal EOG recordings are often contaminated by muscle or lid artifacts, though to a lesser extent than is the vertical EOG. Furthermore, the recording axis of each eye’s monocular horizontal EOG is tilted laterally with respect to the usual bitemporal axis, as the medial electrode has to be placed anterior to the eye on the lateral aspect of the nose. Therefore horizontal eye movements that are identical in both eyes may look different in the monocular recordings, and abducting saccades appear slower than adducting saccades. Particularly on extreme lateral gaze this electrode arrangement may lead to a false appearance of dissociated eye movements, e.g. to a larger amplitude of gaze-evoked nystagmus in the abducting eye, thus mimicking dissociated gazer
evoked nystagmus.

Also important is the degree of cooperation and alertness of the patient, which is critical in ENG. Patients often fatigue or become inattentive, because the behavioral context of an ENG is artificial and the lights are turned down. Also a light or laser spot is not an interesting target, and instructions in some parts of the testing are relatively complicated. Performance of smooth pursuit eye movements (SPEM) or measures of vestibular responses in darkness are particularly vulnerable to decline of attention or vigilance. All instructions should be as clear and precise as possible. Furthermore, optokinetic, caloric, or rotatory testing can cause nausea that is uncomfortable and sometimes intimidating. In this respect, adequate information will help to keep the patient cooperative. The cooperation of the patient is especially important during calibration, since accurate quantitative measurements depend on it.

Clinical evaluation of eye movements

Prior to recording, a detailed clinical evaluation of eye movements is always necessary. As has been pointed out, most eye movement recording techniques in clinical use can not register eye movements in all three dimensions. Furthermore registration of eye movements is often limited to one eye or monocular recordings may be distorted by artifacts so that it is not possible to determine whether both eyes move conjugately. Thus ocular alignment or strabismus should be assessed by clinical observation or by appropriate strabismological tests (cover test, red glass test, Maddox rod test, etc.). Further, direct visual inspection is superior to EOG (resolution 1° or 2°) in detecting small-amplitude eye movements, such as gaze-evoked nystagmus or saccadic intrusions, with a maximal sensitivity of approximately 0.1°. Last but not least, ENG testing must usually be performed in a laboratory so that it is more time consuming than clinical examination and cannot be performed in severely ill patients.

Clinical testing should include the investigation of central and eccentric binocular and monocular visual fixation. Nystagmus during attempted fixation or gaze-evoked nystagmus, saccadic oscillations, disconjugate eye positions, or a vertical divergence may be detected. One should look for pathological head tilts. One should measure ocular
motility in horizontal, vertical, and oblique directions, elicit reflexive and voluntary saccades to visual targets, assess sinusoidal smooth pursuit during tracking of a pendulum swinging with 0.3–0.5 Hz, and OKN while looking at a moving handheld drum. Bedside vestibular testing (Leigh and Zee 1999) should include the examination of spontaneous, head-shaking, hyperventilation-induced, or positional nystagmus under Frenzel glasses or during ophthalmoscopy, and an estimation of the vestibulo-ocular reflex (VOR) by looking at gaze stability during rapid head movements so that visual tracking reflexes can not assist gaze stabilization (Halmagyi-Curthoys or head thrust maneuver, ophthalmoscopy during head shaking, assessment of dynamic visual acuity).

Protocol of the investigation and design of procedures

The following sections outline the most common procedures used in the diagnosis of supranuclear eye movement disorders. The intention of such a battery is to test all basic categories of eye movements (fixation, gaze holding, saccades, smooth pursuit, optokinetic nystagmus, vestibuloocular reflex) and to keep the test as short as possible, as fatigue interferes with oculomotor performance. With respect to the neurophysiological basis of the different oculomotor subsystems, the clinical syndromes resulting from lesions in these systems, and their significance for neurological, otological and ophthalmological diagnosis, the reader is referred to the standard text books (Carpenter 1988; Baloh and Honrubia 1990; Leigh and Zee 1999).

Calibration of eye movements

Eye movements are usually calibrated by the performance of visually-guided saccades from primary position to targets of different visual eccentricities (10°, 20°, 30°) on the horizontal and vertical meridian. By convention, amplification of the EOG signal is set to the level at which an eye rotation of 20° causes a pen deflection of 10 mm on the polygraph recorder. To control the stability of the calibration factor for quantitative analysis, the calibration procedure should be performed about every 15 min. If larger eccentricities (40° or 45°) are also used for calibration, the range of linearity of the signal can be assessed and at the same time any gaze-evoked nystagmus can be recorded.

Saccades

After the calibration, the same procedure can be used to record visually-guided saccades, triggered by centrifugal or centripetal target steps of 10°, 20°, and 30°. In order to avoid anticipatory saccades with latencies of less than 80 ms, visual stimulation should be unpredictable, i.e. the foveal target (LED or laser spot) should be moved to random locations at random time intervals. For assessing the correlation between saccadic amplitude, duration, and peak velocity (the so-called ‘main sequence’) it is important to elicit saccades of various amplitudes. As a prerequisite for the proper analysis of saccadic latencies and saccadic peak velocities, the high-frequency cutoff of the filter must be at least 30 Hz, preferably above 70 Hz, and the paper speed of the polygraph recorder should be 50 or 100 mm/s. The latter is not critical, if the data are digitized and sampled by a computer program that allows an appropriate adaptation of the time scale for off-line analysis later on; the sampling rate, however, must be at least twice as large as the upper cutoff frequency of the filter.

Depending on the clinical diagnosis, one can adapt or extend the investigation of saccadic eye movements accordingly. In cases with double vision, strabismus, internuclear ophthalmoplegia, or impaired gaze holding, the monocular horizontal EOG of both eyes should be recorded in the DC mode during monocular fixation, once with the left and once with the right eye fixating, while the other eye is occluded. In patients with cortical dysfunction or basal ganglia disease, it is useful to record not only visually-guided reflexive saccades, but also specific subtypes of voluntary saccades: In the anti-saccade task, the target appears in one hemifield, and the patient is asked to look into the opposite hemifield. The percentage of erroneous reflexive saccades into the wrong ipsilateral hemifield (towards the target position) is elevated in patients with Huntington’s disease, schizophrenia,
or frontal lobe lesions. Patients with Parkinsonian syndromes or prefrontal lesions show a hypometria of memory-guided saccades, i.e. saccades performed in darkness to the remembered position of a visual target that had been flashed for about 200 ms more than 1 s prior to the saccade.

**Spontaneous nystagmus (SPN)**

The term ‘spontaneous nystagmus’ refers to a nystagmus which is present during attempted fixation in darkness, without vestibular stimulation. Most frequently it is horizontal and reflects a static imbalance in the central or peripheral vestibular system. Its slow-phase velocity may be regarded as a direct measure of the magnitude of this imbalance. Preferably, it should be tested in complete darkness with eyes open, as eyelid closure can lead to an attenuation of nystagmus intensity in some patients. Further, SPN intensity is dependent on the state of arousal and may be increased by mental tasks (called ‘mental activation’, for example serial subtractions of 7 from 100, which is a standard procedure in many labs). In contrast to clinical observation under Frenzel glasses (with the room lights turned off to eliminate fixation capability), EOG recording of SPN, of course, has the advantage that it can be used to record eye movements in total darkness.

**Nystagmus during fixation**

After recording the SPN in darkness, the patient should be recorded during binocular and monocular visual fixation in primary position. Typically, SPN of peripheral vestibular origin is completely or partially suppressed by fixation, whereas primary position nystagmus of central origin and congenital nystagmus usually increase their intensity and change their appearance with visual fixation, thus being called fixational nystagmus. EOG registration during fixation may reveal such a disorder. Binocular fixation should be recorded for at least 3 min in order to exclude periodic alternating nystagmus. The diagnosis of latent nystagmus (a form of congenital nystagmus in strabismic patients) requires occlusion of one eye, as it is accentuated or brought out during monocular fixation. Therefore, when congenital or latent nystagmus is suspected clinically, some parts of the ENG should be repeated with left monocular and with right monocular fixation, namely central fixation, eccentric fixation, smooth pursuit, and OKN.

**Gaze-evoked nystagmus and rebound nystagmus**

Deficits in holding an eccentric gaze position manifest themselves in a slow centripetal eye drift towards primary position, followed by a corrective saccade back to the eccentric target. This sequence of events leads to a pattern of slow and quick phases called gaze-evoked nystagmus. The velocity of the drift increases with larger eccentricities of the target. Within each slow phase, however, eye velocity decreases according to a decaying exponential, caused by a defective eye-velocity-to-position integrator. To quantify the severity of the gaze-holding deficit the patient is tested while fixating targets of increasing eccentricities (10°, 20°, 30°, 40°, 45°) in both horizontal and vertical directions, for about 8 s each. Many normal subjects exhibit a weak nystagmus during extreme lateral gaze at 40° or 45°, which is a physiological endpoint nystagmus and should be differentiated from pathological gaze-evoked nystagmus. The earlier literature distinguished between a gaze-paretic nystagmus (large amplitude, low frequency) and a gaze-evoked nystagmus (small amplitude and high frequency). These are not two distinct phenomena, however, nor are they caused by distinct lesions, but by a continuum of lesions varying in severity. Gaze-evoked nystagmus is a prominent feature of lesions of the vestibular nuclei or vestibulocerebellum including drug-induced gaze-holding deficits. It should be noted, however, that a horizontal SPN of vestibular origin is often enhanced during upgaze and during gaze into the direction of the fast component (Alexander’s law), thus mimicking gaze-evoked nystagmus.

When an eccentric gaze position has been held for about 30 s, gaze-evoked nystagmus may decline or vanish altogether. When the patient is then asked to perform a recentering saccade back to primary position, a nystagmus may occur that beats in the direction opposite to the previous gaze-evoked nystagmus. This is called rebound nystagmus.
being suggestive of a vestibulo-cerebellar deficit. The rebound nystagmus decays in a few seconds.

**Smooth pursuit eye movements (SPEM)**

For recording SPEM, the patient is asked to pursue the foveal light or laser spot, moving back and forth predictively at frequencies of 0.2, 0.3, and 0.5 Hz (amplitudes ±15° or 20°), with constant or sinusoidally modulated velocity profiles. About 6 or 8 cycles should be recorded at each frequency. To enhance selective attention and to achieve an optimal SPEM performance, the patient may be asked to identify numbers or letters located inside the moving target. Thus even an elderly patient should be able to pursue a sinusoidal movement of 0.2 Hz and ±20° amplitude smoothly for at least two cycles. Stimuli of randomly changing velocities and directions are more difficult to pursue, but they are hardly used during clinical ENG, neither stimuli of pursuit initiation that occurs when a target suddenly starts moving after the subject had been fixating (‘ramp’ or ‘step-ramp’ stimuli).

**Optokinetic nystagmus (OKN)**

In a more general sense OKN is used for the sequence of slow eye movements during which a moving visual scene is more or less stabilized on the retina with resetting saccades or quick phases occurring in between. The stimulus may consist of a few small objects eliciting repetitive pursuit eye movements, or at the other extreme, the whole visual field may be filled with contrasts all moving coherently at the same angular velocity. The latter stimulus is used to elicit so-called full-field OKN, being associated with the subjective sensation of visually-induced self rotation (‘circular vection’, which is a vestibular sensation). Thus full-field OKN implies the visually-induced activation of the vestibular system, in addition to the pursuit system. For clinical testing most laboratories use a projected large-field pattern of dark and light bars or of random light dots, moving in either the horizontal or vertical direction at constant angular velocities of 30°, 60°, 90°, and 120°/s and being presented for about 15 s each. For one of these velocities (e.g. 30°/s), however, the full-field stimulus should be presented for at least 30 s, before the lights are turned off, in order to elicit optokinetic afternystagmus (OKAN), which is a weak nystagmus into the direction of the previous OKN that slowly decays in darkness. Horizontal full-field OKN can also be elicited during rotational testing with a constant-velocity stimulus (see the next section) since the vestibular stimulus decays after the chair has been moving at a constant velocity for 30–45 s. The stimulus then becomes purely optokinetic.

**Vestibular nystagmus: rotational testing**

For rotational testing the patient is seated on a rotating chair with the head stabilized in a head rest. To also investigate low-frequency components of the VOR, many laboratories choose a low chair acceleration (of 0.9°/s²) near threshold (which is below 1°/s² in normal subjects), up to a final chair velocity of 90°/s in darkness with eyes open or, if a light proof chamber is not available, with eyes closed. Per-rotatory nystagmus, if present at all, usually vanishes before the final chair velocity is reached. Constant velocity rotation at 90°/s may be used for a test of full-field OKN by asking the patient to open the eyes for 30 s and to watch the objects moving along.

Again with eyes closed (or in darkness, respectively) and after OKAN has disappeared, the chair is abruptly stopped and postrotatory nystagmus I (PRN I) as well as a turning sensation is evoked into the opposite direction. Its maximum slow-phase velocity relative to the previous chair velocity (VOR gain) reflects the VOR response in its medium or higher frequency range. It shows an exponential decay with a time constant varying between 10 and 20 s. Thus postrotatory nystagmus I as well as the turning sensation vanish within about 40 s, the turning sensation earlier than the nystagmus. After this a weak postrotatory nystagmus II (second phase) might appear for 1 or 2 min, beating in the other horizontal direction. Therefore EOG registration should be continued up to 3 min after the stop. Then the same rotational procedure is performed in the opposite direction to test for the symmetry of the vestibular response. Because of the confounding problem of habitua-
tion, some laboratories use a velocity step (acceleration) from 0 to 90°/s within 1 or 2 s, instead of near-threshold acceleration. Thus, habituation-induced directional asymmetries will cancel each other, as they should affect right and left beating nystagmus (per- and postrotatory) to an equal extent. To counteract fatigue vestibular nystagmus may be enhanced by performing a mental task, carrying on a conversation (‘mental activation’), or by imagining a head-stationary target. Further, the use of higher chair velocities (for instance 180°/s or even higher) is preferable with respect to the detection of asymmetries of high-frequency VOR gain in patients with unilateral labyrinthine dysfunction. Alternatively, high-acceleration stimuli may be applied by a sudden chair displacement generated by a torque motor.

It has to be kept in mind that major parts of the vestibular system are not tested by the procedure (i.e. the vertical semicircular canals and the otoliths), as a rotating chair with the usually upright head position stimulates primarily the horizontal semicircular canals. Therefore future developments will have to take these parts of the vestibular system into account. A promising way is to use active head movements in various directions, thereby using natural stimulus profiles instead of the artificial stimuli (constant acceleration, constant velocity, sudden stop) proposed for the rotational testing. A quantitative test of this kind, however, requires the possibility to monitor head position and head velocity exactly.

Postrotatory nystagmus may be attenuated by an active head tilt out of the prior (vertical) axis of rotation; this is reflected in a reduction of the vestibular time constant from 12 or 16 s to about 7 s which is assumed to be the time constant of the peripheral cupula-endolymph system. This shortening of the postrotatory response can be achieved by asking the patient to tilt his head out of the vertical 90° forward, shortly (about 4 s) after the stop from a rotation of 90°/s angular velocity. The forward tilt is the more effective in reducing vestibular nystagmus and is less nauseogenic than lateral or backward tilts. In monkey experiments it has been shown that this inhibition relies on the integrity of the midline structures of the vestibulo-cerebellum (nodulus, uvula, inferior vermis), a finding that has been confirmed in patients with lesions of this region (Leigh and Zee 1999). Thus, tilt inhibition seems to be a specific functional test for the inferior cerebellar vermis, but is not yet commonly used in routine evaluation of patients. As tilt suppression is the result of the static otolith input interfering with input from the semicircular canals, it might also be used for testing otolith function during ENG.

In addition to the application of velocity steps, rotatory testing can be accomplished with sinusoidal stimulation. One can also integrate a test of fixation suppression of the VOR, an important function of visual-vestibular interaction. We perform this test at frequencies of 0.04 and 0.1 Hz and at an amplitude of ±90°/s chair velocity. First the patient is rotated in darkness to assess his vestibular response to sinusoidal stimuli (VOR). Then the patient is rotated in a light surround, the VOR being supported by visual input (visual VOR = VVOR). Finally the patient is asked to fixate a small target that is attached to the chair and therefore stationary with respect to the patient, in order to assess the residual VOR during fixation suppression (VOR-Fix). Alternatively, a stationary visual stimulus could be presented during per- or post-rotatory nystagmus or during caloric nystagmus. In both paradigms vestibular nystagmus is evoked and has to be suppressed by fixation of a stationary visual stimulus. A normal subject should be able to suppress the VOR almost completely by visual fixation. Deficits in fixation suppression may result from lesions at various locations, but are particularly prominent in patients with vestibulocerebellar lesions who also have deficits of smooth pursuit and gaze holding.

Vestibular nystagmus: caloric testing

The caloric response is still the best method for selective stimulation of one labyrinth. Prior to caloric testing the patient’s eardrums must be inspected with an otoscope to verify that there is no perforation. It is advisable to ask the patient whether there is a history of otitis media, acoustic trauma or of vertigo during swimming. In doubtful cases we refer the patient to an E.N.T. specialist as
minor perforations of the tympanum may only be visible when it is inspected with a microscope. For caloric irrigation the horizontal semicircular canals should be positioned vertically. As the plane of the horizontal canal is tilted about 30° upwards at its rostral end, it suffices to lean the patient (at least the head) 60° backwards or to test the patient in a supine position with the head elevated by 30°. As visual fixation or even eye closure can suppress the induced nystagmus, the recording should be performed with eyes open in total darkness (Balogh and Honrubia 1990). It is generally recommended to perform the ‘alternate, binaural bithermal caloric test’ (American Academy of Neurology 1996) by successively irrigating the right and the left external auditory canal for a fixed duration (30 or 40 s) with water of 44°C, followed by irrigation of the left and the right ear with water of 30°C, so that the nystagmus direction alternates with each caloric stimulus. One must wait a minimum of 5 min from the end of one response to the next stimulus to avoid additive effects.

When an ear is unresponsive to bithermal stimulation ice-water irrigation is performed for maximum thermal stimulation of the labyrinth. Eye movements should be recorded with the patient in both the supine position, with the head up 30° relative to the body, and in the prone position. In this way, a more accurate assessment of vestibular function can be obtained since the induced nystagmus should be in opposite directions in the supine and prone positions (American Academy of Neurology 1996).

The physiological basis of caloric nystagmus was assumed to be an upward streaming of endolymph induced by warm water and a downward streaming induced by cold water, due to a temperature-dependent gradient of the endolymph’s specific gravity. However, this cannot be the only mechanism, as experiments in microgravity have shown a preserved caloric response under these conditions. A direct influence of temperature on the discharge rate of the afferent nerve may account for this effect (Balogh and Honrubia 1990). Heat convection certainly plays a major role, which in turn is influenced by the compactness of the bone and the pneumatization of the mastoid. Therefore the strength of the caloric response (as determined by the maximum slow-phase velocity or the cumulative amplitude of caloric nystagmus) varies considerably between individuals so that it is problematic to establish normative values. Consequently the latter refer mainly to side differences of caloric excitability.

In the case of a perforation of the tympanum it is possible to use irrigation with warm and cold air instead of water. According to our experience this stimulus is considerably weaker and less reliable than water stimuli when the same stimulus parameters are used (temperature and duration). Therefore we use a somewhat longer irrigation time (45 s instead of 30 s) and a somewhat larger temperature difference for cold air (27° instead of 30° water). For warm air higher temperatures than 44° elicit discomfort in many patients and thus must be avoided. A direct comparison between water and air caloric stimuli is difficult, and side differences may be mimicked if perforation of one tympanum results in different conditions for heat convection on both sides. Therefore the aim of air caloric testing is mainly to prove that the ear with the lesioned tympanum has preserved vestibular excitability.

**Head shaking nystagmus (HSN)**

Testing for head shaking (HSN) is performed by asking patients to vigorously shake their heads in the horizontal plane for 20 s (about 2 or 3 Hz, ±30° amplitude). HSN is strongest immediately after the end of head shaking and then slowly decays like post-rotatory nystagmus. It is usually accompanied by a turning sensation and may also reverse direction (secondary phase).

Although HSN has been a well-known phenomenon, its significance remained obscure. Mostly it had been regarded as a method to provoke an otherwise not apparent spontaneous nystagmus (SPN). In more recent studies it was shown, however, that HSN is not a correlate of a static imbalance in the vestibular system as SPN. Rather, it is a sign of dynamic vestibular imbalance, which may remain permanent after peripheral vestibular lesions, independent of a SPN. During head rotation, one labyrinth is stimulated, and the labyrinth on the opposite
side is inhibited. For high velocities of the head, the stimulation of the excited labyrinth exceeds the inhibition of the inhibited labyrinth. This is due to a resting discharge rate of about 90 spikes/s that can be increased up to 400 spikes/s, whereas the inhibited labyrinth can only be driven down to 0. At a head velocity of approximately 200°/s this complete inhibition is reached in the labyrinth stimulated in the inhibitory direction so that higher head velocities are only transferred by the labyrinth stimulated in the excitatory direction (Ewald’s second law). If there is a unilateral lesion the intact labyrinth is more strongly stimulated in the excitatory direction than in the inhibitory direction, if the critical velocity is exceeded. Therefore it is necessary to shake the head quite vigorously in order to provoke HSN. The net difference between excitations by rotations to both sides is assumed to sum over time in a central vestibular velocity storage. This concept is in accord with the observation that the initial velocity and the duration of HSN increase with increasing duration of the head-shaking maneuver. In peripheral lesions HSN exhibits fast phases towards the intact labyrinth. HSN can also arise from an imbalance in the central vestibular velocity storage for both horizontal directions. This central vestibular imbalance is further reflected in asymmetric durations and time constants of per- and postrotatory nystagmus. To differentiate between both causes of HSN, rotatory and caloric testing should be performed. Head shaking is a fast and excellent bedside test for vestibular asymmetry in the high-frequency domain. It should not be neglected in a vestibular test battery, even if rotatory and caloric testing are done regularly, as these tests are not fully complementary because they stimulate different frequency components of the VOR.

Positional testing

If there is a history of positional vertigo, positional testing may be included in the ENG. It means the recording of eye movements (with eyes open in darkness or with eyes closed) while the patient is (1) supine; (2) supine with the head turned to the right and (3) left; (4) lying in right-lateral and (5) left-lateral position. Positional testing might include the Dix-Hallpike maneuver, for eliciting benign paroxysmal positional nystagmus (BPPN). It entails rapid positioning of patients from the seated to the head-hanging 45° right or head-hanging 45° left positions. When positional nystagmus is detected, it is appropriate to assess the influence of visual fixation. An inability to suppress or decrease the slow-phase velocity of positional nystagmus with visual fixation suggests a central abnormality, provided that the patient was attentive and had normal vision. In general, the clinical utility of positional testing during ENG is limited, as the most frequent types of positional nystagmus such as BPPN beat predominantly in torsional or vertical direction, thus being not adequately recorded with EOG. In this respect clinical observation of nystagmus through Frenzel glasses is of higher diagnostic value.

Typical applications for the clinical practice

Compared to clinical observation of eye movements, ENG recording has the following advantages:

Recording eye movements without visual fixation is of primary importance for vestibular testing (preferably with eyes open in the darkness), if a peripheral or central vestibular disorder is suspected in a patient complaining of dizziness, vertigo, or dysequilibrium. Only for the diagnosis of positional nystagmus with its vertical or torsional components clinical observation under Frenzel’s glasses is more appropriate than EOG.

Recording and quantifying eye movements helps to identify ocular motor disorders that might be missed during clinical observation, but are of importance for the diagnosis of neurological or vestibular disease. Examples include reduced saccadic peak velocities (slow saccades) in brainstem or systemic neurological disease (such as progressive supranuclear palsy, spinocerebellar ataxia, Huntington’s disease, or multiple system atrophy), saccadic dysmetria in cerebellar dysfunction, prolonged saccadic latencies in cerebral hemispheric dysfunction, directional asymmetries of smooth pursuit or OKN gain in unilateral frontoparietal, cerebellar or pontine lesions. Furthermore,
most measures of vestibular dysfunction can hardly be assessed without ENG records, such as directional asymmetries of VOR gain or time constant, impaired tilt suppression of post-rotatory nystagmus, and impaired fixation suppression of vestibular nystagmus. The latter two deficits are sensitive signs of vestibulo-cerebellar dysfunction and might, for example, confirm the presence of a supraspinal lesion in patients with suspected multiple sclerosis. Also, the proper diagnosis of incomplete unilateral labyrinthine dysfunction requires quantitative ENG records during caloric testing.

ENG has a better temporal resolution for recording fast and complex events, which are difficult to analyze by visual inspection only. This includes the analysis of spontaneous ocular oscillations such as congenital or latent nystagmus, acquired nystagmus during fixation, ocular flutter, oposclonus, and square wave jerks.

ENG as a standardized procedure with quantitative records provides the possibility to compare the actual recording with an earlier one, which is important for estimating the course of a disease.

The comparison between the ENG record and visually observed eye movement often reveals more details of the disorder and trains the doctor’s ability to analyze eye movements by observation.

It should be noted, however, that the usefulness of ENG testing is highly dependent upon test administration and test interpretation. In this respect, there is still variability among different laboratories, and there is no agency that governs credentials for persons who administer ENG testing. For proper ENG administration the experience and training of the laboratory personnel are critical, and a proper ENG interpretation is not possible without knowledge and experience in the neuroanatomy, physiology, and clinical investigation of the oculomotor system.

**Description and analysis of ENG traces**

The waveform characteristics of the three basic types of eye movements are illustrated in the ENG of a normal subject in Fig. 1, recorded on a paper trace by means of a thermograph recorder. The

![Fig. 1](image) Examples of ENG records of a normal subject, written on a thermograph recorder and showing saccades (a), smooth pursuit eye movements (b), and optokinetic nystagmus (c). In each part, the upper traces show binocular horizontal eye positions, the lower traces show horizontal target positions.

paper speed is 50 mm/s in Fig. 1a and 10 mm/s in Fig. 1b and c. The diagrams in (a) and (b) show the records of horizontal binocular eye position (upper traces) and horizontal target position (lower traces) for (a) a leftward saccade in response to a target step of 30° and the subsequent recentering saccade, and further for (b) sinusoidal smooth-pursuit eye movements of 0.33 Hz and ±20°. In Fig. 1a, saccadic latency (= Lat.; double-headed arrow) and peak velocity (= V\text{max}; steepest slope of the intrasaccadic eye position trace) are illustrated. The diagram in Fig. 1c shows an eye position record of horizontal rightward OKN in response to a full-field stimulus moving leftward with a constant velocity of 30°/s. The slope of the line approximated to one of the nystagmus beats corre-
sponds to slow-phase eye velocity. In each of the diagrams, upward deflection (positive ordinate) means rightward eye or target movement, downward deflection (negative ordinate) means leftward movement.

In the following sections we will outline the analysis and normative ranges of ENG results in various parts of the testing. Most of the proposed normal values are global ranges taken from the international standard literature (Baloh and Honrubia 1990; Henn 1993; Leigh and Zee 1999). Nevertheless, these values have to be treated with caution, as due to the different testing conditions including patient instructions, illumination, stimulation and recording devices, each laboratory should establish its own normative data. For assessing the normal range, we and others take the mean ± 2.5 standard deviations.

*Spontaneous nystagmus and nystagmus during fixation*

SPN and nystagmus during fixation are detected by visual inspection of the eye position traces and quantified by measuring the maximal eye velocity during nystagmus slow phases. The velocity is determined by numerical differentiation carried out by a computerized analysis program or graphically as the slope of the eye position trace. This measurement should not be performed on slow phases when the vertical EOG shows eyelid artifacts. A weak SPN in darkness (up to 4 or 5°/s slow-phase velocity) has been found in about 20% of normal subjects and thus cannot be regarded as pathological per se, if there are no other signs of vestibular dysfunction. The same normal range refers to head-shaking or positional nystagmus: slow-phase velocities of 5°/s or less are still within normal limits. The presence of nystagmus during central fixation is always pathological. It should be noted, whether such a nystagmus depends on gaze direction. Gaze-evoked nystagmus is considered pathological if it occurs at eccentricities of less than 40°. Disruption of fixation by saccadic intrusions (square wave jerks, saccadic oscillations, ocular flutter, opsinclonus) is also abnormal.

*Saccadic tests*

The latency of saccades (with respect to the stimulus movement) should be between 100 ms and 300 ms. The maximal eye velocity (visible as the maximal slope of the position trace, as shown in Fig. 1a, or obtained by digital differentiation of the eye position signal) during saccades should be determined. Normal values for saccade duration and peak velocity depend on the amplitude of the saccade, according to their ‘main sequence’, e.g. for a 20°-saccade the peak velocity amounts to 420 ± 70°/s, and a velocity below 250°/s is considered as pathologic. For the assessment of saccade metrics it should be noted whether the patient reaches the target with one saccade, or whether corrective saccades are needed to compensate for either an overshoot or undershoot. An overshoot is usually pathologic, often indicating cerebellar dysfunction, whereas a mild undershoot (see Fig. 1a) is normal. For quantification, many investigators calculate the saccadic amplitude gain (i.e. the ratio between the amplitude of the saccade and the amplitude of target displacement), which on average amounts to about 90% in normal subjects.

*Smooth-pursuit tests*

It is difficult to give exact normal values as conditions change slightly between laboratories, but even an elderly patient should be able to pursue a sinusoidal movement of 0.2 Hz and ±20° amplitude smoothly for at least two cycles. In a young subject this may be possible up to 0.5 Hz. With higher frequencies smooth eye velocity lags behind target velocity, and more and more catch-up saccades occur to foveate the moving target. In pathologic conditions these catch up saccades occur also at lower frequencies and amplitudes, resulting in a saccadic or ‘cogwheel’-like pursuit. If stimuli of randomly changing velocities and directions are pursued, catch-up saccades occur at much lower frequencies than during predictive pursuit. Reduced attention during pursuit might lead to anticipatory saccades, that move the eye off the target by anticipating the target trajectory. The critical measure of smooth pursuit performance is its velocity gain, i.e. the ratio of smooth eye velocity and stimulus velocity. If a computer
program is used for the analysis of the test, a larger interval free of saccades can be selected to assess mean eye velocity. Alternatively, eye velocity can be inferred as the slope of the eye position trace. In general, gain decreases with age, inattention, certain drugs (sedatives, antiepileptics, neuroleptics), and with any brain disease. More important for clinical diagnosis and for the localization of lesions is a direction-specific reduction of pursuit gain. With a sinusoidal stimulus of $\pm 20^\circ$ and 0.2 Hz, a gain above 0.8 should be reached even by elderly subjects.

**Optokinetic nystagmus**

Slow-phase eye velocity during optokinetic stimulation should be assessed either by computer analysis or as the slope of the eye position trace (of at least the 5 steepest slow-phase segments). OKN gain is calculated as the quotient of smooth eye and stimulus velocity. Usually the maximum OKN gain is calculated by averaging slow-phase velocities of the 5 steepest slow-phase segments. OKN gain decreases with increasing stimulus velocities; for 90$^\circ$/s it should be above 0.35. More important, the OKN response is considered pathologically asymmetric, if the quotient $(v_r - v_l)/(v_r + v_l)$ exceeds 20% (where $v_r$ and $v_l$ denote slow-phase velocity to the right and to the left, respectively).

**Rotational testing**

The rotating chair is a good tool to determine the threshold for perrotatory vestibular nystagmus and the turning sensation, furthermore the gain of the VOR (i.e. the maximum slow-phase velocity of postrotatory nystagmus after the stop divided by chair velocity before the stop) and the time course of the decline of nystagmus velocity after the stop (usually a nearly exponential decay is assumed and a single exponential may be fitted to this velocity function thereby determining a ‘vestibular time constant’). The decline of nystagmus velocity, however, is almost linear after stops from low velocities. After stops from high velocities nystagmus changes direction 30–60 s following the stop (secondary postrotatory nystagmus – PRN II). Thus the calculation of a time constant for PRN I remains problematic, but is nevertheless widely used because it helps to assess the symmetry of vestibular velocity storage. VOR gain of per- or postrotatory nystagmus should be between 0.3 and 1.05, and a directional asymmetry of VOR gain or time constant of more than 20% (as assessed for OKN) is pathological (Balah and Honrubia 1990). For clinical purposes the VOR time constant may be roughly estimated as one third of the duration of PRN I. Normal values range between 10 and 20 s. Head tilts performed 4 s after the stop should reduce the time constant to below 10 s.

**Caloric nystagmus**

As described for VOR and OKN, maximal slow-phase velocities induced by stimulation with water of 30$^\circ$C and 44$^\circ$C temperature are determined. The symmetry of the labyrinth responses is assessed by the formula

$$\left( |v_{L,44} + v_{R,30}| - |v_{L,44} + v_{L,30}| \right) / (|v_{R,44} + v_{R,30}| + |v_{L,44} + v_{L,30}|),$$

where R and L denote responses to right and left ear stimulation, respectively, and 30 and 44 denote the temperature of stimulation. If this quotient (index of asymmetry) is above 25%, unilateral labyrinthine dysfunction (vestibular paresis) is diagnosed. Furthermore, asymmetry with respect to nystagmus direction can be assessed as

$$\left( |v_{L,44} + v_{R,30}| - |v_{R,44} + v_{L,30}| \right) / (|v_{L,44} + v_{R,30}| + |v_{R,44} + v_{L,30}|).$$

An index above 30% can be considered as pathological, in terms of a directional preponderance.

As was mentioned earlier, several software programs are available for automatic computerized analysis of eye movement parameters (Balah and Honrubia 1990). When relying on such computer measurements it has to be kept in mind that the programs may have difficulties to cope with the various artifacts and a poor signal-to-noise ratio, thus possibly producing misleading results. It is therefore necessary to scrutinize the original eye position trace and to perform the analysis interactively. For the experienced examiner it is usually possible to detect abnormalities just by visual inspection of the eye position record. This proce-
dure is fast, but does not provide quantitative results. Thus inspection of the record and manual measurements (with paper and pencil) of the most important parameters (maximum velocity of saccades and pursuit, maximum slow-phase velocity of optokinetic, post-rotatory, and aloric nystagmus as well as the duration of postrotatory and caloric nystagmus) may still be a good compromise.

**How to report the results**

The report of an ENG investigation should be divided in three parts:

1. Description of recording and stimulation parameters, such as AC or DC recording, applied filters, number of recording channels, placement and connections of electrodes, sampling rate of data, type and magnitude of visual and vestibular stimuli, short outline of the ENG protocol.

2. Description of qualitative and quantitative results, as outlined on pp. 237–239. This includes reports of spontaneous, fixation, head-shaking, and gaze-evoked nystagmus, saccadic latencies, metrics and peak velocities, gain and directional asymmetries of smooth pursuit and OKN, duration of OKAN, gain and time constant of rotatory vestibular nystagmus, with or without fixation suppression or head tilt suppression, further the index of vestibular asymmetry and the maximal slow-phase velocities of caloric nystagmus. Artifacts should be mentioned as far as they limit the reliability of the results, as well as the alertness and cooperativity of the patient.

3. Summary of abnormalities, cerebral localization of disorders, and diagnosis or at least discussion of results in the clinical context.

**References**

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