The removal of ocular artefacts from the electroencephalogram: a review

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Abstract—The causes of ocular artefacts (OAs) in the human electroencephalogram (EEG) are explained and methods for their removal and their effectiveness are discussed. Recommendations for the best procedures to adopt are given together with suggestions for future research. Analogue subtraction techniques are found to be inferior to time domain techniques based on parameter estimation using the method of least squares applied to a linear function of the electro-oculograms (EOGs). Ways of assessing the effectiveness of different models for time domain removal of OAs are discussed. It is concluded that autorregressive modelling of the error terms, or else differentiated data, must be used to reduce the effects of correlation in the background EEG. The most generally suitable model for the removal of random eye and blink artefacts should contain terms proportional to the right vertical EOG and the two horizontal EOGs. The EOGs should be linearly filtered to remove noise frequency components in excess of 8 Hz. Adaptive methods are preferred as on line OA removal would be desirable but for the fact that this may result in distortion of stimulus-related responses present. A number of difficulties remain and there are some suggestions for future research.

Keywords—EEG, Eye movement, Eye movement artefact, Ocular artefacts


1 Ocular artefacts in the electroencephalogram

Electroencephalogram (EEG) signals are well known to be seriously obscured by the superimposition of large electrical potentials associated with eye movements (EM) and/or blinks. The source of these potentials is the corneoretinal dipole and short-circuiting of it by the eyelid (Hillyard, 1974). Thus EM results in dipole motion and scalp potential changes, modified by any associated eyelid movement. Blinks represent the case of temporary closure of the eyelids and the corresponding artefact is due to the motion of the eyelid over the cornea (Matsuo, et al., 1975; Barry and Jones, 1965). These EM, eyelid and blink artefacts are referred to collectively as ocular artefacts (OA).

It is necessary to be able to remove the OA from the measured EEG so that the true EEG record can be studied. For example, it has been found that OAs are associated closely with the contingent negative variation (CNV) response of co-operative normal subjects (Weerts and Lang, 1973; Straumanis et al., 1969; Wasman et al., 1970; Hillyard, 1974; Low et al., 1966). Because the CNV of Huntington’s chorea (HC) patients is of diagnostic value (Jervis et al., 1984) and is frequently completely obliterated by OA we have devoted considerable effort to identifying the best means of removing the OA from the EEG (Jervis et al., 1980; 1985a; Ifeachor et al., 1986a). In this review we describe the causes of OAs and methods proposed for removing them from the EEG. We use the term ‘electro-oculogram (EOG)’ to refer to the electrical potential measured between two electrodes placed close to the eyes and due to ocular movements.

2 Causes of ocular artefacts

The human eye contains an electric dipole with a positive cornea and negative retina. When the eyes move the electric dipole changes orientation so that the associated electric potential on the scalp, EMA, changes. There are several types of ocular movement (Shackell, 1967; Young and Sheena, 1975), of which the more relevant to EEG work are described here.

Blinks (Fig. 1) are characterised by a brief artefact potential of between 0·2 and 0·4 s in duration and occur at intervals of 1–10 s. Barry and Jones (1965) and Matsuo et al. (1975) showed that the blink potential was attributable to the eyelid moving over the cornea and not to movement as was previously thought. When the eyelid moves over the cornea it shortens the positive cornea to the EOG electrode. This shorting effect is removed when the eyelid is again raised. It was also shown (Corby and...
Fig. 1  Blink potentials. $V_R$ and $H_R$ are the vertical and horizontal EOGs of the right eye. $V_L$ and $H_L$ are the corresponding EOGs of the left eye. EEG is the EEG recorded between the vertex and linked earlobe electrodes.

KOPELL, 1972; OVERTON and SHAGASS, 1969) that the scalp distribution of blinks was different from that of normal EM, and therefore probably had a separate origin. OA due to blinks is always of concern in any experiment in which the eyes are open.

Saccadic eye movements (Fig. 2) are rapid conjugate movements of speeds between 100 and 500 ° s⁻¹. Normal everyday movements of the eye from one fixation point to another come under this category. These include the 'jump and pause' fixation movements performed when reading or scanning a visual field.

During vertical eye movements with the eyes open, a brief potential remarkably similar to blink potential is sometimes observed in the EOG (BARRY and JONES, 1965; FORD, 1959). This artefact was called the rider artefact by Ford and was later demonstrated (BARRY and JONES, 1965) to be due to eyelid movement. Rider artefact is reported to occur mostly during vertical eye movements or blink reflex. We have, however, observed it in both voluntary vertical and horizontal EOG recordings (Fig. 2). We have found that OA removal in the presence of rider artefact is sometimes difficult (IFEACHOR et al., 1986b).

Smooth pursuit movements involve tracking smoothly visual targets travelling at about 1–30° s⁻¹ (GASSER et al., 1985). Smooth compensatory EMs are used to compensate for the motion of the head or trunk during tracking.

Optokinetic nystagmus EM is elicited by a visual field which contains repeated patterns. The potential change produced in optokinetic nystagmus follows a characteristic sawtooth pattern. The eye fixates on a part of the field and tracks it as in pursuit movement. Then there is a return saccade, and the process is repeated.

In vergence EM the eyeballs move in opposite directions, as when the eyes focus from far to near objects and vice versa.

Miniature or fixation EMs include a number of movements that are generally less than 1° in amplitude and occur when the eyes are supposedly stationary, as for example during a fixation on a stationary target. The three main miniature EMs are flicks, drifts and tremor. Flicks, or microsaccades, are small EMs lasting for about 30 ms and which are performed to correct a drift and redirect the eyes to the fixation target. Drift is a slow involuntary EM during fixation that makes the eye wander away from a target for short periods of time before correction by flicks. Tremors are rapid oscillatory EMs which may be superimposed on flicks and drifts. Flicks and drifts from both eyes are partially correlated, whereas tremor is a disconjugate EM. The existence of miniature EM means that there is always a measurable EOG signal. This is important because it means the signal is 'persistently exciting', which is a necessary requirement for our online recursive least squares ocular artefact removal technique (IFEACHOR et al., 1986a).

Eye flutter is a rapid eyelid movement that tends to occur when the eyes are closed or nearly closed. Flutter frequency is usually in the range 3–7 Hz but occasionally in the range of 8–10 Hz and sometimes as high as 14 Hz. Eye flutter can be mistaken for a seizure discharge, especially during medication (HARLAN et al., 1958).

3 Measurement of ocular movements

Optical methods of detecting EM have been developed (YOUNG and SHEENA, 1975). In most cases they consist of a light source, optical detectors and a lens system. The limiting disadvantages of optical methods include that they cannot be used on unco-operative subjects such as children and some adult patient categories, that they are bulky, and that they may not give an output when the eyes are closed.

Eye and eyelid movements can be detected from electro-oculograms (EOGs) (HILLYARD, 1974; SHACKELL, 1967; QUITTER et al., 1977). The advantages of the EOG method are that all types of eye movements are detected including voluntary and involuntary, vertical, horizontal, and diagonal movements. They are also easy to record from skin electrodes placed around the orbit, some of which are often already placed for EEG recording. The method can be used whether the eyes are open or closed. It is also simple and can be set up quickly with minimal calibration.

It should be noted that

(i) the relative contributions of movements of the eyeball...