Dipole models of eye movements and blinks *

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Summary   Average EOGs were recorded from 4 subjects for vertical and horizontal eye movements of 15° away from and back to a central fixation point, and for eyeblinks while looking at the fixation point. Using spatio-temporal dipole modelling, several alternative dipole models of the electrical activity of the eyes were compared. A reasonable fit was only obtained if the equivalent dipoles were allowed to take up different locations and orientations depending on the type of eye activity. It appears that (a) the equivalent ocular dipole is located away from the axis of rotation of the eyeball, (b) eyelid movements contribute to a change in location of the dipole in vertical eye movements and blinks, and (c) some of the apparent dipole movement is due to inadequacy of the 3-shell spherical head model near to the eyes. Consequences of the results for eye-artifact correction are discussed.

Key words: EOG; Eye movements; Dipoles; Spatio-temporal dipole model

The eyes are electrically charged, positive at the cornea and negative at the retina. When the eyes or eyelids move, the potential field arising from the charge changes, and this change can be measured on the head as the electrooculogram (EOG). The source of the electrical charge lies in a potential difference across the retina, mainly arising from current generated by the pigment epithelium. The electrical and magnetic properties have often been described in terms of an equivalent dipole located somewhere within each eye (e.g., Barry and Jones 1965; Katila et al. 1981; Antervo et al. 1985; Elbert et al. 1985). Modelling of the magnetooculogram (MOG) has been carried out by Antervo et al. (1985) for eyeblinks and by Katila et al. (1981) for eye movements, with reasonable agreement between dipole models and data. Models of electrical eye activity in terms of dipoles have so far not been tested in detail. It was the main aim of the present study to provide such a test.

For investigators of EEG and event-related potentials, eye movements and blinks are a constant source of artifact. A number of computational methods have been developed to attempt to eliminate the artifacts, most of which are based on the assumption of a linear relationship between various components (e.g., vertical and horizontal movements, and blinks) of the EOG signal recorded near the eyes and the artifact measured at EEG electrodes (for critical comparisons of such methods, see, for example, Berg 1986; Gasser et al. 1986; O'Toole and Iacono 1987; and in particular, Brunia et al. 1989). The assumption of a linear relationship seems to hold reasonably well, although no one has claimed to be able to perform a perfect artifact correction, and different correction methods produce slightly different results, especially in their effects on slow components of the signals (Brunia et al. 1989). It is generally regarded that the assumptions are based on some sort of compromise with the complexity of the real situation in which the EOG is a result of a number of factors, including eyeball rotation and movement, eyelid movements, and EEG. Elbert et al. (1985) used the equivalent dipole interpretation of the EOG generators to argue that for eye movements, rotation of the dipole during eye movements makes it necessary to record 3 EOG channels in order to be able to take up components of each of the 3 orientation axes of the dipole. They assumed that the dipole rotated about a single location. Preliminary modelling of data by Berg and Scherg (cf., Berg 1989) suggested that the dipole location was not fixed, but moved in such a way as to suggest that the vertical eye movement dipole is located behind the axis of rotation of the eyeball. A change in location provides difficulties for most eye artifact correction methods because it implies that the assumptions about a simple linear relationship between signals at EOG and EEG electrodes are not true. It was thus a further aim of the present study to investigate whether

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such a change in location does occur during eye movements and blinks.

In practice, when we measure EEGs or EOGs, we start out from some baseline which subtracts the effects of the static ocular (equivalent) dipole. When eye movements or blinks occur, the dipole moves, and the field changes. It is these *changes* that are recorded as EOG. When looking at the ocular dipole of an eye we are therefore only able to see the result of its having *changed* its location or orientation. The dipoles we observe and model are *difference* dipoles, representing the difference between two positions of the ocular dipole. Therefore, each type of eye movement away from a baseline can be modelled separately and can be expected to have a different orientation determined by the start and end points of the ocular dipole. From the behavior of the difference dipoles we can make conclusions about the behavior of the ocular dipole. For instance, if it only rotates, the difference dipoles should only change their orientation, but not their location. If it changes its location, then so should the difference dipoles. The experiment was designed with these points in mind: each type of movement was carried out with reference to a fixation point. The voltages at the fixation point were subtracted from the data to define the baseline, so that each separate eye movement could be modelled independently.

Source analysis

Dipole modelling was carried out using a method developed by Scherg and others (Scherg 1984; Scherg and Von Cramon 1985a,b, 1986; Scherg et al. 1989; see Scherg 1990 and Scherg and Picton 1991 for a review and detailed description of the method used here) which is designed to distinguish the effects of temporally overlapping activities generated at various locations in the brain by modelling each generator with an equivalent stationary dipole. Similar approaches have recently been discussed and proposed by others (Maier et al. 1987; Achim et al. 1988; Möcks 1988). The spatio-temporal dipole model allows the evaluation of hypotheses about dipole sources underlying a given set of surface potentials, using a 3-shell head model (Scherg 1990; Scherg and Von Cramon 1985a). For a given set of dipoles at a given location and orientation, the source wave forms can be computed that provide the best fit to the data. Subject to constraints such as left-right symmetry, which the user can determine, location and orientation of the dipoles are adjusted in an iterative procedure in an attempt to maximize the amount of variance in the data explained by the model. One criterion for evaluation and comparison of models is therefore the 'residual variance' (RV), the amount of variance in the data which is unexplained by the model. Another criterion is Occam's razor: a simple model with fewer sources is to be preferred over more complex solutions unless the more complex model provides a qualitatively better explanation of the results. Furthermore, the models must be physiologically reasonable. For eye movements it is thus reasonable to expect there to be dipoles located somewhere in each eye and to expect there to be some left-right symmetry between the sources.

The model assumes stationary dipoles. In the case of eye movements and our hypothesis about changes in dipole location, the ocular dipole is assumed to move. Nevertheless, by asking subjects to move their eyes through a fixed angle, we can assume that the difference dipole for a given eye movement is stationary. The question about whether the dipole moves then boils down to the question whether the dipole location or orientation is different for different eye movements.

In addition to testing hypotheses about the ocular dipoles, such modelling provides a test of some of the limits of the method and its underlying head model. It can be expected that there will be some deviations from the model when the dipoles are near the surface of the head, especially at the eyes, where the skull is not closed and deviates considerably from the 3-shell spherical ideal head.

Method

Subjects and recording

Four subjects, 2 males and 2 females, aged between 25 and 35 years were tested. Twenty-three chlorided silver-cup electrodes, of which 10 were located on the right, 10 on the left, and 3 central (nasion, intermediate between Fz and Fpz, intermediate between Cz and Fz) were used. The approximate positions used are indicated in Fig. 1, which shows the averaged data at each head location for the 3 types of eye activity in 1 subject. After attaching the electrodes, their positions on the head were measured in relation to the nasion and to Cz in order to compute their spherical coordinates for entry into the BESA program. The subject's head was fixated using a chin and forehead rest.

EEGs were recorded with a 12-channel Van Gogh 50000 EEG machine using a 10 sec time constant and 15 Hz low-pass filter. Measurements were carried out 12 channels at a time, referred to the right mastoid. In order to control for constant head position between measurements, 2 channels, above the left eye and to the left of the left eye, were repeated in each measurement, and the remaining channels were changed, leading to a total of 22 channels that could be recorded with 2 measurements. The channels were divided up so that adjacent positions on the head were allocated to different measurements if possible.

A board covered with black paper was placed 93 cm away from the subject. In the middle of the board at eye level was a yellow light-emitting diode (LED). Four
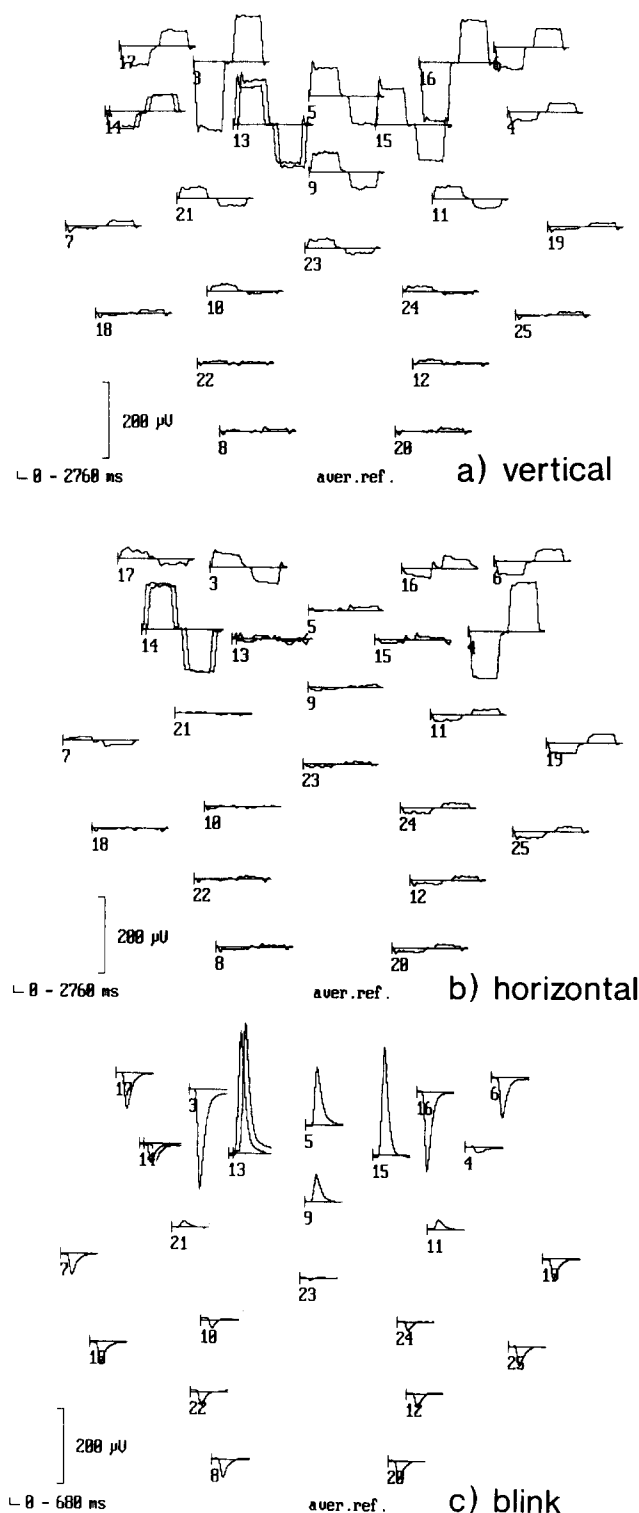
Fig. 1. Averages for one subject with the data from each electrode drawn at the approximate corresponding location on the head for (a) vertical and (b) horizontal eye movements, and (c) blinks. Data for electrodes 1 (above left eye) and 2 (left of left eye) overlap with 13 and 14. Some other electrode positions are mastoids (18, 25), nasion (5), cheeks (6, 17), below eyes (3, 16), O1 (8), O2 (20). Cz is between 10 and 24. Electrodes 1–12 were recorded during the first and fourth measurement blocks, 13–24 during the second and third blocks.

yellow LEDs were located 25 cm above, below, left and right of the center LEDs. The angle subtended between the center and peripheral LEDs was 15° (a pilot study had indicated that 15° movements generated sufficiently large signals for modelling using the BESA program).

Procedure

A single trial consisted of the following sequence of events:

(1) Recording started with the central LED on, 100 msec.

(2) The central LED was switched off and a peripheral LED was switched on, 1100 msec.

(3) The peripheral LED was switched off and the central LED was switched on, 1500 msec.

(4) A fixed intertrial interval of 500 msec.

There were 4 different types of trial, depending on which peripheral LED was switched on, presented in the fixed order: (a) up, (b) down, (c) left, and (d) right.

The subjects were instructed to look at the LED which was switched on. They were told to use the fixed inter-stimulus interval and constant sequence of events to try to make their eye movements simultaneous with the switching of the LEDs. They were instructed to blink immediately after returning their gaze to the center LED. This had the combined effect of reducing the number of blinks occurring simultaneously with eye movements and producing blinks in the second half of the trial which could be analyzed separately as a fifth condition of the experiment.

One measurement consisted of 30 trials on each of 4 eye movement conditions, leading to 120 trials, lasting approx. 12 min. Four measurements were made: (1) first set of electrodes, (2) second set, (3) second set, (4) first set.

Data analysis

The data were collected, controlled, and averaged using an HP 1000 mini-computer. Raw data were converted to DC by integrating over the time constant (Elbert and Rockstroh 1980; Gaillard and Näätänen 1980). The main error arising from such integration over the time intervals used here is the introduction of trends to signals on which the technical zero is not estimated correctly. The experimental design allowed for the definition of a baseline defining a constant DC level at both ends of the epoch, and a sloping baseline correction was therefore employed (see below) to remove trends. Data were visually controlled by examining the first 2 channels of each trial. Trials were rejected if blinks occurred during the eye movement part of the trial, if the wrong type of eye movement occurred (e.g., a vertical movement when a horizontal movement was required), or the eye movement occurred too early (less than 50 msec after the beginning of the trial). Trials

containing blinks that were uncontaminated by eye movements in the region of the blink were marked for separate averaging. Because the subjects' responses were not well synchronized to the LEDs, averaging of eye movements was carried out in relation to the movement onset and offset, using visual judgment to determine the latencies. Three different types of average were computed: (1) 100 msec before to 500 msec after onset of the eye movement towards the periphery, (2) 500 msec before to 300 msec after onset of the return eye movement towards the center, (3) 200 msec before to 500 msec after the maximum of the blink potential.

Averages were made combining the 2 measurements on a single set of channels. In 1 subject, 1 of the 4 measurements was rejected because the head position appeared to have changed, since the averages for the repeated pair of channels deviated from those of the remaining 3 measurements. The averaged data were then transferred to an IBM-AT-compatible computer for dipole modelling.

Finally, the averages for eye movements were concatenated and baseline adjusted as follows: (a) average sweeps for movements back to the central LED (600 msec) were appended to those for movements away from the central LED (800 msec), (b) from the resulting signals (1400 msec) a sloping baseline was subtracted, such that the first and last 50 msec of the signals averaged to zero (thus defining electrical zero as coinciding with fixation of the central LED), and (c) sweeps for horizontal right eye movements were then appended serially to left eye movements, and vertical downward movements were appended to upward movements, giving rise to segments of 2800 msec duration. The sloping baseline correction was also applied to the blink data (700 msec duration). Three sets of data were thus obtained: blinks, vertical eye movements, and horizontal eye movements. For each of these data sets dipole modelling was carried out independently with the aid of the Brain Electric Source Analysis (BESA) program (Scherg 1990).

Results

Note that in the following description, no attempt was made to model the ocular dipole directly, but only *difference* dipoles arising from possible changes in orientation or location of the ocular dipole. For each type of eye activity the following questions about equivalent (difference) dipoles were asked:

(a) Can the data for any one eye movement (up, down, left, right, blink) be explained by one dipole, or are two necessary (one per eye)?

(b) How do dipole *orientations* vary as a function of the type of eye movement?

(c) Do dipole *locations* change between left and right or between upward and downward eye movements?

(d) As an extension to (c), can all types of eye activity be explained in terms of a single *regional source*, i.e., a dipole which takes up different orientations but not different locations depending on the type of movement?

Fig. 1 shows typical data from one subject.

To test single-dipole models, a dipole was placed somewhere near the eyes, and the BESA program was allowed to adjust its position and orientation until the residual variance (RV — the variance in the data unexplained by the model) was minimized.

For multiple-dipole models, a number of constraints, based on our physiological expectations, were applied to reduce the set of alternative models. For example we expect the eyes to be symmetrically placed in the head. To test vertical eye movements and blinks with 2-dipole (one per eye) models, a constraint of left-right mirror symmetry was applied, i.e., only models with dipoles at equivalent positions on the left and the right of the midline were tested. The orientation of left-right dipole pairs was constrained to be mirror symmetrical, to reflect the symmetry of the eyes in relation to the head. For the 2-dipole models of horizontal eye movements, left-right dipole pairs were initially constrained to symmetrical locations, but the orientations of the left and right dipoles were not constrained. When testing the hypothesis about location changes of horizontal dipoles, the left-right symmetry constraint was dropped, but another location constraint was applied, that the horizontal angle subtended by the 2 dipoles from the center of the head be kept constant. This constraint allows the question to be asked whether or not the dipoles change their location (together) between left and right eye movements and in which direction such changes may occur. When testing the hypothesis that the dipole changes its position with direction of eye movement, separate dipole pairs were fitted for eye movements to the left and to the right, and again for movements up and down.

In all model fitting, the BESA program was allowed to adjust the unconstrained location and orientation parameters iteratively, until the residual variance (RV) was minimized. In most cases, except for those listed below, there was a very sharp minimum in RV, i.e., slight shifts of the dipoles away from the best fit gave rise to a large increase in RV. Exceptions were (a) the single-dipole model of horizontal movements, and (b) the RV for models of vertical eye movements and blinks was not very sensitive to changes in horizontal position of dipoles. A consequence of the clear minimum was that BESA located the dipoles in the same place at the same orientation regardless of the initial hypothesis. Residual variances for each model and subject are shown in Table I.

(1) One or two dipoles?

For vertical eye movements and blinks, the optimum position of a single dipole was close to the sagittal plane between the eyes and oriented close to the vertical for vertical eye movements and approximately 45° forward

from the vertical for blinks. For horizontal eye movements there were two minima of residual variance, one at each eye, and there was a tendency for BESA to move the dipole to one or the other position, depending on the initial hypothesis. The RV given in Table I is the

up   down   left   right

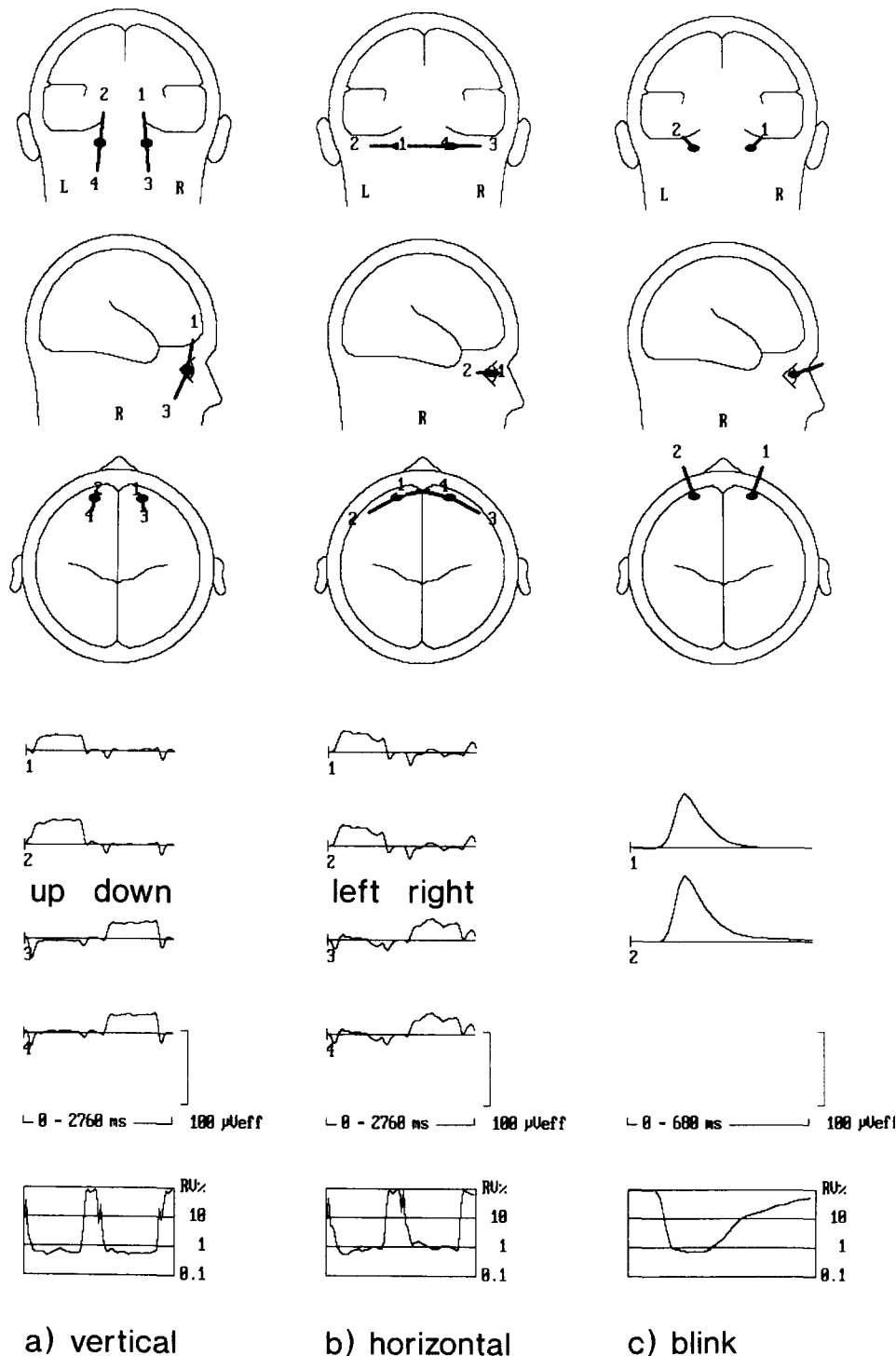a) vertical   b) horizontal   c) blink

Fig. 2. Top: approximate orientations and schematic locations of dipoles in the 4-dipole models for (a) vertical and (b) horizontal eye movements, and (c) the 2-dipole model for blinks. Dipoles 1 and 3 are in the right eye, 2 and 4 are in the left eye. Middle: wave forms showing the dipole magnitudes that model the data shown in Fig. 1, numbered as in the top section. Bottom: time courses of the corresponding residual variance (RV). Note that at time points where RV is high, the overall signal variance is low, i.e., the model is bad at explaining the noise.

TABLE I

Residual variances (in percentage of total variance) for each model of eye dipole activity: (a) one dipole, (b) one dipole in each eye, (c) two dipoles in each eye, (d) regional source fitted to vertical movements.

Subject	Movement	Model			
		One dipole	One/ eye	Two/ eye	Regional source
1	vertical	2.94	0.99	0.72	0.37
	horizontal	31.9	1.23	1.03	1.02
	blink	5.1	1.05		5.03
2	vertical	2.79	2.58	0.61	0.76
	horizontal	23.9	2.89	1.29	7.54
	blink	6.14	0.76		6.67
3	vertical	2.31	1.48	0.75	0.82
	horizontal	29.4	6.83	2.56	3.90
	blink	24.5	1.15		9.09
4	vertical	7.98	1.52	0.63	0.58
	horizontal	23.9	1.57	1.13	0.81
	blink	16.8	0.77		2.38
Means	vertical	4.0	1.6	0.7	0.63
	horizontal	27.3	3.1	1.5	3.31
	blink	13.1	0.9		5.79

lower of the two. The dipole was oriented in the horizontal plane.

For all types of eye activity, 2-dipole models produced, as expected, a lower RV than single-dipole models. For horizontal eye movements the improvement was particularly large (RV reduced from a mean of 27.3% to 3.1%). For blinks the improvement was also large (13.1% reduced to 0.93%), and for vertical eye movements the improvement was smallest (4.0% to 1.6%). Fig. 2c shows the orientation and approximate position, and the source wave forms and residual variance for one subject as a function of time for blinks. For every individual comparison there was an improvement from a single to a 2-dipole model (cf., Table I).

(2) Different orientations for each type of movement?

Here we compared models where 2 dipoles (one per eye) were used to fit horizontal or vertical movements with those where 2 dipoles modelled a single eye movement (e.g., left), and 2 additional dipoles *at the same location* modelled the opposite movement (e.g., right).

There is an improvement from the 2- to the 4-dipole model for each subject and movement type (cf., Table I, columns 2 and 3), although these improvements are less remarkable than from the single- to 2-dipole models.

(3) Fixed dipole location?

The 4-dipole model with fixed locations was compared with one in which the location of the dipole pairs was allowed to vary between directions of eye movement. Fig. 2 shows schematically how the dipoles in the 4-dipole model were oriented for vertical (Fig. 2a) and horizontal (Fig. 2b) eye movements. The source wave

forms and residual variance as a function of time are shown for one subject. For eye movements (Fig. 2a,b), sources 1 and 2 are only active during upward (left) movements, and sources 3 and 4 during downward (right) movements, i.e., the model separates the movements cleanly into distinct components.

Table II shows how the vertical position of dipoles changes between up and down movements, and the horizontal position changes between left and right movements. The direction of the changes is opposite to the direction of gaze for vertical eye movements, and the same as the direction of gaze for horizontal eye movements. Note that these changes are in the same direction for each subject.

(4) Is there a single combined model?

So far we have applied separate models to vertical and horizontal movements and to blinks. The positions and orientations of dipoles varied depending on the type of eye activity. The question arises whether dipole activity for all types of movement could be combined into a single model. The simplest type of combined model would assume one pair of dipoles which can take up any orientation but remain in a fixed position. This type of model, described by Scherg and Von Cramon (1986) as a regional source, can be represented by a set of 3 orthogonal dipoles of fixed orientation. We have noted that variations in position have a smaller effect on model fits than variations in orientation, so a pair of fixed regional sources may provide a good fit to the data. A simple test of this hypothesis is to fit a regional source to, say, vertical eye movements, and then see how well this model fits the data for horizontal eye movements and blinks. A small residual variance (comparable to the values obtained for the individual models in Table I) for all 3 types of eye movement would indicate that a combined model is adequate. The values are shown in the right-hand column of Table I. The

TABLE II

Dipole positions for eye movements. Measurements are given in degrees (latitude) from the vertex for vertical and (longitude) from the right mastoid to the right-hand dipole for horizontal movements.

Subject	Movement	Position	Movement	Position
1	up	115.5	left	67.7
	down	113.9	right	66.8
2	up	121.3	left	68.4
	down	118.1	right	67.5
3	up	120.1	left	69.6
	down	116.4	right	69.0
4	up	111.0	left	66.4
	down	109.2	right	65.7
Means	up	117.0	left	68.0
	down	114.4	right	67.2
Delta		2.6		0.8

high RVs for the combined model compared with those for separately fitted models show that a combined model with stationary dipoles does not explain the data as well as if the dipoles are allowed to change their location depending on the type of eye movement.

When the locations of the regional sources were fitted to each type of movement separately, the results were similar in magnitude and the same in direction as for the single dipoles (cf., Table II). Although the regional sources provide a good fit to the data for individual movement types, the fits are even better and the differences in position are systematic, if movements up and down, and left and right are modelled separately.

(5) Relationship between dipole position and type of eye movement

Apart from those movements listed above, the following additional relationships between dipole positions held for each subject:

(a) Blink dipoles were in front of and above vertical eye movement dipoles (mean change in vertical angle 4.6°, eccentricity, i.e., percentage distance from the center of the head, 3.9%). Blink dipoles were also located further apart (mean change in horizontal angle 4.2°).

(b) Horizontal dipoles were in front of vertical dipoles (mean change in eccentricity 2.5%).

(c) Vertical dipoles changed orientation with the direction of gaze, in the direction of the shift in gaze, i.e., approximately at right angles to the direction of gaze. Discounting the opposite direction of the dipoles, the mean change in vertical orientation was 12.1°. The equivalent change for horizontal movements was present only for 3 out of the 4 subjects (again discounting the opposite direction of the dipoles, the mean change in orientation was 8.7°).

(d) Horizontal dipoles were oriented approximately tangential to the surface of the head and were, therefore, consistently oriented differently between right and left eye dipoles (mean difference 33.2°).

(6) Stability: single trial analysis

In order to evaluate the stability of the results, for each subject 2 single (unaveraged) data sweeps were selected from the data for each subject and each type of eye movement, and the 4-dipole model was applied to each sweep individually. The orientation and position of the dipoles were similar to those for the average and, in particular, all the relationships between the dipoles, both in position and orientation, that were consistent over subjects in the average data, held for each of the single sweeps.

Discussion

With some limitations, clear answers to the questions about movements of the ocular dipoles could be pro-

vided using the BESA analysis to model difference dipoles. Not surprisingly from physiological considerations, a model using one equivalent dipole between the eyes did not explain the data well. Neither was a model with fixed dipoles of arbitrary orientation (regional sources) in each eye capable of explaining the data because, depending on the type of eye activity, the equivalent (difference) dipole appears to take up a different location. Eyeblink dipoles appear to be located in front of and above those for vertical eye movements and are oriented forward and slightly upward (cf., Fig. 2). Eye movement dipoles are oriented approximately tangential to the head in the direction of the movement, with small radial components directed toward the center of the head. In the following we first consider explanations for the obtained results, and then some consequences of the results for attempts to correct EOG artifacts.

When considering physiological explanations for the results we have to bear in mind that deviations from the 3-shell spherical head model may have contributed. Such deviations are particularly large around the eyes, since they are not completely covered by bone, have bone behind them, and are embedded in a layer of fatty tissue. In the light of this, the ability of the head model to explain the results so well (in terms of a small residual variance) with relatively simple equivalent dipole solutions is remarkable. We shall argue that most of the results are of physiological origin, but because of some inconsistencies, our interpretation is speculative.

Because of the limitations of the head model we cannot take the *absolute* locations determined by model fitting seriously. More important are the *relative* changes in location and in orientation of the difference dipoles, which are less likely to be affected by inaccuracies in the head model.

Physiological and other explanations of the results

Most of the results can be explained in terms of movements of the ocular dipole with eye rotation or eyelid movement. By vector arithmetic, rotations of the ocular dipole through 15° to either side (or up and down) should produce a difference in orientation between the difference dipoles of 15°. The obtained angles were in the expected direction, but were smaller than expected (12.1° for vertical, 8.7° for horizontal), although it is not possible to tell with the present data whether these differences from expectation are significant. A possible explanation for the underestimation of the angle between dipole pairs could lie in deviations from the simple head model. The eyes, and hence the current sources of the ocular dipoles, are outside the skull. Current will reach scalp electrodes more readily through the bone-free path which takes it anteriorly over the orbital rim than via the more direct but high resistance path through the frontal bones. The propor-

tion of current funneling through this low resistance anterior path will appear to scalp electrodes to have a stable origin around the orbital rim. Summing with current paths through the bone, it will reduce the apparent angle through which the ocular dipole rotates, and therefore the angle between the difference dipoles.

During vertical eye movements dipole *locations* moved in the opposite direction to the eye movement. One possible explanation is that the dipole is located behind the axis of rotation of the eyes. The results for horizontal movements argue against this interpretation, because the horizontal dipoles moved in the *same* direction as the eye movement, although it is conceivable that the horizontal location change was in some way related to the particular constraints applied in the fitting procedure. During vertical eye movements, the eyelids move with eyeball rotation. It is probable that both eyeball rotation and eyelid movement contribute to the EOG measured during vertical eye movements (Barry and Jones 1965). Thus the upward movement of the dipoles when the direction of gaze goes down could be due to the increase in conductivity between the eyeball and the forehead as a result of the lowered eyelid. This is consistent with the changes in dipole location between vertical eye movements and blinks, and the orientation of the blink dipole. During blinks, the equivalent ocular dipole appears to move forwards and upwards, causing the difference dipole to be in front of those for vertical movements.

Unfortunately the above explanation is not consistent with the *location* of the horizontal dipoles. If eyelids contribute to vertical but not to horizontal movements, the horizontal dipoles should be located behind the vertical dipoles, which was not found to be the case. An explanation can be found in terms of deviations from the spherical head model, and the relative strengths of signals at different electrodes. Electrodes with the largest signals have the greatest weighting when estimating goodness of fit of a model. Thus for horizontal movements, the electrodes at the outer canthus carry large signals, whereas those above and below the eyes carry small signals. The opposite is the case for vertical eye movements and blinks. For blinks, the largest activity is measured at the electrodes above the eyes. Now let us consider the positions of these electrodes relative to the perfect sphere of the 3-shell head model. The model assumes that the electrodes are on the outer surface of the sphere. The forehead is further away from the center of the head than the outer canthus, whereas the model assumes they are at the same distance. If dipoles with the same location are determined by the outer canthus they will appear to be located nearer the surface of the sphere than if they are determined by the forehead. Thus horizontal movement dipoles will appear to be nearer the surface. Note that this cannot explain the relative positions of blink and vertical movement dipoles. In that case, deviations from the perfect spherical model would predict the opposite to the present results.

Could the apparent movements of dipoles between left and right horizontal and between up and down vertical eye movements be explained in terms of head model inaccuracies? The relative strengths of the signals vary only slightly between the eye movements at each electrode (the main difference being a change in signal polarity), whereas the apparent dipole movements are of the same order of magnitude as the differences in position between horizontal and vertical dipoles. It is therefore improbable that head model inaccuracies, at least with the mechanism we have considered above, can explain these results.

A possible further explanation for the apparent changes in position of the ocular dipoles may lie less in physical movement of the dipoles or head model inaccuracies and more in the assumption that the electrical activity can be represented by a single equivalent dipole in each eye. Perhaps for the electrodes placed near the eyes it is necessary to include quadripolar components. More detailed modelling is necessary to clarify this question.

In order to clarify the results, improvements in the head model would be useful, or measurements in which the deviations from the head model are smaller, as might be obtained from MEG records. So far, MEG recording of eye movements and blinks (Katila et al. 1981; Antervo et al. 1985) has not been carried out in sufficient detail to be able to compare the different types of movement as we have attempted to do here. EEG recording with a larger number of electrodes would also allow more accurate modelling with less need for external constraints to the set of possible models — the more electrodes, the more constraints are applied in terms of the obtained signal magnitudes at locations on the scalp.

Consequences for eye correction methods

The results help to understand some of the difficulties associated with eye artifact correction in EEG recording (extensively discussed in Brunia et al. 1989). Differences in dipole orientation illustrate clearly why vertical eye movement and blink EOGs differ in how they propagate over the head and therefore cannot be corrected together using procedures with only one correction factor (see, for example, Gratton et al. 1983). Changes in dipole location with direction of gaze provide difficulties for methods based on stationary dipoles with horizontal, vertical and radial components (Elbert et al. 1985). Such methods will only function well if eye movements are small and will probably not cope properly with mixed eye movements and blinks. The larger the eye movements, the more degrees of freedom need to be catered for by the correction method. Thus, in-

cluding more EOG channels in a multiple regression technique to remove artifacts will be necessary for large eye movements (as, for instance, in the method of Möcks in Brunia et al. 1989).

Changes in location of dipoles with eye movements may have a disproportionately large effect on most eye movement correction methods because the methods make use of EOG signals recorded near the eyes to compute the size of the eye artifact and estimate its effect at other electrodes. Dipole movements will have little effect on distant electrodes but will affect the local EOG electrodes, thus introducing non-linearities where the correction methods assume a linear relationship between the signal at local EOG electrodes and the artifact at other electrodes.

Dipole modelling could provide an alternative family of methods for correcting eye artifacts. EOG signals at all electrodes could be used to estimate the activity of the equivalent dipoles, after which the signal predicted by the dipoles could be subtracted from each EEG signal. Such an approach should in principle be more powerful than the regression methods because it is able to use the information at all electrodes simultaneously to estimate eye activity, whereas past methods have only been able to relate one EEG channel at a time to EOG electrodes located around the eyes. Simultaneous modelling of eye and brain activity could also enable the separation of frontal EEG sources from EOG activity, which has often been considered a problem of eye artifact correction methods (cf., Brunia et al. 1989), because the EEG present at EOG electrodes leads to a distortion of scalp topography after correction.

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