Source Localization of EEG Versus MEG: Empirical Comparison Using Visually Evoked Responses and Theoretical Considerations

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Summary: Theoretically, the information we can obtain about the functional localization of a source of brain activity from the scalp, for instance evoked by a sensory stimulus, is the same whether one uses EEG or MEG recordings. However, the nature of the sources and, especially of the volume conductor, poses constraints such that appreciable differences between both types of data may exist. We present here empirical and theoretical data that illustrate which are the main constraints and to what extent they may affect electric potential and magnetic field maps. The empirical data consists of visual evoked potential and magnetic fields to the appearance of a checkerboard pattern (half-visual field stimulation). The concept of equivalent dipole is presented and its limitations are discussed. It is considered that the concept of equivalent dipole (ED) yields only an approximate description of the activity of a patch of cortex. A main difference between EEG and MEG recordings is the fact that radially oriented dipoles can hardly be seen in the MEG in contrast with the EEG. Accordingly, a weak tangential dipole component is difficult to distinguish in the EEG if a strong radial component is also present. However, a combination of both methods can give useful complementary information in such cases. A factor that influences largely such differences is the model of volume conductor used. A four concentric spheres model, as commonly used for solving the inverse problem of source localization, causes appreciable errors when EEG data are used but much less in case of the MEG. The use of a model consisting of eccentric spheres fitting the four compartments, brain, CSF, skull and scalp, provides a better approximation of the real geometry of the head and allows to obtain comparable results for visual evoked potentials and magnetic fields. It is emphasized that for precise localization of EDs, especially based on EEG recordings, a realistic model of the different compartments of the head is necessary. The latter must be tailor made to a given subject using MRI-scans, in view of the large variability in head geometry between subjects.

Key words: Visual EPs; MEG; Source localization.

Introduction

The computation of the sources from the measured EEGs and/or MEGs is called the solution of the inverse problem. This solution is not unique. In order to solve this problem, one has to make assumptions: one has to model both the sources and the volume conductor. These assumptions have to take into account the electrophysiological reality. However, in general, one does not know how many sources are active in a given case or whether there are any regions of different conductivity in the vicinity of the sources, for example, a brain tumour or other lesion. What is known is that the real nature of the source and of the volume conductor is highly complex. In practice, however, the MEG and the EEG corresponding to the same current source, may differ. This is due to the constraints imposed by the complexity of the volume conductor and the nature of the source. Consequently, it would be important to be able to use both the MEG and EEG in the inverse solution, since the EEG and MEG contain information which is partly independent and because the noise in the measurements is also to a large extent uncorrelated. If both methods would lead to the same solution, this would give confidence in the results obtained. Recently, this question was investigated by a comparative study of the locations of EDs corresponding to implanted dipoles obtained from potential and magnetic measurements (Cohen et al. 1990). However, this study gives only information about the influence of the volume conductor in a particular region of the head for a particular subject, but not about the influence of the structure of the source. The volume conductor description which is usually used for the solution of the inverse problem based on the measured potential distribution consists of four concentric spheres with conductivities which were adapted by Cohen and Cuffin (1983) in order to get the same tangential dipole for measured EEGs and MEGs in the

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somatosensory cortex. Previously, a number of these problems has been addressed by us and collaborators (Stok 1986; Maier et al. 1987; Meijs and Peters 1987; Meijs et al. 1987; Van Dijk and Spekreijse 1990; De Munck 1989; Stok et al. 1990). Here we consider empirical data by combining EEG and MEG sets of data in the same estimation. We analyze and compare the two approaches - electro - and magnetoencephalographic - in attempting to localize intracerebral sources of fields evoked by sensory stimulation. We concentrate on the question of the sources of visual evoked activity because most of the experience of our group concerns this sensory modality. First, we present empirical data on visual evoked potentials (VEPs) and visual evoked magnetic fields (VEFs). In the second part, we discuss these data in relation to theoretical aspects and to computer simulation studies.

Empirical Comparison of VEPs and VEFs

Introduction

The experiments on which this empirical comparison is based, were carried out using as stimulus the transient appearance-disappearance of a checkerboard presented on a small visual field. Such a stimulus can be assumed to evoke activity in a restricted and well-defined area of the cortex, at least within the initial 150-200 ms (Spekreijse and Estevez 1977; Maier et al. 1987). This feature is of importance since it makes a model of the source of the VEPs/VEFs consisting of a single equivalent dipole (ED) acceptable as a first approximation.

Material and Methods

The methods used are the same describe by Stok (1986) and Stok et al. (1990). Transient responses to left or right visual half field patterned stimulation were measured in healthy subjects, 20 to 30 years old, with normal or corrected to normal vision and normal binocular function. The stimulus used consisted of a pattern that abruptly appeared and stayed for 300 ms; the pattern was replaced for 500 msec by an isoluminant grey screen (on-off). The pattern consisted of a checkerboard (0.35 x 0.27 m^2) with black and white square fields (40% contrast, 24 mm side) with an average luminance of 60 cd m^{-2}. The grey screen had an equal average luminance to avoid flash stimulation. The stimulus was presented on a TV-screen and was viewed binocularly from a distance of 5.40 m. Hence, the angle subtended by the TV-screen was approximately 3 degrees and the angle subtended by a check 19 minutes. The fixation point was either at the left or right edge of the TV screen.

Twenty three electrodes were used to measure the VEP distribution in the occipital region of the head. Eight channels were measured simultaneously with the electrode at C_Z as ground and the midfrontal electrode as reference. The EEG was bandpass filtered (0.3 - 70 Hz) and digitized at 200 Hz with 8 bits accuracy. On-line averaging with automatic artefact rejection was performed on a micro computer (de Waal et al. 1983) until 100 responses were averaged. This relatively small number of responses averaged was chosen to keep the recording sessions short such that the subject's state and fixation were kept as constant as possible. The average response was stored on floppy disk and evaluated off-line. As a rule each VEP was recorded twice.

VEFs were recorded from 31 to 40 locations in a plane 12 mm above the occipital region. The field is defined as positive when the field lines enter the head. We measured the field component normal to the head, which is advantageous with regard to the accuracy in the determination of the gridpoints and the orientation of the field component.

This component of the magnetic field was measured by a symmetric second-order home-made gradiometer with a baseline of 60 mm and a coil diameter of 30 mm coupled to a SQUID and its electronics (S.H.E. Corporation, now B.T.I. Corporation). The Dewar containing the SQUID and gradiometer was kept stationary during the measurements. The axis of the gradiometer was oriented vertically, with a distance of 12 mm between the pick-up coil and the subject's scalp at the inion. The subject was positioned under the gradiometer by moving the bed where he or she was lying (accuracy of 2 mm in all coordinates). Measurements were thus performed along a horizontal plane which had the distinct advantage of fast and accurate positioning without the need for a complex positioning apparatus. The subject was kept in a well known position with respect to the gradiometer (which was not moved at all) by using a mouth piece that was made to fit the teeth of the upper jaw.

The magnetic signal was prefiltered (bandwidth 0.3-200 Hz) and then digitally filtered (256 points linear phase filter, 1000 Hz sample frequency) with a passband 0.7-95 Hz. Sample frequency was then reduced to 200 Hz. On-line averaging was performed until 200 responses were averaged. The growing average was displayed to monitor the signal to noise ratio during the measurements. The plus-minus average (Schimmel 1967) was computed to estimate the signal to noise level in the VEF. The averaged responses were stored on floppy disk.

Signal to noise ratios for the MEG were small (0 to 10 dB at response peak, after averaging) but the single response duration (800 ms) prevented prolonged averaging. Because the responses were measured one at the time, the acquisition of the data for one half field stimulation took one to three sessions of 2-3 hours. Along with VEF measurements, VEPs were recorded simultaneously to monitor the stability of the responses, i.e., when a certain stimulus was repeated in order to measure the VEF at different sites the VEP at one particular site was repeatedly recorded for testing the reproducibility of the responses.

The noise level after averaging was expressed as the square root of the power per unit bandwidth. The average variance was 8.1×10^{-27} T^2 within the frequency band 0.7 - 95 Hz ($\approx$ 9.2 fT/√ Hz). Across 203 measurement points that were obtained in this study over a period of three months, it varied between 4 and 20×10^{-27} T^2 ($\approx$ 6.4 and 14.5 fT/√ Hz), excluding 10 outliers.

Plots of single average responses and contour plots of VEPs and VEFs were used for visual inspection of the data.

The VEP and VEF data during selected time periods in the on-response were subjected to equivalent dipole estimation. Contour plots at 5 ms intervals of the VEP and VEF distribution were generated for selected periods of time during the first 35 till 160 msec of the pattern on-response. To make these plots we, first, filled in the missing points using an interpolation procedure (Akima 1978); second, we united the points with the same values by contour lines according to the method of Snyder (1978). Equivalent Dipoles (EDs) were estimated by a least squares fitting procedure (Stok 1986) at 5 ms intervals from VEP and VEF distributions in the period 55-160 ms. A single dipole was used to model the source and a set of four concentric spheres was used to model the volume conductor, i.e., the brain, the cerebrospinal fluid, the skull and the scalp. The radii of the spheres used were 63, 65, 71 and 75 mm. These radii were based on magnetic Resonance Images of the head of subject CS by a least squares fit to the data in the occipital region (Meijs et al. 1987). The ear to ear distance, measured along a straight line, which gives a good indication for the diameter of the outer sphere, was about the same for all subjects. The conductivities used for the scalp, skull, fluid and brain compartments were respectively 0.33, 0.0042, 1.0 and 0.33 $(\Omega m)^{-1}$. These conductivity values have the same ratios as those used by Cohen and Cuffin (1983). The ratios of the conductivities and those of the radii, determine the properties of the volume conductor.

Because a radial current dipole in a sphere does not produce a magnetic field outside that sphere, the radial component of the ED can not be estimated from the VEF distribution. Hence the VEF based ED is described by 5 parameters only.

The effect of the gradiometer (Stok 1986) on the VEF based EDs can be large, depending on the source. However, since the effect is mainly on the strength of the ED, we did not include the gradiometer in the model which was used for the inverse calculations. The mid-frontal reference electrode was included in the calculations of the VEP based ED.

The projections of eleven consecutive EDs (positions and components) on three orthogonal planes were plotted. Such plots were not always suited for comparisons. The position and direction of the EDs were checked for consistency by visual inspection of the contourplots of the measured and forward calculated distributions. The goodness of fit (Stok et al. 1990) for each ED estimate was represented in the plots by the thickness of the line corresponding to the ED. The better fits were indicated by thicker and the worse fits by thinner lines. In order to obtain data reduction, EDs computed for successive 5 ms time samples were clustered in case their position and orientation were similar. The average ED of such a cluster was computed. This average ED corresponds thus to a given time interval. Such an interval was determined on basis of the stability of the dipoles and of the contour plots.

Results

In order to establish the validity of the estimated EDs, the computed contour plots were compared to those that were measured experimentally as illustrated for the same subject and for two time samples in Figure 1. An examination of these plots revealed the theoretically expected differences between VEP and VEF contour plots: 90 degrees rotation in case of a tangential dipole, a more tight VEF than VEP pattern and no influence of a radial dipole component on the VEF. The latter effect can be seen by comparing the measured VEP contour plot in Figure 1 (time sample: 100 ms), which shows no negativity, with the corresponding computed plot that was based on the ED calculated from the VEF data, and that shows a left negativity - right positivity, typical of a horizontal tangential dipole. A direct comparison between the EDs calculated from plots of VEPs and from the corresponding VEFs for the same subject are shown in Figure 2. An obvious difference between the EDs estimated from EEG recordings (E-EDs) and those estimated from MEG recordings (M-EDs) is the lack of radially oriented dipoles in the latter. At the same time, the M-EDs reveal the existence of clear tangentially oriented components. Nevertheless, we may conclude that the position of the corresponding EDs, both E-EDs and M-EDs, is approximately the same, at least for the first time epoch (75-105 ms). However, there are differences in the orientation of the E-ED and M-EDs. In both cases, successive EDs could be clustered into two groups; the first group of E-EDs corresponded to the epoch starting approximately at 80 ms up to about 120 ms. At approximately 125 ms, the E-EDs appeared to move towards the mid-line and rotated, forming a second cluster from 125 to 150 ms. In comparison, the ED calcu-

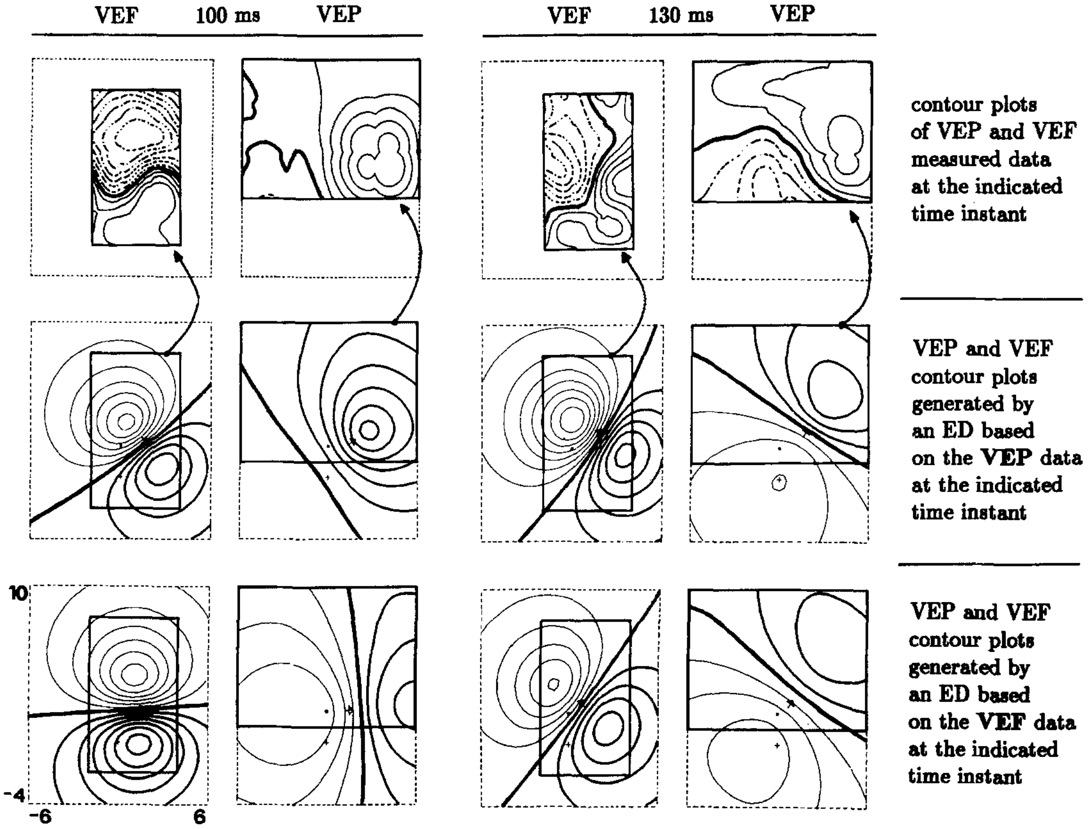


Figure 1. Measured and calculated VEP and VEF distributions. Data of subject JM. Top row shows measured VEF and VEP contour plots for two instants of time during the on-response: (a) 100 ms and (b) 130 ms. Middle row shows simulated VEF and VEP contour plots which correspond to the EDs which were estimated from the measured VEP distributions. Bottom row shows the simulated contour plots which correspond to the VEF based EDs. The dashed rectangles indicate the simulation area of 12 x 14 cm^2. (Measures are in cm and with respect to the inion). In the contour plots of measured data, negativity is indicated by dashed lines and in the contour plots of simulated data by thin lines. The thick lines indicate the zero level. Note that these plots present theoretical and experimental examples of the three differences that can be expected between EEG and MEG contour plots.

lated from the corresponding VEFs showed consistent estimates in the period 70-135 ms but two clusters could be distinguished, one corresponding to the epoch 70-115 ms and the second to 120-135 ms. The difference between both epochs can be best seen in the occipital projection. Taking into consideration that the radially oriented EDs encountered in the early phases of the VEP, at about 80-120 ms, are not seen in the VEFs a fair comparison between EDs obtained from MEG and EEG recordings should only be made for the EDs that correspond to tangential components. The results are summarized in Figure 3.

This figure presents summaries of the average EDs during the on-response to left visual half field stimulation in three subjects. The averages were computed from the EDs based on VEFs (M-EDs) and for the tangential component of the EDs based on VEPs in the corresponding experiments (E-tED) (The complete ED based on the VEP is called E-ED). We should emphasize that a comparison of M-EDs and E-tEDs presents a number of difficulties. Among these, we must consider the fact that estimates for both types of EDs could not always be obtained within the same time range. The data of Figure 3 illustrates these difficulties and allows a critical analysis of such comparisons.

In subject JM, the M-EDs (Nrs. 1 and 2) and E-tEds (Nrs. 3 and 4) in Figure 3 are comparable: 1 and 3 respectively 2 and 4 span corresponding time periods. The orientations of 1 and 3 differ somewhat but those of 2 and 4 are rather similar. The division between epochs I and II that was made for the E-tEDs Nrs. 3 and 4, was also applicable to the M-EDs Nrs. 1 and 2. In subject HM the M-ED (Nr. 1) had a similar position and direction as the earlier of the two E-tEDs (i.e., Nr. 2) but did not cover

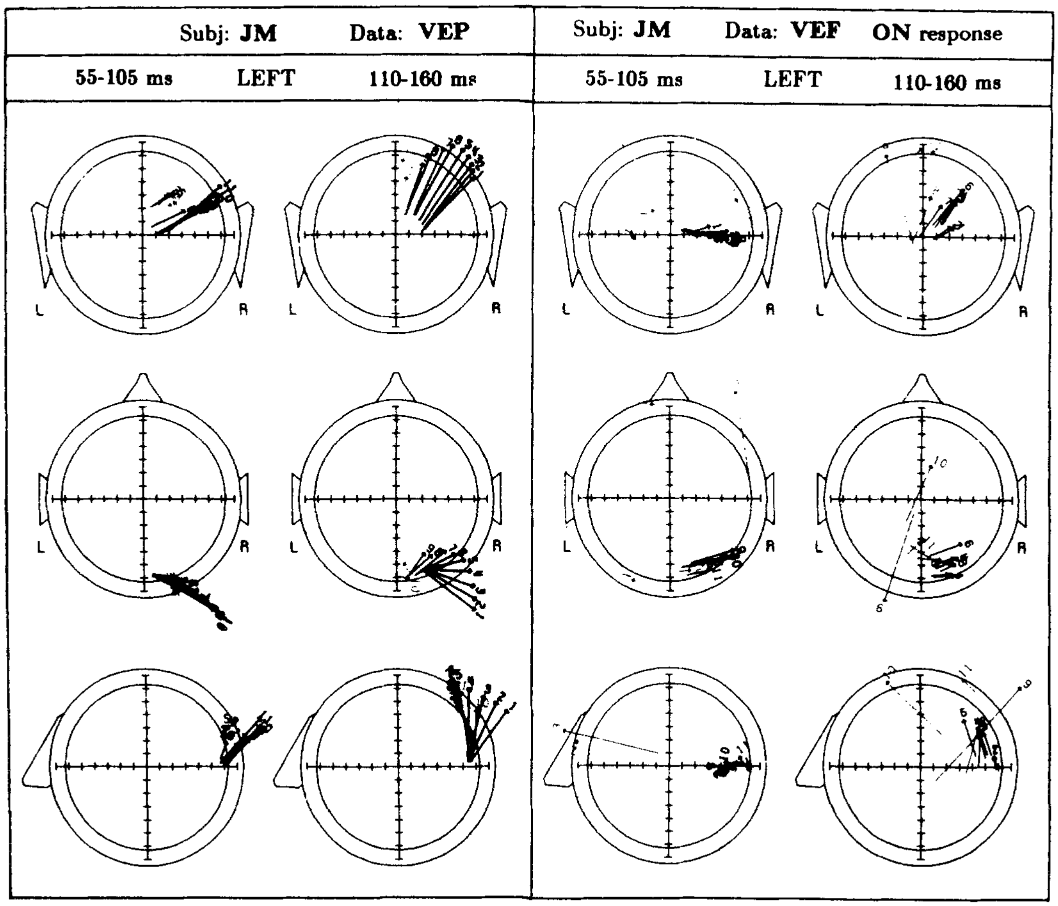
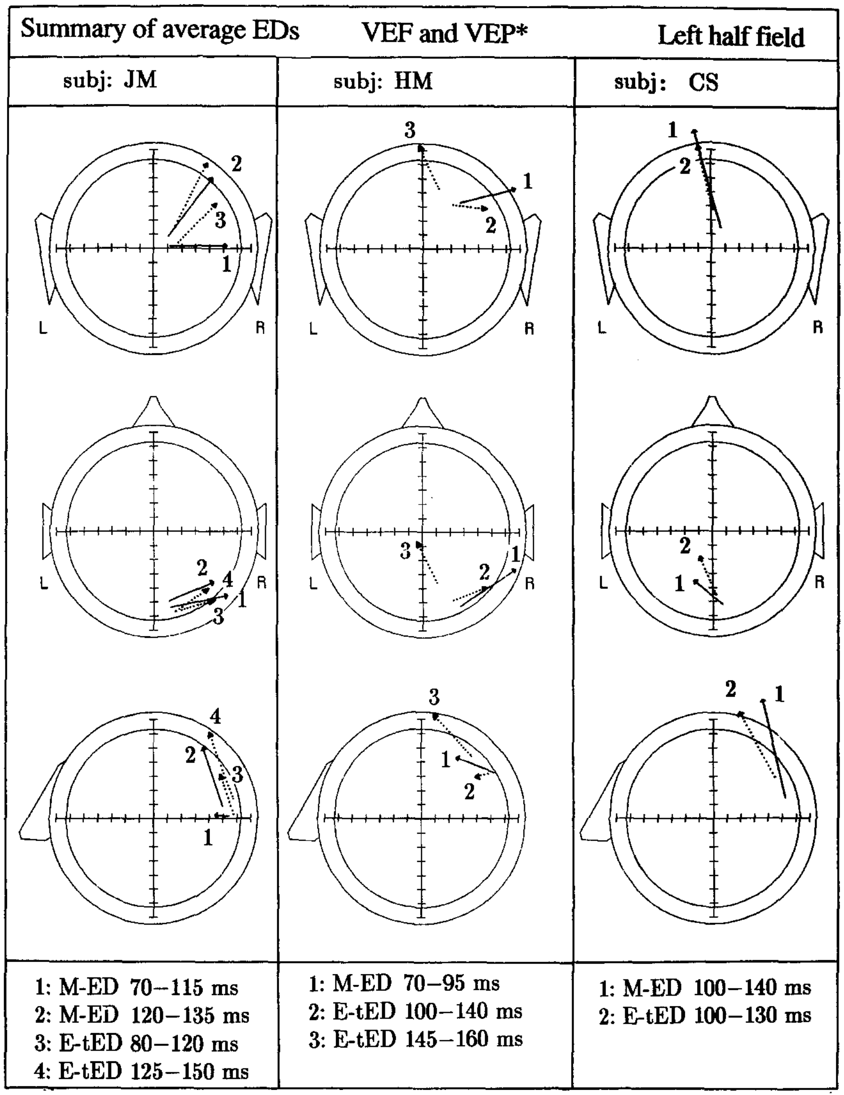


Figure 2. Evoked activity from subject JM to stimulation of left half visual field (on-response). Left-handed side: VEP data; right-hand side: VEF data. Projections of EDs for successive 5 ms time samples on three planes: occipital (top), horizontal (middle) and sagittal (bottom). The EDs are represented by arrows and are identified by numbers (not always easy to see) that represent the corresponding time sample starting from lower limit of the epoch analyzed indicated above (these time limits represent latencies relative to the moment of stimulus presentation). For example ED #5 on the left-hand column corresponds to time sample 75 ms. The starting point of the arrow indicated the projection of the dipole location. Scale: are division indicates 10 mm for the position coordinates and 6.7×10^{-9} Am for the strength of the components based on VEP and 10×10^{-9} Am for those based on VEF. The dipole is plotted with a line width that corresponds to the measure of fit: thickest for $\chi < 0.1$, medium for $0.1 \leq \chi < 0.2$, thin for $0.2 \leq \chi < 0.4$, thinnest for $\chi \geq 0.4$.

the same period. In subject CS only one M-ED (Nr.1) and only one E-tED (Nr. 2) were obtained. These covered almost equal periods of time and were also rather similar in position and orientation.

Discussion

The estimates of the EDs for successive time samples based either on VEPs or VEFs clustered approximately within the same epochs. In this way, two clusters were obtained. For two subjects (JM and HM) presented here cluster I was centered around 95-100 ms and cluster II around 130 ms. In one subject (CS) only the equivalent to cluster II could be identified. The positions of these EDs are compatible with the interpretation that the early components correspond to the activation of different parts of the visual cortex. Cluster I corresponds mainly to the polar area and Cluster II to the medial bank of the occipital lobe. The position of these clusters cannot be more than a rough indication of the centre of gravity of the cortical area mainly activated at a given time. Different patches of cortex may be activated simultaneously but one will be dominant within a certain epoch and this will be revealed in the EDs. Based on the position of the two clusters of EDs, we may interpret these two clusters as corresponding roughly to the activation of extrastriate cortex (Brodmann's areas 18 and/or 19) for cluster I, and of striate cortex (Brodmann's area 17) for cluster II. This



VEP*: tangential ED component only

Figure 3. Summary of VEF based average EDs of subjects JM, HM and CS in case of left visual half field stimulation. The average of the tangential components of VEP based EDs is also indicated (dotted arrow). Components scale of M-EDs is 10nAm and of E-tEDs is 6.7 nAm. See caption of figure 1 for additional informaion.

interpretation is based on the fact that in man, area 17 is folded onto the medial bank of the occipital cortex (see for further arguments van Dijk and Spekreijse 1990). Considering that processing of visual stimuli occurs in parallel in different patches of cortex, it is most likely that these two clusters should not be interpreted as representing a sequential activation of different cortical areas. They may just reflect, rather, a change in the relative strength of the activation of different visual areas with time after the appearance of the checkerboard pattern, as discussed in Lopes da Silva and Spekreijse (1991).

The comparison between EDs based on VEPs (E-tDs) and on VEFs (M-EDs) should be made according to three aspects:

a) position of EDs - the cases studied showed relatively small differences in position for E-tEDs and M-EDs corresponding to the same epochs. In any case, these differences are usually smaller than 10 mm (Figure 3).

b) orientation of EDs - Radial dipoles that appeared in the EDs corresponding to the early phase of the VEPs were, of course, not seen in the VEFs. This puts in evidence a limitation of the magnetic recordings. This limitation, however, may also be seen as an advantage, since in this way a tangentially oriented dipolar component that is normally overshadowed by a radial component in the VEP, may be detected using MEG recordings. A comparison of the orientation of the E-tEDs with that of the M-EDs showed conspicuous differences between both sets of data although in some instances, a good agreement was also encountered (Figure 3). These differences in orientation between E-tEDs and M-EDs may be attributed to the characteristics of the topology of the activated cortical area and, thus, to limitations of the model of the source. Although a single ED may be an appropriate model to simulate a source of localized cortical activity, in many cases a current dipole sheet is most likely needed to approximate the real situation. The form of such a dipole sheet may have different consequences for the electric and magnetic fields. For example, the activated cortical dipole sheet may consist of a patch corresponding to the top of a gyrus where the dipoles are oriented perpendicularly to the scalp surface and another patch corresponding to the bank of an invaginated sulcus where the dipoles are oriented parallel to the scalp. If this would be the case, the latter patch could be approximated by a tangential ED but the former would have a strong radial component. In this way, the estimated orientation of EDs representing the whole cortical path based on EEG and MEG recordings can differ considerably although their position may differ little. It should be noted that it is possible to calculate (De Munck et al. 1988a, b) the equivalent dipole parameters for a disk- or annular-shaped dipole sheet. In such a case, the ED will be somewhat deeper in the brain compartment than the geometric midpoint of the dipole sheet and the amplitude of the activity will appear to be a little larger.

c) strength of EDs - The ED strength can be determined independently from VEP and VEF measurements. In case of the VEP, the model parameters (sphere radii and compartment conductivities) have a large influence on the strength of the ED and to a lesser degree on its position and direction (Stok 1986). Based on the ED strength estimated from the MEG, we can roughly estimate the size of the active cortical layer. The largest EDs have a strength of 100 nAm. Assuming that the poles are separated by 1 mm (this is of the order of magnitude of the length of the soma and dendritic arborization of large pyramidal cells) and the current density is 250 nA/mm^2 (upper limit value; Freeman 1975) then the cortical area is at least 400 mm^2 in size. Estimation of the cortical area, corresponding to a 3 x 3 degrees foveal half field, on the basis of the cortical magnification factor, leads to a value of about 900 mm^2 (Drasdo 1980; Dagnelie 1986). In view of the averaging effect of the shape of the cortical area on the strength of the equivalent source, especially due to the sulci, these estimates are of the same order of magnitude. However, we should add a note of caution, since it is not possible to estimate the size of an active patch of cortex if the depth of the activated region, its form and strength, are not known a priori (De Munck 1989).

Theoretical Considerations

Here we consider, first, (a) those aspects of the model of the source that may influence differently the E-EDs and the M-EDs. Second, (b) we analyze the influence of the volume conductor models.

Models of the source

Earlier, we have already discussed that the shape and orientation of the cortical dipole sheet that at any given moment is activated by the stimulus, may have different effects on the E-EDs and on M-EDs. This question may even become more complex if we take into account another property of the cortical sources, e.g., whether these should be described by fixed or by moving dipoles (Lopes da Silva and Spekreijse 1991). Indeed, a principal component analysis (Maier et al. 1987) showed that both cortical areas are most likely active within the entire epoch. This is also the assumption on which Scherg and Von Cramon (1985) have based their dipole localization studies. Be as it may, differences of shape and orientation of the activated cortical areas may be reflected differently in the electric and magnetic recordings.

Models of the volume conductor

Most studies aimed at the estimation of the EDs that can describe a recorded EEG or MEG map, have used the concentric spheres model approximation of the head. However, this approximation is always rather limited and for certain regions of the head, it may be very poor. A spherical model may be acceptable as an approximation to the occipital pole of the skull but is less likely to fit the temporal or frontal areas. Even in the former case, the different compartments, brain, meninges, skull and scalp, are not necessarily concentrically oriented, as MRI scans, can clearly show. Also, the variation from subject to subject of brain (Brindley 1972) and skull anatomy imposes also constraints in the possibility of using generally valid models of the volume conductor. In addition, in the majority of studies until now, it is assumed that within each compartment of the head, the conductivity is isotropic. In reality, however, this is not generally the case, particularly for the skull compartment. De Munck (1989) presented calculations based on simulated situations from which it can be concluded that errors in estimating an equivalent dipolar source can be found due to neglecting the anistropy of the skull and of the cortex. In both cases the effect is mainly a deviation in the estimation of the depth and the error is large for deep

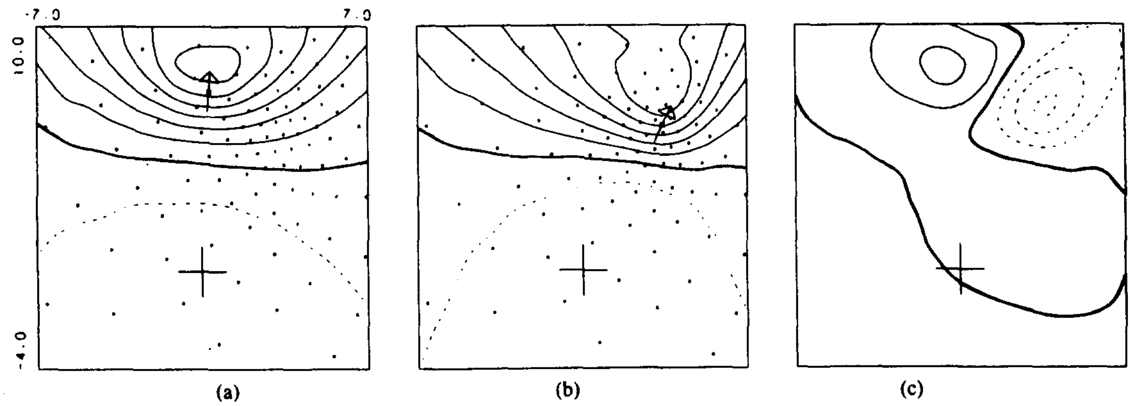


Figure 4. (a) Potential map corresponding to the E-EDs clustering within 105 to 125 ms following pattern onset in one subject (KS, zie Stok, 1986) for left half-field stimulation. The four concentric spheres model of the head was used for the inverse procedure. (b) Potential map corresponding to the M-EDs for the same time epoch and stimulus condition and adding a radial component to obtain the best fit. The four eccentric spheres model was used. (c) Difference between the maps presented in (a) and (b).

lying than for more superficial sources.

In this discussion, we will consider, first, the constraints imposed by the shape of the head and second, the necessity of making realistic models of the head using MR-I-scans.

Influence of the shape of the head on ED estimation

This was extensively studied using computer simulations by Meijs and Peters (1987) and Meijs et al. (1987). The electric potential and the magnetic field distribution of a current dipole was computed in the forward manner using a realistic model of the head. Thereafter, the inverse problem was solved using a concentric spheres model, i.e., a model where the outer sphere fits the scalp surface. The influence of different head models on the electric potential and magnetic field distributions was assessed by means of the relative difference measure defined as follows:

$$\mathrm{RDM} = \left[\frac{\int_S (F_r - F)^2 \, dS}{\int_S F_r^2 \, dS} \right]^{\frac{1}{2}} \qquad (1)$$

there F_r is the reference field (or potential) computed using the realistic model of the head; F is the field (or potential) computed for the same source but using another head model and S is the segment of the recording surface considered. The influence of different head models on EEG and MEG was investigated (Figure 4). A four eccentric spheres model, where a sphere was fitted to each compartment boundary individually had more influence on the EEG than on the MEG. Comparisons between the two types of model, concentric and eccentric spheres, were performed both for the case of VEPs as for VEFs. In both cases, formula (1) was used. Here, F_r was either the potential or the normal component of the magnetic field calculated using the concentric spheres model. F corresponded to the corresponding fields calculated using the eccentric spheres model. The value of RDM (E) for the case of potential fields calculated using either model was about 0.5. However, the value of RDM (M) for the case of the normal component of the magnetic field was only 0.05, which is an order of magnitude smaller than for the electric potential. Thus the computed magnetic field distribution based on a model consisting of eccentric spheres does not differ much from the distribution based on a model consisting of concentric spheres. However, the difference is apprecially for the case of the electric potential distribution. The maps of figure 4 show that the ED corresponding to the concentric spheres model was displaced in relation to the ED corresponding to the eccentric spheres model. However, in the later case, the EDs deduced from VEPs and VEFs coincided.

In conclusion, for the estimation of equivalent dipoles from electric potential maps preference should be given to the eccentric spheres model. This provides a more accurate approximation to reality and allows to obtain comparable results for VEPs and VEFs. It is also important to note that the geometry of the surface where the recordings are made has also influence. The differences between a concentric and an eccentric head model are the smallest when the recording surface of the normal components of the magnetic field is a sphere that fits the scalp the best, as shown by Meijs and Peters (1987).

These conclusions are of practical importance, since they imply that an acceptable localization of EDs can only be obtained if precise knowledge of the geometry of the different compartments of the head is available. This requirement is essential for the case of electric recordings but less stringent for the case of magnetic field recordings. This is a practical advantage of MEG over EEG measurements.

The Construction of Realistic Head Models

Since there exists a great variability of head shapes and of the relative form of the different compartments within the head between subjects, it is unlikely that precise results on ED localization can be obtained using a generalized model of the head. On the contrary, this objective requires a realistic description of the head of a given subject. This implies that it is necessary to have realistic three-dimensional (3-D) pictures of the different compartments of the head of a subject. These 3-D image reconstructions of the head can be made using MRI scans (Gevins and Bressler 1988; Wieringa and Peters 1991). For generating models of the head that are appropriate to use in ED localization, a series of MRI-scans have to be analyzed and quantified. In each MRI slice, the boundaries between the different compartments have to be discriminated using automatic segmentation procedures. Ideally, the position of an ED should be represented in such a way that it corresponds to an anatomical well defined structure. This objective poses a problem since the MRI pictures and the brain maps, whether electric or magnetic, are usually not obtained using the same coordinate system. Thus, the different coordinate systems have to be precisely matched using appropriate markers (Wieringa and Peters 1991).

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