Principles and Practice of Clinical Electrophysiology of Vision

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33

Topographical Evoked Potential Mapping

Wolfgang Skrandies

This chapter illustrates how visually evoked components are derived from multichannel recordings and are analyzed topographically.

Component latencies and amplitudes of brain electric activity recorded as potential waveshapes depend on the nature of the stimulus and the subject's nervous system, and are influenced by the recording site on the scalp as well as by the choice of the reference location. Peaks of potential waveshapes may show systematic changes in latencies that suggest a continuous movement of electrical activity over the scalp. However, when such electrophysiological data are displayed topographically as map series or potential profiles and are analyzed independent of the reference electrode, it becomes clear that there is no such systematic location change of components over larger distances. Scalp location of major evoked potential components remains stable and only potential gradients change over time. Such stable epochs correspond to potential fields displaying a large amount of activity that can be quantified by the computation of *global field power* (GFP) at each poststimulus time point. Maxima of GFP plotted as a function of poststimulus time correspond to *component latency,* which is accordingly defined topographically independent of the reference electrode. In a second step the scalp locations of potential maxima and minima as well as potential gradients are determined at component latency.

In addition, it is possible to identify time segments during which the scalp potential field configuration is stable. Such stable topographical patterns extend over longer time ranges and have been shown to relate to experimental stimulus conditions.

The aim of evoked potential (EP) studies in vision research is to identify putative brain subprocesses that reflect steps of visual information processing in the human brain. Such processes presumably occur at specific poststimulus times and in specific brain areas. This chapter discusses the topographical mapping of electrical brain activity, which has gained increasing popularity during the past few years as reflected by review papers and conference proceedings.[1, 8, 9, 11, 12]

Electrical brain activity produces a current field that spreads via volume conduction to the scalp where, conventionally, voltage differences are recorded between pairs of electrodes and are displayed as a function of time. Such potential waveforms are ambiguous since they are only a very limited sample of the available electric field data reflecting the potential gradient along the line between the two electrode locations. Since we are dealing with potential differences, the position of both the reference and the recording electrode influences the waveform pattern of electrical activity. Simultaneous recording from many points on the scalp makes it possible to assess the features of human electrical brain activity independent of the location of the recording reference. The correct interpretation of electrical brain activity data rests on the use of unambiguous recording and data analysis techniques in order that one may arrive at physiologically meaningful interpretations of the electrical data recorded. Such an approach treats electrical brain activity as potential fields, and topographical analysis methods have been developed for both spontaneous and evoked brain activity during recent years.[3, 6, 7, 16, 17]

Figure 33–1 shows visual EP waveshapes recorded simultaneously from a row of nine scalp electrodes placed along the saggital midline. As is evident in this figure, different recording channels

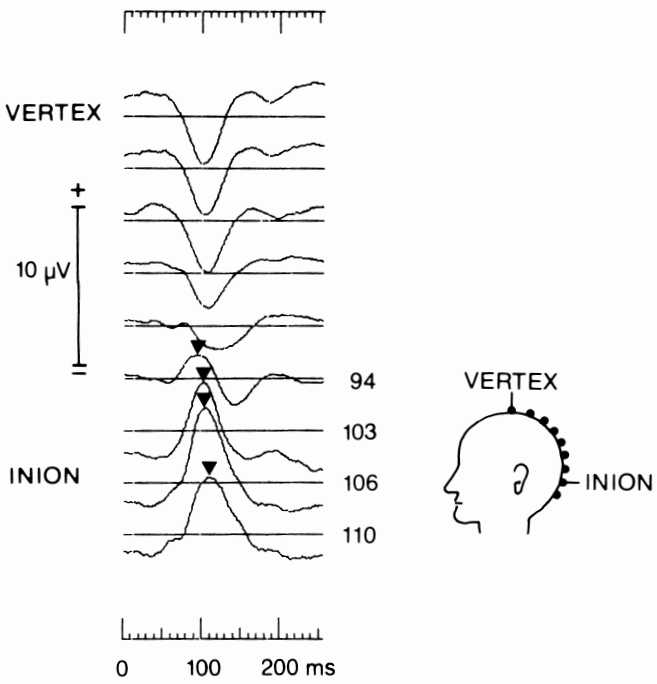

FIG 33–1.
Potential waveshapes elicited by a contrast-reversing checkerboard pattern presented to the upper hemiretina as a test field of 8.7 by an 11.4-degree arc. Nine recording electrodes were regularly spaced along the midline from the vertex to an electrode 2 cm below the inion as shown in the head schema. *Arrowheads* and *numbers* indicate peak latencies in milliseconds. Data are referred to the average reference. (From Skrandies W: *Prog Sens Physiol* 1987; 8:1–93. Used by permission.)

display different peak latencies ranging over the occipital areas between 94 ms (channel 6) and 110 ms (channel 9). Such a systematic peak latency change suggests that the site of generation of electrical activity moves continuously with time from anterior to posterior brain areas. On the other hand, each of the nine electrodes could be used as a reference, and thus from nine recording electrodes 72 different waveshapes may be obtained. The effect of changing the recording reference is illustrated in Figure 33–2, which shows the EP data of Figure 33–1 recomputed with three different sites used as a reference: on the left the data are referred to the vertex electrode, in the center an electrode 2.5 cm posterior to the vertex is used as reference, and on the right of Figure 33–2 the reference electrode is located 5 cm posterior to the vertex. Note how this change in reference location causes changes in the peak latencies in all channels. For example, channel 8 has peak latencies of 103, 105, and 106 ms, depending on which reference electrode is used. It is important to keep in mind that we are dealing with identical data that had simply been recomputed and all our statements on peak latency are correct. There is no objective reason to prefer one set of EP waveshapes over the others. From this figure it becomes clear that it is impossible to evaluate such extensive data sets that contain redundant information by simple inspection or by waveshape comparisons, and thus, an analysis of electrical activity must not deal with reference-dependent potential waveshapes. The confusion of different component latencies seen with different electrode combinations illustrated in Figure 33–2 may be solved when the data are analyzed topographically, and it will become evident that in reality there are not different latencies at different scalp sites but that there is one component latency that may be determined unambiguously.

In Figure 33–3 the data are displayed as a topographical potential profile at 106 ms, where the amplitude values measured in each channel are plotted as a function of electrode position. This is a simple rearrangement of the data, and it is important to note that the shape of the potential profile is independent of the reference electrode: at 106 ms there is an occipital peak surrounded by steep gradients, while a flat distribution prevails over anterior areas. Changing the reference location only results in a change in the zero level (which is shifted to the potential value of the reference electrode) and labeling of the potential values while the shape of the potential distribution as well as the locations of the potential maxima and minima and the potential gradients remain unaffected. Thus, topographical mapping allows us to analyze brain electric activity unambiguously and independently of the reference electrode.

A series of potential profiles is used in Figure 33–4 as a topographical display containing all the information of Figure 33–1. Poststimulus time runs from top to bottom and electrode position from left to right. Note that there are times at which the voltages and gradients are small while at other times the profiles show high peaks and steep gradients. Scalp field maps with large extreme values (peaks and troughs) and steep gradients (containing densely spaced field lines) are thus interpreted indicating times and places of neural information processing. Lehmann[3] and Lehmann and Skrandies[7] have proposed a quantitative measure of "hilliness" or Global field power (GFP) that assesses the amount of activity within each potential field distribution independent of the reference electrode, by considering all recording electrodes simultaneously. Thus, GFP has nothing to do with dipoles or electrode locations or

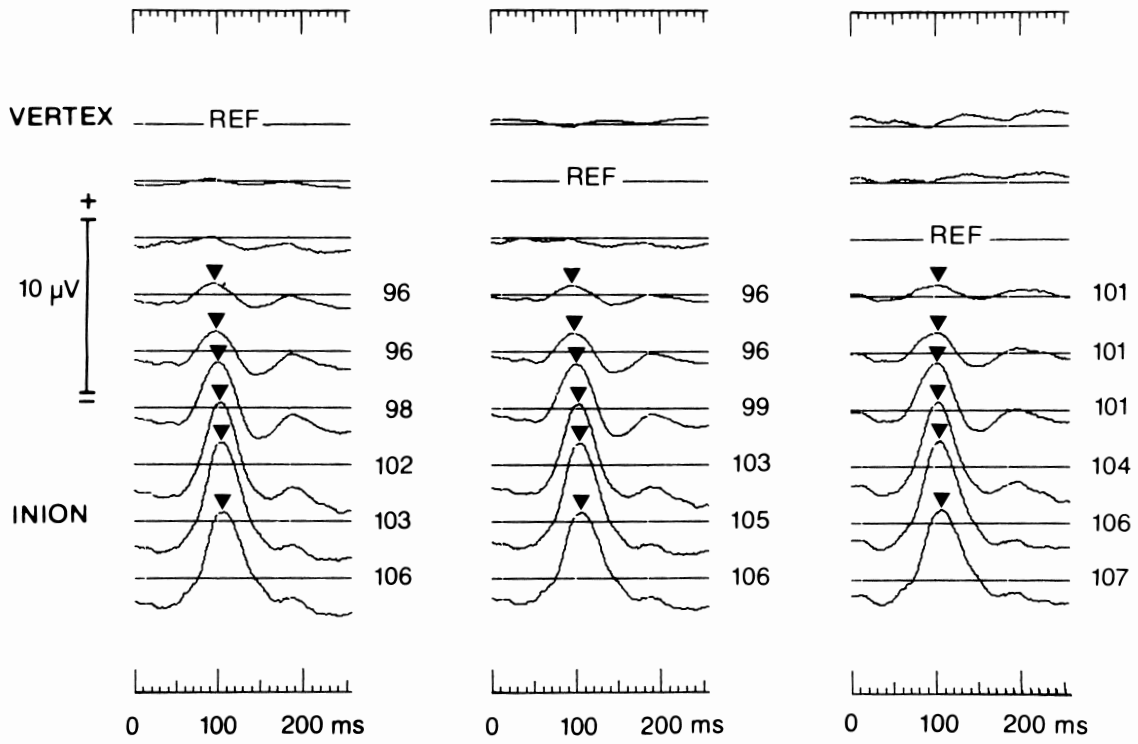

FIG 33–2.
Data of Figure 34–1 computed vs. different reference sites *(REF).* The reference electrodes are located at the vertex *(left),* 2.5 cm posterior to the vertex *(center),* and 5 cm posterior to the vertex *(right).* Note that peak latencies change with different reference sites. (From Skrandies W: *Prog Sens Physiol* 1987; 8:1–93. Used by permission.)

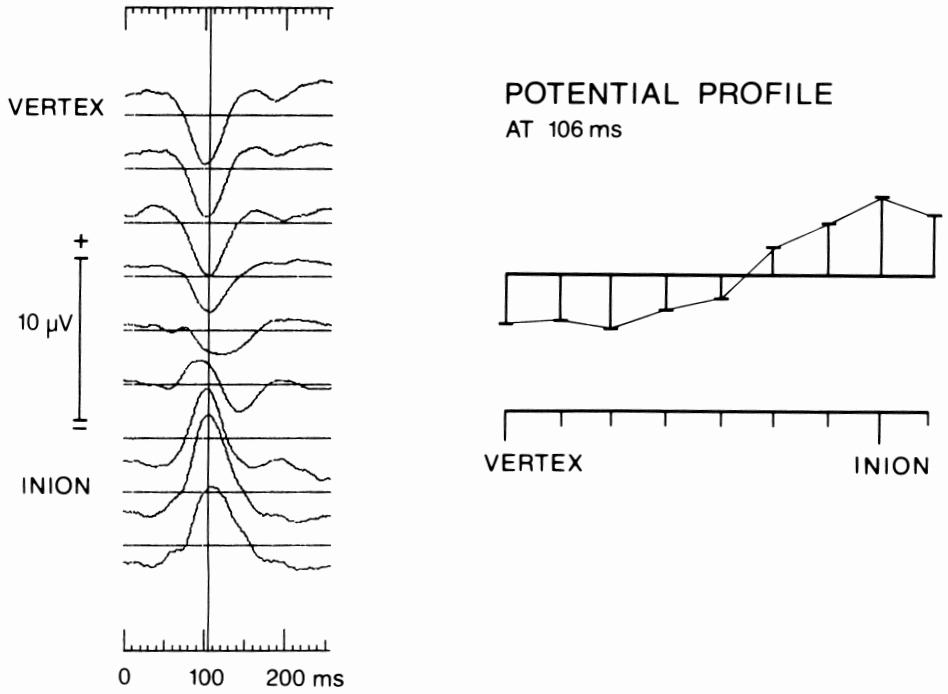

FIG 33–3.
Construction of a topographical potential profile. At 106 ms latency the amplitudes are measured in each channel and are plotted as a function of electrode position. The zero line of the profile corresponds to the average reference. Changing the reference site simply shifts the zero line up or down without affecting the shape of the profile. (From Skrandies W: *Prog Sens Physiol* 1987; 8:1–93. Used by permission.)

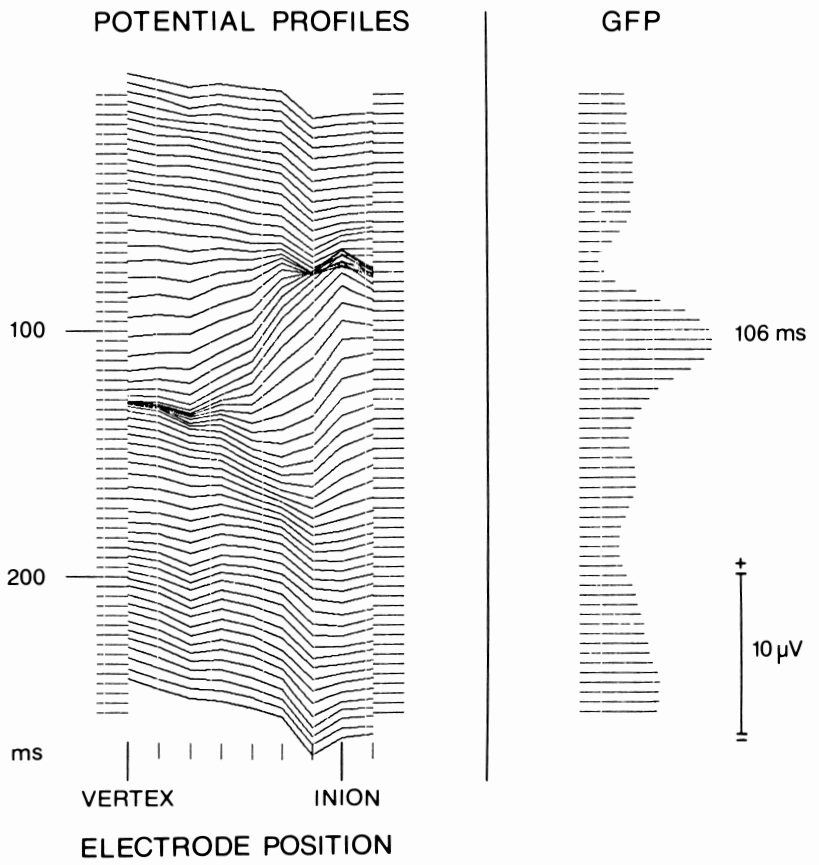

FIG 33–4.
Series of potential profiles and global field power *(GFP)* between 4 and 256 ms computed every 4 ms. The time axis runs from *top to bottom*, the anterio-posterior electrode positions from *left to right.* Data are the same as in Figure 33–1. (From Skrandies W: *Prog Sens Physiol* 1987; 8:1–93. Used by permission.)

polarities; it is a function of time measured in microvolts (e.g., the insets in Plate 3 display GFP as a function of poststimulus time).

GFP may be computed as the mean of all possible absolute potential differences within the field and corresponds to the spatial standard deviation. With nearly equidistant electrodes, the potentials e_i, $i = 1 \ldots n$ yield the measured voltages $U_i = e_i - e_{common\ reference}$. From this potential distribution a reference-independent measure of GFP is obtained:

$$GFP = \sqrt{\frac{1}{2n}\sum_{i=1}^{n}\sum_{j=1}^{n}(U_i - U_j)^2} \qquad (1)$$

i.e., the root mean square deviations between all electrodes in a given potential field. Note that this measure is independent of the reference electrode used for measuring EP or electroencephalographic (EEG) data. This is a central point since it allows for reference-independent treatment of electrophysiological data.

In a similar manner GFP may be computed from average reference data:

$$GFP = \sqrt{\left(\sum_{i=1}^{n}U_i - \frac{\sum_{j=1}^{n}U_j}{n}\right)^2} \qquad (2)$$

This is mathematically equivalent to formula 1.

Potential fields with high peaks and troughs are associated with high GFP values (high spatial standard deviation), while in flat fields the GFP is small. As practical experience has shown, GFP is quite robust, and related measures like hilliness or the voltage range within the field at each time point yields very similar results.[7, 16] The amount of activity within each profile or potential map may be determined by GFP computation independent of the reference electrode, and on the right side of Figure 33–4 GFP is plotted as a function of time adjacent to the corresponding potential profiles. At early and late poststimulus times flat field distributions prevail, and GFP is low: it increases around 100 ms and reaches its maximum at 106 ms. This is the latency of the conventional P100 component topographically identified.

Changes in field topography over time may be analyzed in detail when the potential profiles are plot-

ted at successive time points. Figure 33–5 presents an enlarged display of part of the complete profile series between 90 and 120 ms with a higher time resolution. Note that contrary to what was suggested by the potential waveshapes of the same data in Figure 33–1, there is no change in component location. The potential maximum remains at the same electrode between 90 and 120 ms, and only the potential gradient changes during this interval.

A second step in topographical analysis is evaluation of the scalp potential field features at component latency. The locations of the maxima and minima as well as the potential gradients are derived measures that are by definition independent of the reference electrode. Such derived measures may then be used for statistical comparisons of scalp field topography evoked in different experimental conditions.

The concept of GFP is thus very useful in determining component latencies and defining instances of topographically important potential distributions that may then be used for quantitative comparisons. Visual activity evoked by contrast-reversing grating stimuli presented to different retinal areas is illustrated in Fig 33–6 and Plate 3. The map series illustrated between 70 and 141 ms show the development of the P100 component over the occipital brain areas. With central stimuli (Plate 3,B) the potential fields are roughly symmetrical with respect to the midline, and with left (Plate 3,A) or right hemiretinal stimuli (Plate 3,C) lateralized field distributions result. Between 88 and 105 ms the maps appear to be most pronounced with all stimulus conditions where high peaks and steep gradients may be seen. The exact component latencies of these data were determined quantitatively by computing the GFP, and Plate 4 also shows the corresponding GFP functions. For the central stimulus a latency of 97 ms results, left retinal stimuli yield a latency of 96 ms, and the latency for stimulating the right hemiretina was 94 ms. It is also obvious that with central stimuli the strength of the EP fields reflected by GFP is larger than when lateralized retinal stimuli are presented.

For quantitatively comparing experimental stimulus conditions in terms of scalp topography, electrical fields are used latency. The potential fields thus obtained at component latency are illustrated in Fig 33–7 and Plate 4. This display enables a direct comparison of the topographical features of electrical brain activity elicited in different experimental conditions. Visual pattern reversal stimuli presented to hemiretinal areas elicit a characteristical "paradoxical" lateralization of the potential maximum over the hemisphere contralateral to the hemiretina stimulated, and the amount of component lateralization depends on the extension of the test field (for further discussion of such results see Skrandies and Lehmann[17]). We note that the scalp location of these

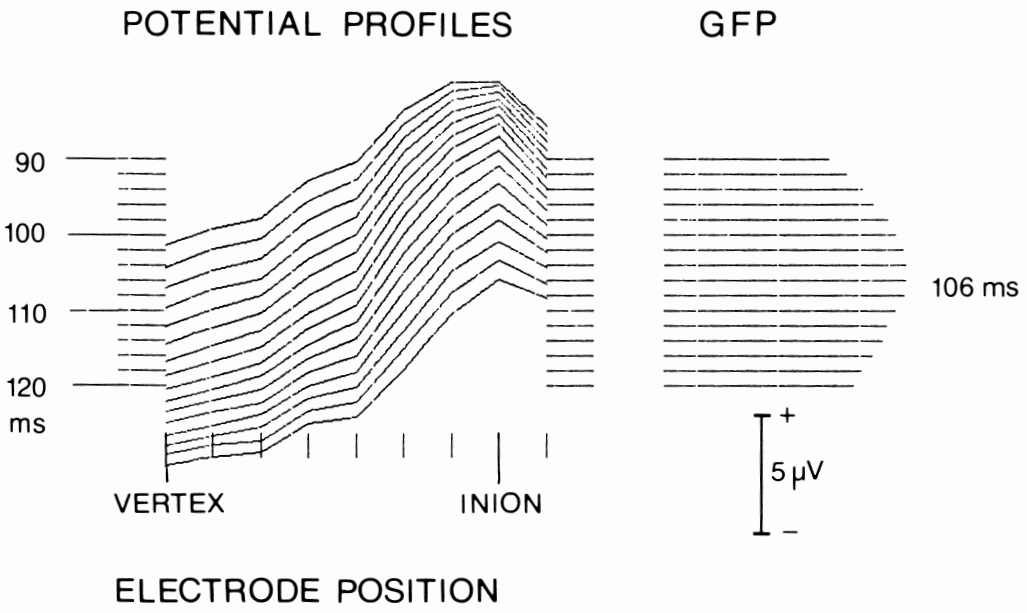

FIG 33–5.
Enhanced display of the potential profiles of Figure 33–4 between 90 and 120 ms with 2-ms intervals. Note that there is no change in component location over time as was suggested by the waveshape patterns in Figures 33–1 and 33–2. (From Skrandies W: *Prog Sens Physiol* 1987; 8:1–93. Used by permission.)

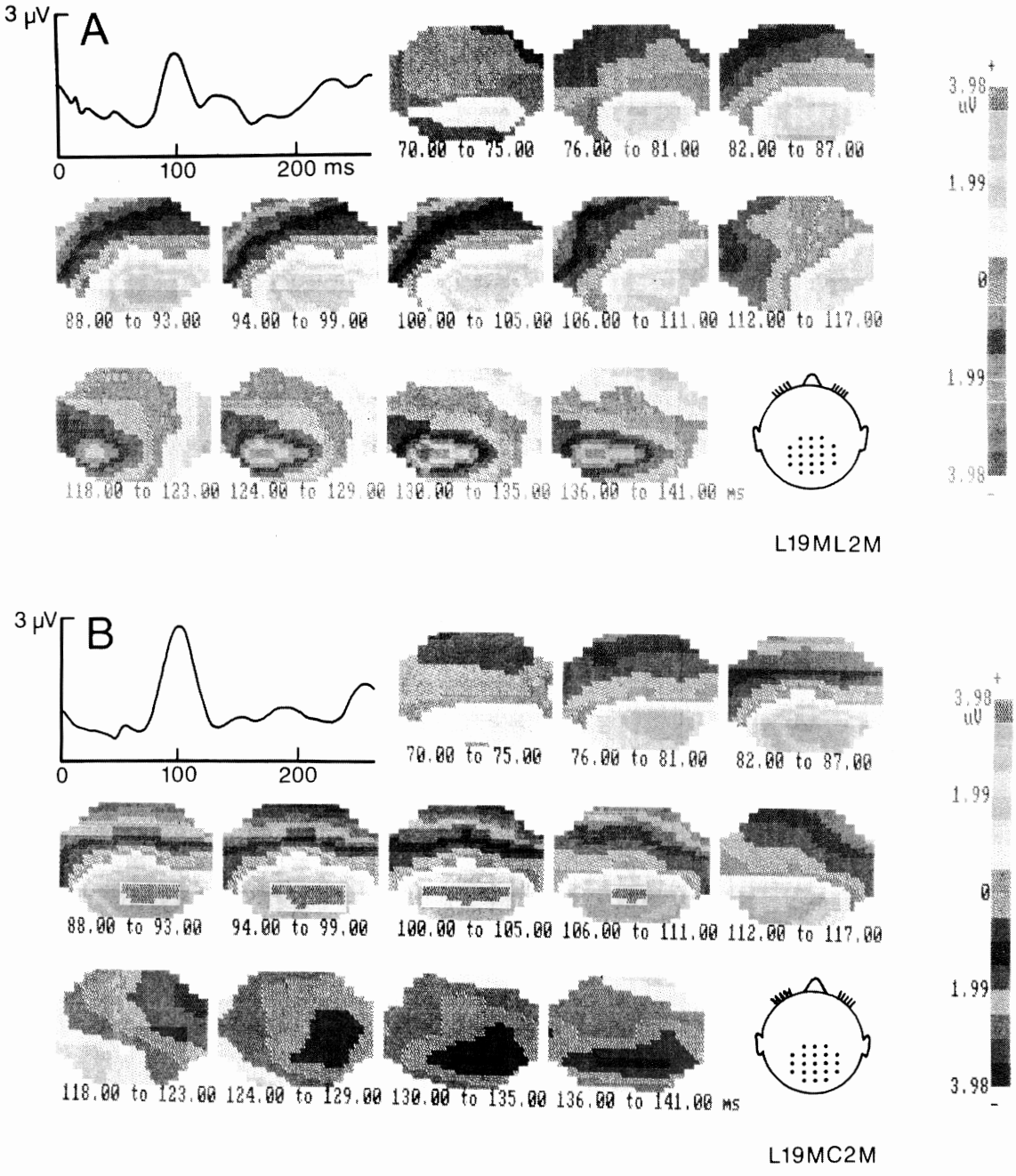

FIG 33–6.
Potential map series between 70 and 141 ms and GFP as a function of time evoked by a contrast-reversing vertical grating stimulus of 2.5 cd presented monocularly as a 17.1-by-13.4-degree arc test field in the center **(B)** or to the left **(A)** or right hemiretinas **(C)**. In all map series an occipital positive component develops around 100 ms and shows some lateralization with lateral visual stimuli. Values are means of average reference data; 21 channel were recorded by using a *Bio-Logic Brain Atlas II* with the most anterior electrode row at 40% of the nasion-inion distance above the inion and the most posterior electrode row at the inion. Potential levels are color coded between +3.98 and −3.98 μV as indicated in scale on the right. **See also Plate 3.**

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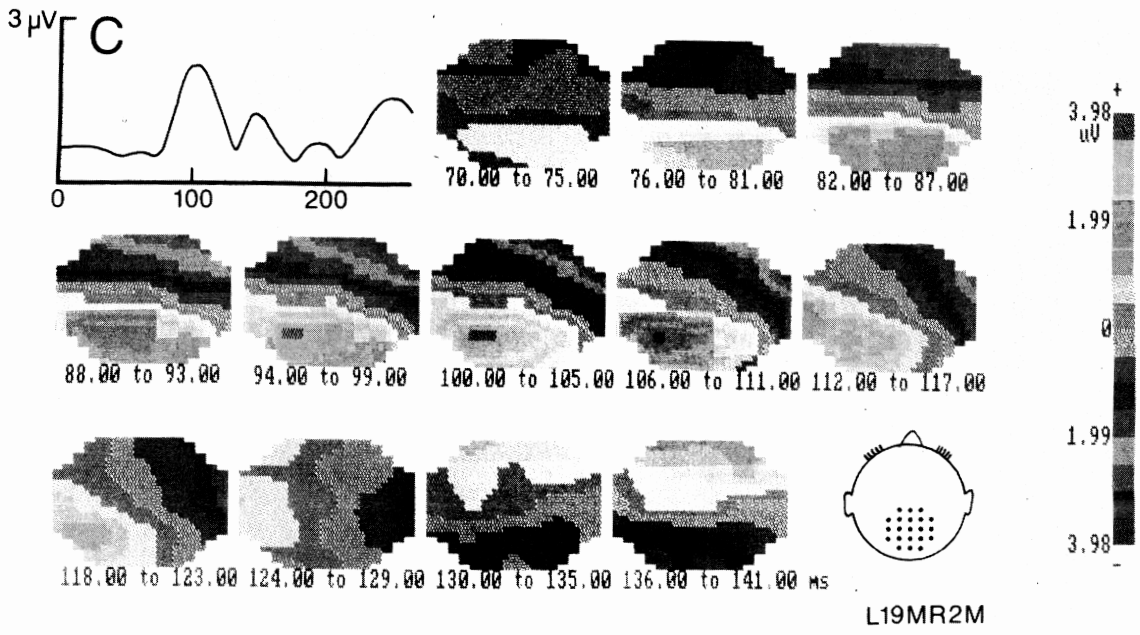

FIG 33–6 (cont.).
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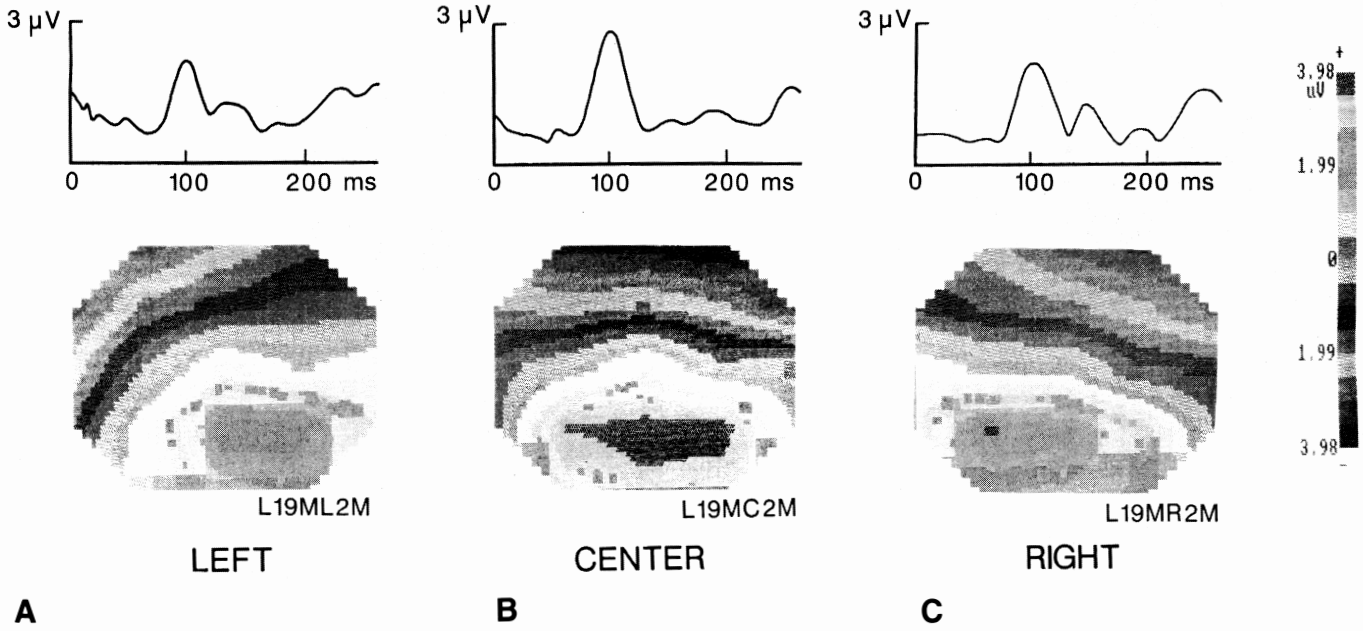

FIG 33–7.
GFP functions and EP maps at component latency of the data presented in Figure 33–6. With central stimuli **(B)** the occipital positivity is located concentrically in the midline, while with left **(A)** or right **(C)** hemiretinal stimuli the maximum is located over the hemisphere contralateral to the hemiretina stimulated, and there occur steep potential gradients over the ipsilateral hemisphere. Note the larger field strength with central than with lateral stimuli. Component latencies are similar in all conditions. Potential levels are color coded between +3.98 and −3.98 μV as indicated in scale on the *right*. **See also Plate 4.**

evoked components may be explained by the net orientation of neural-generating processes in the occipital part of the hemisphere ipsilateral to the hemiretina stimulated. This interpretation has been supported by model dipole computations as well as by direct intracerebral multichannel recordings from human patients.[4] There are several stimulus characteristics that influence the scalp topography: Lehmann and Skrandies[6] and Skrandies[12–15] present experimental evidence that there are significant differences in scalp location of the evoked components when different retinal areas are stimulated or when an identical stimulus is presented as pattern reversal, pattern onset, or pattern offset.[12] In addition, multichannel activity evoked by dynamic random-dot stereograms yields a different topographical pattern from comparable stimuli containing contrast borders.[5, 18] It has also been shown that in patients with visual field defects asymmetrical scalp potential fields result.[2]

Following the determination of component latency, the absolute scalp locations of potential maxima or minima may be compared directly between experimental conditions, or t-statistics may be computed by using complete scalp distribution maps in order to determine significant differences of corresponding scalp locations. Multivariate statistical methods may also be used for analysis. Skrandies and Lehmann[17] reported that multichannel EP fields may be reduced statistically to fewer dimensions: only three components of a spatial principal component analysis accounted for more than 93% of the variance in the electrical data obtained from 45 channels. In addition, it was shown that relating the principal components to experimental stimulus conditions is a meaningful way.[17] The application of principal component analysis to multichannel visual EP data has been described in more detail by Skrandies.[10]

Epochs of high GFP are mostly associated with similar, topographically stable potential fields, while the field configurations change rapidly during times of low GFP.[16] The occurrence of evoked components thus may also be identified by topographically stable segments in a series of potential distribution maps. In a paper on time range analysis of multichannel potential fields evoked by grating stimuli of different orientation and different spatial frequency, Skrandies[13] has illustrated that segments of evoked activity may be identified by statistical methods and that the characteristics of topographically stable segments attain functional meaning showing significant differences between various visual stimulus input conditions.

We note that all these topographical analysis methods offer the possibility of analyzing scalp-recorded electrical brain activity in an objective and unambiguous way, and a meaningful neurophysiological interpretation of electrical brain activity becomes possible. The data presented in this chapter indicate that component latency of evoked electrical brain activity may only be interpreted unambiguously when basic topographical features are considered. Analysis of waveshape patterns may yield erroneous interpretations of underlying physiological processes. This may also influence clinical conclusions since the most important parameter for clinical application of visual EPs is the latency of components, and latency prolongations of only a few milliseconds may identify a patient's result as pathological. For clinical purposes the use of preselected subsets of the electrical scalp field data (i.e., a given electrode montage) may be regarded as perfectly valid for comparisons of data obtained from normal individual and clinical patients given standardized stimulus and recording conditions. However, physiological and pathophysiological interpretations should not be derived from such data since the assessment and interpretation of scalp-recorded brain activity must draw on features and parameters that are unambiguous and reference-independent. Topographical analysis stressing the spatial domain of electrophysiological scalp recordings may result in unambiguous statements about underlying neural processes in the human brain.

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