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Edited by Christoph M. Michel, Thomas Koenig, Daniel Brandeis, Lorena R. R. Gianotti and Jiri Wackermann

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Chapter

From neuronal activity to scalp potential fields

Daniel Brandeis, Christoph M. Michel and Florin Amzica

Introduction

The EEG, along with its event-related aspects, reflects the immediate mass action of neural networks from a wide range of brain systems, and thus provides a particularly direct and integrative noninvasive window onto human brain function. During the 80 years since the discovery of the human scalp EEG¹, our neurophysiological understanding of electrical brain activity has advanced at the microscopic and macroscopic level and has been linked to physical principles, as summarized in standard textbooks^{2–5}. The present introduction builds upon these texts but focuses on spatial aspects of EEG generators, many of which are applicable to both spontaneous and event-related activity^{6–8}. In particular, it is critical for the purpose of electrical neuroimaging to know which neural events are detectable at which spatial scales. As we will show, the spatial characterization of the neural EEG generators, and the advances in spatial signal processing and modeling converge in important aspects and provide a sufficiently sound basis for electrical neuroimaging. Because of the unique high temporal resolution of the EEG, electrical neuroimaging not only concerns the possible neuronal generator of the scalp potential at one given moment in time, but also the possible generators of rhythmic oscillations in different frequency ranges. In fact, understanding the intrinsic rhythmic properties of cortical or subcortical–cortical networks can help to constrain electrical neuroimaging to certain frequency ranges of interest and to perform spatial analysis in the frequency domain^{9–10}. This is why this chapter not only discusses the general aspects of the generators of the potential fields on the scalp, but it also discusses the mechanisms underlying the genesis of the oscillatory behavior of the EEG.

Spikes and local field potentials

Invasive neurophysiological studies, mainly in animals, have proven crucial in clarifying the principles of neural activation and transmission at different spatial scales. Since the physics of currents and potential fields ensures their linear superposition, some understanding at both the microscopic and the macroscopic levels is essential for understanding spatio-temporal properties and constraints of the EEG generators. *Intracellular recordings* from individual neurons in animals demonstrate that the dominant electrical events at the microscopic level are focal, large and fast action potentials depolarizing the cell's resting potential by more than 80 mV (from -70 mV to positive values and back in less than 2 ms) when measured across the few nanometers of the cell membranes. These action potentials frequently originate at the soma (axon hillock) and propagate within < 1 ms to the axonal terminals. Nearby

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extracellular recordings reveal corresponding spikes, which resemble the first temporal derivative of their intracellular counterparts and can reach at least 600 μV . The *multi-unit activity* filtered to include only frequencies above 300 Hz is dominated by these spikes which mainly reflect neuronal output, while the slower local field potentials (< 300 Hz) reflect mainly postsynaptic potentials and thus neuronal input. However, in general both signals strongly correlate with local intracellular spiking as well as with metabolic demand¹¹. Spatial aspects of such activity are revealed by multichannel intracranial recordings with regularly spaced electrodes. These recordings confirm that spike amplitudes fall off rapidly to a tenth (< 60 μV) outside a 50 μm radius¹², which limits their spatial spread to the sub-millimeter scale. This property thus prevents the fields due to individual spikes becoming potentially measurable as “far fields” in the EEG, i.e. at the scalp, which is at least 2 cm away from brain tissue. Also, the short spike duration makes summation in time less likely. As a consequence, individual spikes or action potentials propagating along the axons, and more generally electric events in white matter structures such as large fiber bundles, can be neglected as direct EEG generators. A possible exception are very small (< 0.5 μV), fast (latency under 20 ms), high frequency oscillations (above 100 Hz) which may contribute to the heavily averaged evoked patterns measured at the scalp such as the early auditory brain-stem potentials¹³ or early somatosensory oscillations¹⁴.

Spiking correlates with the less focal, and typically slower and weaker extracellular field potentials¹⁵. These reflect neural mass activity due to linear superposition of those fields which do not form closed field current loops. In brain regions such as the neocortex, this extracellular activity is synchronized well beyond the sub-millimeter scale and reflects summation of excitatory or inhibitory postsynaptic potentials in space and time. Such neural mass action occurs if neurons are both arranged in parallel over some distance, and receive synchronized synaptic input in a certain layer as typical for the neocortex with its aligned pyramidal cells. Although the EEG of patients with focal epilepsy is dominated by slow frequencies, very strong high-frequency oscillations (fast ripples, 100–500 Hz) can be recorded intracranially from the seizure onset zone. These oscillations typically extend over a few millimeters^{16,17}, which suggests that they reflect synchronized field potentials rather than spikes. Their focality, and the fact that they are typically accompanied by more widespread and even stronger lower-frequency oscillations limit their detectability in scalp recordings.

Sinks and sources

The major generators of the scalp EEG are extended patches of gray matter, polarized through synchronous synaptic input either in an oscillatory fashion or as transient evoked activity, which reflects additional generators rather than just phase reorganization of ongoing oscillations¹⁸. In the cortex, such patches contain thousands of cortical columns, where large pyramidal cells are aligned perpendicularly to the cortical surface, and where the different layers are characterized by synaptic connections from different structures. The extracellular currents which flow between the layers of different polarity are matched by reverse intracellular currents. Models which consider the realistic cell geometries suggest that not only apical but also basal dendrites may contribute to EEG¹⁹. Such variable generator regions are consistent with the variety of laminar potential and current density distributions. While evoked activity often starts with prominent current sinks in cortical layer IV^{20,21}, more variable laminar distributions are found for later components of the evoked potentials as well as for epileptic activity²². Unfortunately, there are only rough indirect estimates regarding the degree

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(defined by the local dipole strength and the percentage of neuronal elements contributing) and the spatial extent (area) of polarization due to neural synchronization, particularly for the healthy human brain.

The relation of intracortical activity to surface-recorded EEG is far from simple. The surface EEG does not allow distinguishing between the various possible arrangements of sinks and sources in the different cortical layers²⁰. This is due to the fact that the scalp potentials represent only the open field dipolar component of the complex multipolar current generators within the different cortical layers²³. It has already been mentioned above that the scalp EEG reflects not only the activity of the uppermost parts of the apical dendrites, but also activities in deeper layers or structures. In addition, there have been studies showing that early surface evoked potential components can be related to presynaptic activation of the thalamocortical afferents and excitatory postsynaptic potentials on the stellate cells in area 4C^{23,24}. This questions the generally held notion that only cortical pyramidal cells are generating open fields that can be detected by the EEG. Additional concerns are raised by the possibility that glial cells, if organized along an axis parallel to the apical dendrites, could constitute a powerful dipole which could constitute a source of EEG activities. This aspect is discussed in detail below with respect to the generators of delta rhythms. The difficulty of relating the scalp potential to a specific distribution of sources and sinks in the different layers of the cortex is illustrated in Figure 1.1. It shows the scalp evoked potentials recorded from 32 epicranial electrodes in anesthetized mice during whisker stimulation as well as the intracranial evoked potentials and the current source density profile from a multi-electrode probe inserted in the S1 barrel cortex²⁵. A complex distribution of sinks and sources in the different layers can be seen in the intracranial recording that drastically changes across time. The initial activation at around 10 ms is dominated by sinks in layers II–III and layer V and sources in layers I, IV and VI. A nearly reverse distribution is seen at around 40 ms. Despite this very different source/sink distribution at the two time points, the same positive potential is measured on the epicranial electrode and nearly similar configurations of the potential maps are seen. Thus, the scalp potential represents a weighted sum of all active currents within the brain that generate open fields (for a detailed discussion and comparison with human evoked potentials see Megevand *et al.*, 2008)²⁵. The sum of all these open field generators forms what is often called an equivalent dipole generator²⁶. The current dipoles are thus used as simple, idealized models describing strength, orientation and localization of the sum of the volume-conducted open field activity of all layers of the cortex (see also Chapter 3).

Equivalent current dipoles

Current dipoles of 10 nA are considered typical when modeling evoked activity at the scalp in normal physiological conditions; this holds for the EEG as well as for the MEG (magnetoencephalogram) which reflects the magnetic field generated by the same current dipoles^{19,27}. This estimate is also consistent with laminar recording of current source density. However, estimates regarding degree and spatial extent of postsynaptic neural synchronization represented by such a dipole vary considerably. They range from just 50 000 pyramidal neurons¹⁹ to 1 million synapses in a cortical area of 40–200 mm²²⁷, which would mean that less than 1% of the synapses contribute to the EEG at any given moment. Stronger activity is observed during spontaneous oscillations, and the largest activities exceeding 500 μ V are observed during epileptic seizures and during slow-wave sleep, particularly in children; whether this

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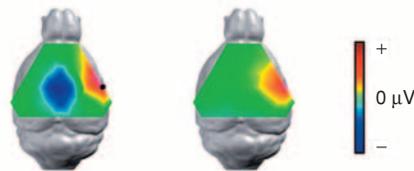
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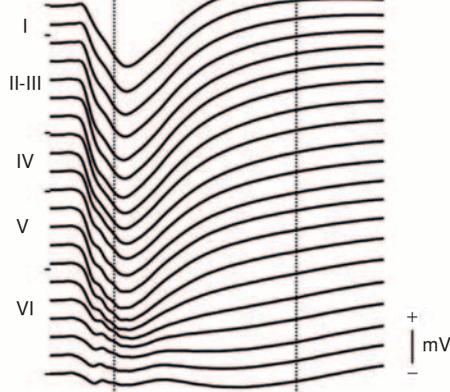
A Epicranial potential maps



B Epicranial potential waveform



C Local field potential



D Current source-density

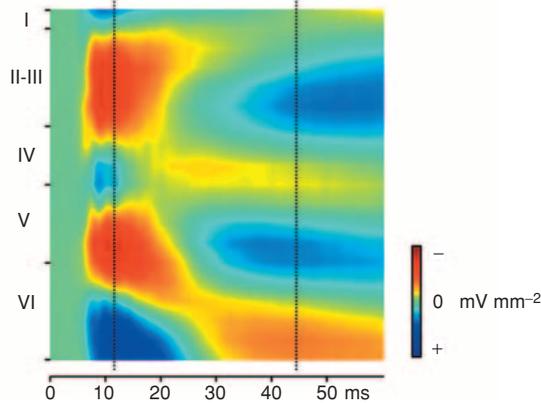


Figure 1.1 Time course of epicranial and intracranial potentials evoked by left whisker stimulation in anesthetized mice. A. Epicranial potential maps recorded from 32 electrodes placed in equidistance over the whole cortex. Maps are selected at two time points (12 and 45 ms). Note the positive potential on the electrode over the S1 barrel cortex for both time points. B. Evoked potential waveform for the electrode over S1 (marked in the map in A), showing two positive components at around 8–14 ms and 30–50 ms. C. Intracranial local field potential recorded from a multi-electrode probe in the cortex underlying the S1 electrode, spanning all cortical layers. Note the negative potential over all electrodes during the first component, and the positive potential during the second component. D. Current source density (CSD) profile calculated from the intracranial local field potentials (red = sink, blue = source). Note the nearly inverted source/sink distribution between the first and second component. (Modified from Megevand *et al.*²⁵ with permission from Elsevier. Copyright © 2008 Elsevier Inc.)

is due to a larger extent or a larger degree of synchronization is essentially open. Simplifying assumptions, such as that the EEG generators reflect mainly surface negativity of cortical patches due to excitatory postsynaptic input at the apical dendrites, are thus not supported.

To qualify as major EEG generators, patches of consistently polarized brain tissue also need an approximately planar geometry to ensure that linear summation produces a net

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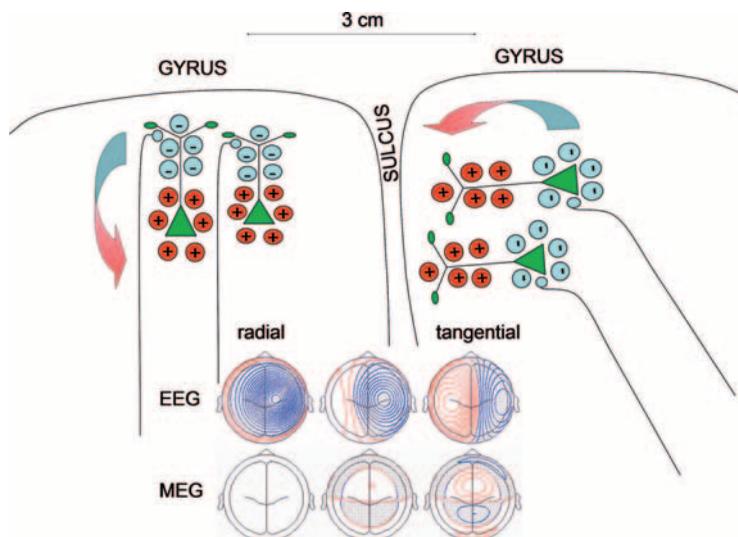
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Figure 1.2

Electroencephalography and MEG sources.

Volume currents due to mass activity of synchronized, aligned pyramidal neurons can be modeled as point-like polarization dipoles and corresponding EEG and MEG maps. Maps with $0.2 \mu\text{V}$ (EEG) and 50 fT (MEG) contour spacing. Red for positive, blue for negative electric potential and magnetic field. Dipole model with 20 nA peak strength.



polarization or “far field” along the dominant or mean orientation. This typically holds for activity on the cortical gyri (parallel to the skull, with radial polarization), but also on the walls of cortical sulci (with tangential polarization) or in deeper structures like the cingulate gyrus. Both radial and tangential polarizations give rise to characteristic but distinct scalp EEG maps, while radial polarization generates no MEG maps, as illustrated in Figure 1.2. Closely folded brain structures only generate “closed fields” which cancel within a few millimeters due to nearby sources with random or opposite orientations. Although some structures like the cerebellum were historically considered to generate only closed fields and no EEG, recent MEG findings of consistent cerebellar activation^{28–30} strongly suggest that the cerebellum can also generate scalp EEG. The same is true for mesial temporal structures such as the hippocampus and the amygdala as demonstrated in EEG and MEG studies with simulations³¹ as well as with recordings in patients with mesial temporal lobe epilepsy^{32,33}.

Forward solutions of the electric scalp field can be computed in an accurate and unambiguous fashion from the intracranial electrical distribution, provided the geometric and electric properties of the head (i.e. the shape and conductivity of all compartments) are known (see Figure 1.2 and Chapter 3). However, a full description of the electrical distribution at all spatial scales, starting at the microscopic level with its large intracellular voltages, is obviously beyond reach. Spatial considerations which constrain this description to potential EEG generators are thus critical.

Electroencephalography sources generate field potentials which still fall off steeply within the brain, but far less so if measured through the scalp. This is because the lower conductivity of the skull compared with the brain causes spatial blurring at the scalp. Superficial sources are thus attenuated more strongly than deep ones, as confirmed by recordings of the intracranial and scalp distribution induced by intracranial stimulation in patients³⁴ which closely matched predictions from dipole models. Accordingly, scalp voltages generated by the deepest sources in the center of the head still reach 20–52% of the voltages generated by the most superficial sources of the same source strength; this percentage would be considerably reduced (to only 4–15%) with equal skull and brain conductivities.

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The important consequence for electrical neuroimaging is that the EEG displays a considerable sensitivity to deep sources which is more pronounced than for the MEG (Figure 1.2) and is often underestimated. Neglecting the contribution of deep sources to the EEG is thus generally not justified. Another consequence is that the relative sensitivity to superficial versus deep sources depends critically upon the conductivity of the skull. The systematic developmental changes in relative conductivity thus need to be considered in electrical neuroimaging³⁵. Higher conductivity of infant skulls leads to less spatial blurring which emphasizes superficial sources and lowers spatial correlations³⁶. The issue of conductivity and spatial blurring is discussed in detail in Chapter 4.

Spatial smoothness

The spatial extent and the spatial smoothness of the synchronized polarization in EEG generators is another crucial but only partly resolved issue for electrical neuroimaging. The most direct knowledge about the spatial extent of human EEG generators comes from the few studies where intracranial and scalp recordings in epilepsy patients were combined for diagnostic purposes. Despite the caveat that the coverage with intracranial electrodes is typically very limited, and that the epileptic EEG is not typical of normal oscillatory or event-related activity but characterized by particularly strong and synchronized EEG events, these findings provide crucial constraints for source models, and illustrate the different scales of spatial smoothness and resolution which govern intracranial and scalp EEG. Intracranial recordings find that interictal spike activity reaches 50–500 μV and is often limited to 2–3 cm (i.e. to 2–3 contacts of multicontact electrodes with typical spacing), with sharp fall-offs beyond the active region (to under 10% at the next contact)³⁷, or to less than 6 cm^2 on an electrode grid. These focal spikes are usually hard to detect in the scalp EEG, even despite considerable intracranial amplitude and averaging based on an intracranial channel^{37–40}. Similarly, strong synchronization (using coherence estimates, see Chapter 7) between neighboring electrodes of intracortical grids is typically limited to well-demarcated regions of 2–5 cm diameter⁴¹. This corresponds well to historical estimates based on a cadaver model, where at least 6 cm^2 of a model generator is needed to contribute for scalp amplitudes of 25 μV ⁴², and to models suggesting that at least 4–6 cm^2 need to be activated synchronously^{19,27,43}. More recent work with epilepsy patients even suggests that for such epileptiform activity, synchronization of at least 10 cm^2 is required, and that synchronization of under 6 cm^2 does not generate visually detectable scalp amplitudes³⁹, but such estimates may be somewhat inflated due to the use of isolating grids⁴⁴. Intracranial recordings of spontaneous rhythmic activity are particularly rare. They provide evidence for a similar spatial extent over a few centimeters, with some polarity reversals between adjacent occipital electrodes spaced about 1 cm apart⁴⁵.

What amplitude is detectable in the scalp EEG clearly depends on both the detection method and the signal-to-noise ratio. Typically, epilepsy potentials above 10–20 μV at the scalp exceed the level of spontaneous activity and noise in some EEG channels and become reliably visible. Averaging can also retrieve much smaller activities at the scalp ($< 0.5 \mu\text{V}$ as for the brain-stem potentials) provided they are systematically time locked to external (or larger intracranial) events.

Taken together, evidence from basic neurophysiology and from intracranial recordings suggests that the main source of the EEG is the dynamic, synchronous polarization of spatially aligned neurons in extended gray matter networks, due to postsynaptic rather than action potentials. Important constraints regarding the spatial extent and the maximal

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physiological polarization of effective EEG generators can be derived from this evidence. However, further constraints regarding orientation and depth of EEG generators are rarely justified. Recent evidence rather suggests that a wider range of active brain structures than previously thought may contribute to the EEG. This point is particularly relevant with respect to some of the potential generators of EEG oscillatory rhythms that are discussed in the following section.

Oscillations in brain networks

An important question for electrical neuroimaging is whether spatial aspects of the activated networks can be derived from frequency characteristics of the scalp-recorded oscillations. The characteristic rhythms in cortical structures have long been thought to be mainly under thalamic control, and thus to involve an entire thalamocortical network in both normal^{46,47} and pathological conditions^{48,49}. However, recent research emphasizes, on the one hand, the intrinsic rhythmic properties of cortical networks⁵⁰ (for review, see Amzica & Steriade, 1999⁵¹); on the other hand, it is known that some of the rhythms recorded at the EEG level are exclusively generated within specific structures: either the cortex alone, or the thalamus alone, or outside the thalamocortical system, in the hippocampus.

An EEG analysis is often made according to the spectral content of the recording signals (see Chapter 7). Although this might confer certain advantages, it also contains numerous pitfalls that prevent correct conclusions. This is mainly due to the fact that a given frequency band may ambiguously reflect various conditions, or phenomena originating at different locations. We will organize this section according to the frequency bands traditionally encountered in the EEG praxis, however, emphasizing the possible sources of haziness related to the interpretation of EEG signals. The reader should keep in mind, when extrapolating from cellular data to EEG, that:

- (1) Cellular recordings are almost exclusively performed in animals, whose phylogenetic development, behavioral and structural peculiarities are often neglected.
- (2) The study of the intrinsic properties of cells is mostly carried out *in vitro* or in cultures, preparations that are as far as one can imagine from the complex reality of the whole brain, both in terms of network linkages and physiological state. At best, these preparations would correspond to a deeply comatose brain.
- (3) The study of the network interactions, however multisite they might be, are still based on recordings from spatially discrete and limited locations rather than continuous.
- (4) Anesthesia is often unavoidable in animal studies and the elimination of the pharmacological effect is more complicated than a mere subtraction.

Slow, delta rhythms

Grey Walter⁵² was the first to assign the term “delta waves” to particular types of slow waves recorded in the EEG of humans. Although Walter introduced the term delta waves in correspondence to pathological potentials due to cerebral tumors, with time delta activities became more related to sleep and anesthesia. The IFSECN⁵³ defines delta waves as waves with a duration of more than 1/4 s (which implies a frequency band between 0 and 4 Hz). There have been various studies aiming at disclosing the relationship between cellular activities and EEG and the sources of delta activities^{54,55}. In the following it will be emphasized that the 0–4 Hz frequency range reflects more than one phenomenon and that definitions based exclusively on frequency bands may conceal the underlying mechanism. Studies have

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unveiled the electrophysiological substrates of several distinct activities in the frequency range below 4 Hz during sleep and anesthesia. Their interaction within corticothalamic networks yields to a complex pattern whose reflection at the EEG level takes the shape of polymorphic waves.

It should also be stressed from the beginning that delta activities cover two EEG phenomena: waves and oscillations with some regularity of the variation, with no clear separations between the two, as far as spectral analysis is concerned.

As for now, there are at least two sources of delta activities: one originating in the thalamus and the other one in the cortex.

Thalamic delta oscillations have been found in a series of in vitro studies. They revealed that a clock-like oscillation within the delta frequency range (1–2 Hz) is generated by the interplay of two intrinsic currents of thalamocortical cells. Whereas most brain oscillations are generated by interactions within networks of neurons, but also glial cells, the thalamic delta oscillation is an intrinsic oscillation between two inward currents of thalamocortical cells: the transient calcium current (I_t) underlying the low-threshold spike (LTS) and a hyperpolarization-activated cation current (I_h)^{56,57}.

This oscillation was also found in vivo, in the thalamocortical neurons of the cat, after decortications⁵⁸. Thalamocortical neurons from a variety of sensory, motor, associational and intralaminar thalamic nuclei were able to display a clock-like delta rhythm either induced by imposed hyperpolarizing current pulses or spontaneously. However, in intact preparations, with functional cortico-thalamic loops, the regular thalamic delta oscillation was absent or largely prevented by the ongoing cortical activity⁵⁹. This raises concerns as to the emergence of this intrinsically generated thalamic rhythm at the level of the EEG.

The existence of *cortical delta* was suggested on the basis that delta waves, mainly at 1–2 Hz, survive in the EEG of athalamic cats⁶⁰. Whether such procedures generate a physiological or a pathological pattern remains an open question; nonetheless, they create a deafferentation of the cortex. Extracellular recordings of cortical activity during pathological delta waves (as obtained by lesions of the sub-cortical white matter, the thalamus or the mesencephalic reticular formation) have shown a relationship between the firing probability and the surface-positive (depth-negative) delta waves, whereas the depth-positive waves were associated with a diminution in discharge rates⁶¹. These field-unit relationships led to the assumption that the depth-positive component of delta waves reflects maximal firing of inhibitory interneurons. However, this has not been found. It was suggested that EEG delta waves are rather generated by summation of long-lasting after-hyperpolarizations produced by a variety of potassium currents in deep-lying pyramidal neurons⁶².

A third type of delta patterns appeared with the discovery of a novel oscillation dominating sleep EEG activities (around, but generally below 1 Hz)^{63–68}. Its thorough investigation at the cellular level (see below) set the basis for revisiting the cellular basis of delta rhythms. The frequency of this slow oscillation depends on the anesthetic used and the behavioral state: it is slower under anesthesia than during natural sleep. It is found in both animals^{63,68} and humans^{64–68}. The slow oscillation is generated within the cortex because it survives after thalamectomy⁶⁹, is absent from the thalamus of decorticated animals⁷⁰ and is present in cortical slices⁷¹. At the intracellular level, the slow oscillation showed that cortical neurons throughout layers II to VI displayed a spontaneous oscillation recurring with periods of 1–5 seconds, depending on the anesthetic/sleep stage, and consisting of prolonged depolarizing and hyperpolarizing components (Figure 1.3A). The long-lasting depolarizations of the

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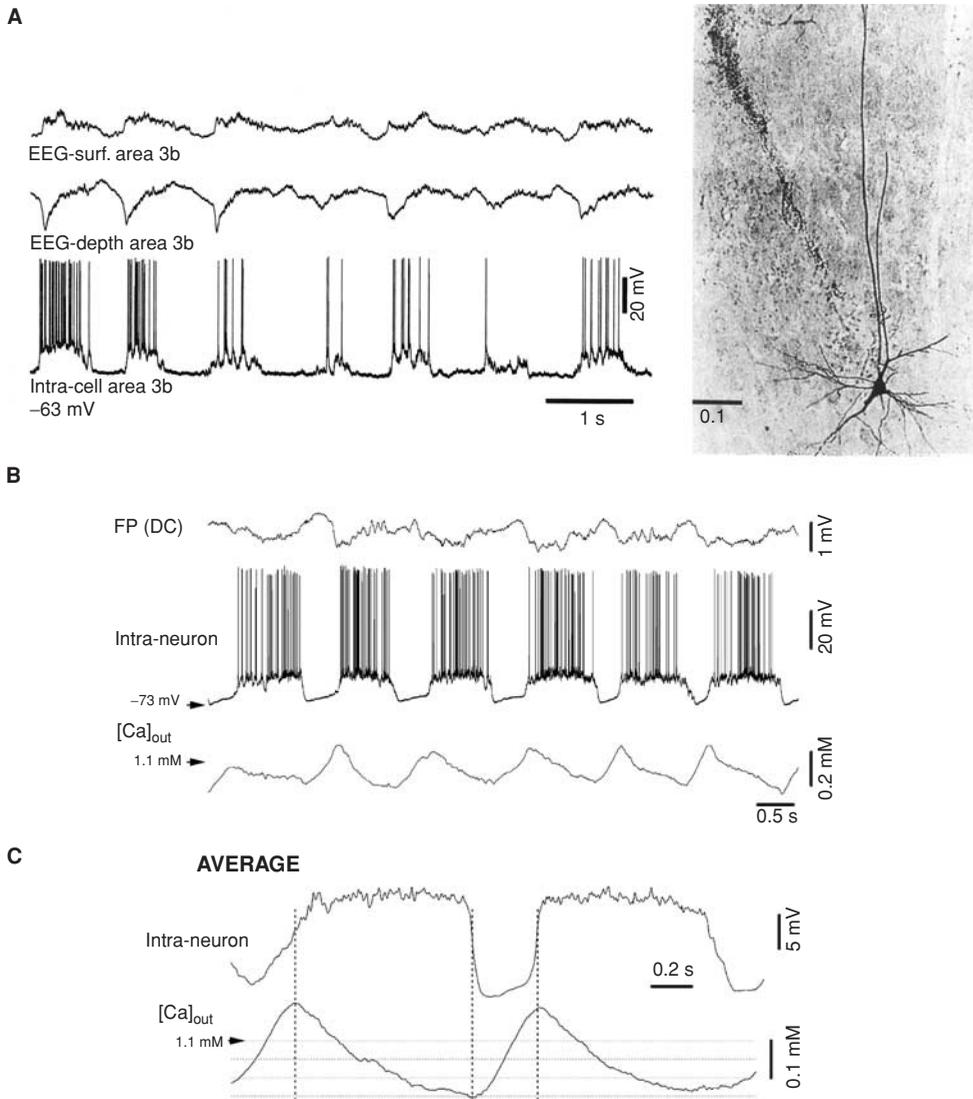


Figure 1.3 A. Pyramidal cell from the somatosensory cortex (area 3b) during the slow (< 1 Hz) oscillation. The left panel shows intracellular recordings and simultaneously recorded EEG in the vicinity (~ 1 mm) of the cell. The EEG was recorded by means of coaxial electrodes located on the surface and at a depth of ~ 0.6 mm. The cell oscillated at 0.9 Hz with depolarizing phases corresponding to depth-EEG negative (surface-positive) potentials. The right panel shows the corresponding cell stained with Neurobiotin (calibration bar in mm). (Modified from⁴¹.) B. Fluctuations during the slow oscillation. Relationships between intracellular membrane potential, extracellular calcium ($[Ca]_{out}$) and field potential. Periodic neuronal depolarizations triggering action potentials were interrupted by periods (300–500 ms) of hyperpolarization and silenced synaptic activity. $[Ca]_{out}$ dropped by about 0.25 mM during the depolarizing phase reaching a minimum just before the onset of the hyperpolarization. Then, $[Ca]_{out}$ rose back until the beginning of the next cycle. C. Thirty cycles were averaged (spikes from the neuronal signal were clipped) after being extracted around the onset of the neuronal depolarization. The vertical dotted lines tentatively indicate the boundaries of the two phases of the slow oscillation. (Modified from Massimini & Amzica⁷⁴ with permission from the American Physiological Society. Copyright © 2001.)

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slow oscillation consisted of EPSPs, fast prepotentials and fast IPSPs reflecting the action of synaptically coupled GABAergic local-circuit cortical cells⁷². The long-lasting hyperpolarization, interrupting the depolarizing events, is associated with network disfacilitation in the cortex⁷³ achieved by a progressive depletion of the extracellular calcium ions during the depolarizing phase of the slow oscillation⁷⁴ (Figure 1.3B–C).

All major cellular classes in the cerebral cortex display the slow oscillation^{72,75}. During the depth-positive EEG wave they are hyperpolarized, whereas during the sharp depth-negative EEG deflection cortical neurons are depolarized (Figure 1.3). The spectacular coherence between all types of cortical neurons and EEG waveforms mainly relies on the integrity of intracortical synaptic linkages, but other projections, possibly cortico-thalamo-cortical, as well as networks of gap junctions (see below) might contribute to the synchronizing of the slow oscillation.

The better comprehension of the mechanisms determining the pacing of the slow oscillations came from experiments considering the possible dialogue between neurons and glial cells. Dual simultaneous intracellular recordings from neurons and adjacent glial cells explored the possibility that glia may not only passively reflect, but also influence, the state of neuronal networks⁷⁶. The behavior of simultaneously recorded neurons and glia is illustrated in Figure 1.4. During spontaneously occurring slow oscillations, the onset of the glial depolarization did, in the vast majority of the cases, follow the onset of the neuronal depolarization with an average time lag around 90 ms (Figure 1.4). This time lag is, however, longer than the one obtained from pairs of neurons (around 10 ms in Amzica & Steriade⁷⁷). The glial depolarization reflects with virtually no delay the potassium uptake⁷⁸. Toward the end of the depolarizing phase, the glial membrane begins to repolarize before the neurons (Figure 1.4)⁷⁹. Glial cells might thus control the pace of the oscillation through changes in the concentration of extracellular potassium⁷⁸.

The overall synchronization of the slow oscillation in the cortex is also assisted by glial cells, which are embedded in a gap junction-based network, through the phenomenon of spatial buffering^{80,81}. Spatial buffering evens local increases of extracellular potassium by transferring it from the extracellular milieu to the neighboring glial cells, then through gap junctions and along the potassium concentration gradient, at more distant sites with lower concentrations of potassium, where it is again expelled into the extracellular space. The local spatial buffering during slow oscillations might play two roles: (i) it contributes to the steady depolarization of neurons during the depolarizing phase of the slow oscillation, and (ii) it modulates the neuronal excitability. The latter mechanism could favor the synaptic interaction within cortical networks at the onset of the depolarizing phase of the slow oscillation, but it could equally induce a gradual disfacilitation.

The same cortical glial cells, if organized along an axis parallel to the apical dendrites, could constitute a powerful dipole, which, together with the already existing dipole of arterioles plunging into the cortex from the pial surface, could constitute a source of EEG activities. This aspect of utmost importance still remains to be investigated.

The complex electrographic pattern of slow-wave sleep results from the coalescence of the slow oscillation with spindle (see below) and delta oscillations⁸². The weight of each of these major components is dynamically modulated during sleep by synaptic coupling, local circuit configurations and the general behavioral state of the network. Through its rhythmic occurrence at a frequency that is lower than that of other sleep rhythms (spindles and delta), and due to its wide synchronization at the cortical level, the cortical slow oscillation