

Local Field Potential, Relationship to Unit Activity

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Synonyms

[Electroencephalogram, relation to unit activity](#); [Local field potential, contamination by spikes](#); [Local field potential, spike contribution](#); [Local field potential, spike-triggered average](#)

Definition

Unit activity usually refers to timing of spikes elicited by individual neurons (single-unit activity, SUA) or local ($r < 140 \mu\text{m}$) population of neurons (multiunit activity, MUA; Buzsáki 2004). Although local field potential (LFP) reflects both subthreshold and spiking activities that are summed over larger population of neurons ($r < 450 \mu\text{m}$; Berens et al. 2008), usually it does not display discriminable spikes. Nevertheless, the amplitude of high-frequency LFP ($>40 \text{ Hz}$) often correlates with population firing rate, whereas the phase and amplitude of low-frequency LFP ($<10 \text{ Hz}$) modulate this relationship. The LFP–spike relation is very sensitive to neuronal correlations – at high synchrony levels, neurons produce macroscopic spikes visible in the raw LFP signal (“population spikes”).

Detailed Description

The basic physical phenomena involved in generation of LFP are common across all types of neuronal activities, including unit activity (spikes). However, there are several factors that differentiate unit contributions from, for example, synaptic contributions: (1) Their spatial locality leads to rapid decay of their contribution with distance. (2) Their short duration hinders the summation of contributions from multiple units. (3) Their high-frequency power is cut off by biological medium and hardware filters.

Despite these difficulties, some experimental paradigms unveil a substantial spike-related component in the low- and high-frequency LFP signals.

Spike Correlates in High-Frequency LFP ($>40 \text{ Hz}$)

In cat visual cortex, presentation of light bars evokes oscillations at frequencies 35–50 Hz that are tightly correlated with spikes in local neuronal population (MUA; Gray and Singer 1989). These gamma-band oscillations most likely reflect synchronous activation of a larger population of cells.

Coupling between LFP and spikes is even stronger at frequencies above 60 Hz: as demonstrated by experiments in visual cortex, the power of stimulus-induced high-gamma LFP (60–200 Hz)

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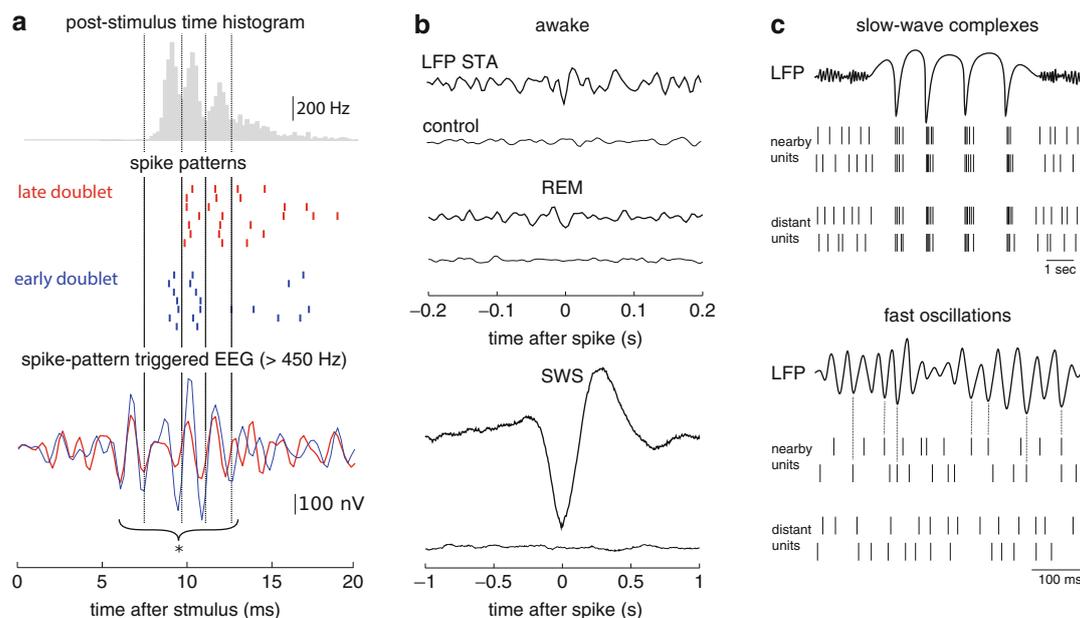


Fig. 1 Relation of LFP to unit activity in monkeys and cats. **(a)** High-frequency EEG waveforms covary with temporal spike patterns of single units in somatosensory cortex of macaques. Neurons respond to identical stimulation with variable bursts of spikes (*top panel*: average poststimulus time histogram in *gray*, *dotted lines* – intraburst intervals), which can be classified into one of a few stereotypical spike patterns (raster plot: sample spike trains of two of such patterns). Peaks of high-frequency EEG align to the preferred “spike windows,” and their amplitude depends on the spike pattern of simultaneously recorded unit (*bottom*: average EEG traces coincident with a spike pattern plotted in same color; *significant difference, $p < 0.05$) (Modified from Telenczuk et al. (2011)). **(b)** LFP–spike correlation depends on the brain state. Spike-triggered LFP average (LFP-STA) calculated in awake state (*top*) and REM sleep (*middle*) of cats is shorter in time and smaller in amplitude compared to the slow-wave sleep LFP-STA (SWS, *bottom*). In all three states, randomly shuffling spikes with respect to LFP eliminated the correlations (*thin lines* below each LFP-STA). **(c)** LFP reflects unit activity that is locally correlated with respect to fast oscillations and globally correlated with respect to slow oscillations. Schematic representation of synchrony of nearby and distant units in relation to troughs of slow (*top*) and fast oscillations (*bottom*) (**(b)** and **(c)** were modified from Destexhe et al. (1999))

closely follows the concomitant increase in population firing rate (Ray et al. 2008; Burns et al. 2010). Similar relationship between spontaneous LFP and MUA is also observed in ongoing activity (Destexhe et al. 1999).

Owing to its fine temporal resolution, high-frequency LFP allows to discriminate the timings of spikes. When multiple neurons become tightly synchronized, they elicit coincident spikes, which jointly produce discriminable peaks in field potentials (LFP or EEG) even at distant locations (“population spikes”; Andersen et al. 1971). This mechanism, for instance, is involved in the generation of macroscopic high-frequency (>200 Hz) bursts in somatosensory cortices of nonhuman primates (Fig. 1a; Baker et al. 2003) and rodents (Jones et al. 2000) and frequency following neurophonic potentials in auditory system of barn owls (Kuokkanen et al. 2010).

Since MUA and LFP are often recorded with the same electrodes, spike waveforms of nearby units may contaminate the LFP, exaggerating the observed correlations. Indeed, low-frequency band of extracellularly recorded spikes overlaps with gamma/high-gamma band of LFP. However, the subtraction of spike waveforms from LFP affects mainly frequencies above 100 Hz (Belluscio et al. 2012), decreasing but not completely eliminating correlation between spikes and high-gamma LFP (Zanos et al. 2011).

Relationship Between Low-Frequency LFP (<10 Hz) and Unit Activity

Often the population firing rate may be inferred from the LFP alone, but only when both its low- and high-frequency bands are considered. The most informative features are high-gamma power (40–90 Hz) and the phase and amplitude of low-frequency oscillations (<10 Hz; Rasch et al. 2008).

Low- and high-frequency LFP bands are interrelated: when awake monkeys are presented with natural movies, the correlation between MUA and gamma-band EEG (which shares many features with LFP) is the highest in the troughs of delta oscillation (2–4 Hz; Whittingstall and Logothetis 2009).

LFP signals in the frequency band between 10 and 40 Hz are not clearly related to unit activity (Rasch et al. 2008; Belitski et al. 2008).

Mechanisms of Spike Contribution to LFP

The sources of correlations between LFP and unit activity are very diverse, and it is impossible to single out any particular cause except in few specific scenarios. Nevertheless, two main mechanisms underlie most of the phenomena listed above: (1) contribution through synchronous synaptic release triggered by a spike arriving at axon terminals and (2) direct contribution of ionic currents underlying the spike.

A spike of a single neuron triggers a large number of synaptic potentials in its postsynaptic targets. Despite their small amplitude, postsynaptic potentials can produce large extracellular field (“unitary field potential”), provided that they are spatially and temporally clustered. This occurs at synapses formed by hippocampal interneurons (area CA3), whose spikes generate a LFP bump at monosynaptic latency (Bazélot et al. 2010). Fast, synchronous postsynaptic potentials may also underlie bursts of high-frequency oscillations *in vivo* (Fig. 1a; Telenczuk et al. 2011).

Action potentials initiate and propagate due to an interplay between a variety of membrane currents. Axon currents that are involved in propagation of action potentials produce only slight extracellular fields except at both axon ends or while crossing volume conductor boundaries (Jewett et al. 1990). However, action potentials activate also sodium currents in soma and calcium currents in the dendrites, which, in turn, generate strong contribution to field potentials especially at high frequencies (Murakami et al. 2003). In contrast, slow potassium currents, which hyperpolarize membrane after a spike, can contribute significantly to low-frequency LFP; for example, a slow potassium current shapes the wave component of so-called spike-and-wave complex (Destexhe 1998). Since extracellular medium is more conductive at low frequencies, it favors these slow currents over faster sodium spikes (Bédard et al. 2004).

Rather than contributing directly to LFP, active ion channels may also modulate low-frequency LFP by shunting synaptic currents (Reimann et al. 2013).

Recent evidence for monopolar effects in LFP generation (Riera et al. 2012) has triggered a discussion about possible physical mechanisms for neuronal monopoles (Destexhe and Bedard 2012; Bedard and Destexhe 2013; Gratiy et al. 2013). If confirmed, such monopolar effects should have strong consequences on the genesis of LFP, even if they occur transiently (Destexhe and Bedard 2012). This possible monopolar contribution should be clarified by future theoretical and experimental studies.

Correlation between low-frequency LFP and unit activity is not always causal; sometimes it results from a common source of variations, such as global changes in the excitability level. For example, in up-and-down states, membrane potential switches periodically between depolarized and hyperpolarized states, inducing simultaneously slow LFP oscillations (<10 Hz) and alternations in

firing rates. Here, modulations in unit activity follow the phase of the slow oscillations, but they are linked only through an external factor – fluctuations in the membrane potential (Fig. 1b; Destexhe et al. 1999). Similarly, slow shifts in excitability may explain relation between phase of low-frequency LFP and firing rate (discussed above), both of which are under control of sensory inputs and fluctuations in ongoing network activity (Mazzoni et al. 2010).

Effects of Neuronal Correlations on LFP–Spike Relation

LFP amplitude is far more sensitive to correlations between neurons than to the number of active units and their firing rate. For example, simulations show that if cell-to-cell correlations increase just by 2 %, high-gamma LFP power rises by a factor that would normally require tenfold increase in firing rate of uncorrelated population (Ray et al. 2008). As discussed above, strong synchrony within the population may produce macroscopic “population spikes,” but even a small neuronal assembly can generate a synchronous event (“unitary event”) that is related to a distinct temporal pattern in LFP (Denker et al. 2011).

One particularly useful technique to investigate field–unit relation is to correlate field potential and single-unit spikes by means of spike-triggered averaging (Fig. 1b). Interestingly, magnitude and waveform of spike-triggered LFP in low- and gamma frequency bands (<20 Hz and 25–75 Hz, respectively) correspond more closely to the dynamics of synchrony between the synaptic inputs rather than to network events associated with spikes (Okun et al. 2010).

Temporal correlations between spikes of single units may also produce small but detectable change in LFP signal. For example, a burst of spikes generated by a single neuron can induce a switch of cortical state and corresponding change in the LFP spectrum (Li et al. 2009). Similarly, sensory-evoked spikes in somatosensory cortex are organized in stereotypical spike burst patterns whose incidence covaries with the amplitude of high-frequency EEG burst (>400 Hz; Fig. 1a; Telenczuk et al. 2011).

Neuronal correlations are under control of the brain states, such as different arousal and attention levels. Consequently, the brain states have large impact on the LFP–unit relation. Specifically, spikes elicited in slow-wave sleep are associated with LFP deflections of longer durations and broader spatial coherence compared to waking and REM sleep (Fig. 1b, c; Destexhe et al. 1999).

Other Factors Influencing LFP–Unit Relation

Neural anatomy and micro-architecture determine the physical aspects of LFP generation. The neuronal morphology (Murakami and Okada 2006), geometry of cortical circuits (Buzsáki et al. 2012), and local circuitry may affect LFP in all frequency bands. In addition, composition of neural tissue such as presence of neurons of different types, glial cells, and vasculature affects the conductive properties of the medium (Nelson et al. 2013). Therefore, the quantitative and qualitative aspects of LFP relationship with unit activity must be always considered in the context of the specific brain area.

Further, the experimental protocol and recording system are the key features determining the LFP and their relationship to unit and synaptic activity. In particular, the type of stimulation is essential in shaping the spatial and temporal properties of spike-triggered LFP (Nauhaus et al. 2009; Reimann et al. 2013). Other factors include the type of electrodes, analog and digital filters, tissue preparation, position of signal, and reference electrodes.

Implications for Electrophysiology

Unit-related LFP components offer an excellent opportunity for electrophysiologists to study the output of neuronal computation, the spiking, in anesthetized and behaving animals or even noninvasively in humans. Population firing rate and synchrony are two properties that can be currently assessed by means of LFP, and the list may increase as we learn more about the physical and physiological basis of LFP generation.

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