Control of Spatiotemporal Coherence of a Thalamic Oscillation by Corticothalamic Feedback

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The mammalian thalamus is the gateway to the cortex for most sensory modalities. Nearly all thalamic nuclei also receive massive feedback projections from the cortical region to which they project. In this study, the spatiotemporal properties of synchronized thalamic spindle oscillations (7 to 14 hertz) were investigated in barbiturate-anesthetized cats, before and after removal of the cortex. After complete ipsilateral decortication, the long-range synchronization of thalamic spindles in the intact cortex hemisphere changed into disorganized patterns with low spatiotemporal coherence. Local thalamic synchrony was still present, as demonstrated by dual intracellular recordings from nearby neurons. In the cortex, synchrony was insensitive to the disruption of horizontal intracortical connections. These results indicate that the global coherence of thalamic oscillations is determined by corticothalamic projections.

Despite the pervasive presence of corticothalamic (CT) cells by cortical afferents innervating the lateral geniculate (LG) nucleus was suggested, on the basis of the observation that LG cells showed stimulus-dependent synchronization, which was disrupted by removal of the visual cortex (8). This observation indicates a dynamic role for the corticothalamic feedback projection in selecting or focusing input signals with specific features. The corticothalamic feedback may also be an essential component in shaping dynamic spatiotemporal maps that code for stimulus information in the somatosensory thalamus (9).

We investigated the influence of the massive corticothalamic projection on the spatiotemporal coherence of spontaneously occurring global spindle oscillations generated in the cat thalamus under barbiturate anesthesia. Recording of local field potentials (LFPs) from the thalamus, with eight tungsten electrodes (Fig. 1) designated Th1 through Th8, revealed that spindling occurs almost simultaneously in most of the thalamus (Fig. 1, intact).
termination time of spindle sequences were less than 10% of the duration of a spindle sequence. We then found that the cortex resection (n = 8) and repositioned the electrodes in approximately the same position (Fig. 1). In the decorticated cat, the occurrence of spindle sequences in the different electrodes was largely not coincident in time (Fig. 1), however, some spindle sequences were still nearly synchronous (Fig. 1, Decorticated). (Fig. 2, top) by plotting the LFP voltage as a function of time and space. In the left column, with intact cortex, spindle activity was highly coherent over the entire recorded thalamic area, as indicated by the formation of horizontal yellow (maximum oscillatory) and blue (local silence) stripes at 8 to 10 Hz on the vertical columns. Not only were spindle sequences initiated synchronously, but also oscillatory shifts among the thalamic sites. Removal of the cortex markedly diminished the spatio-temporal coherence of the LFP. The decorticated pattern (Fig. 2, Decorticated) was characterized by an absence of stripes, indicating that oscillatory activity was not longer synchronized among thalamic sites located more than 2 or 3 mm apart.

The coincidence in the appearance of spindle oscillations among the thalamic...
tion between their spindle-related intracellular activities.

A possible mechanism by which the cortex exerts its global effect on spatiotemporal organization of thalamic oscillations is the neuroneme propagation of thalamocortical axons as compared to the reciprocal projections between the RE nucleus and the dorsal thalamus. The action of the cortex could be exerted through direct excitation of TC cells, timing their output spike-bursts by precipitating the onset of the cyclic IPSPs through excitation of RE cells and synchronization of the onset of the IPSPs or both. We favor the role of the RE nucleus, taking into consideration the divergent projections of its rostral pole (14), that in turn receives convergent projections from various cortical areas (12).

An alternative explanation for the synchronizing role of the cortex would be that synchrony is attained within cortical circuits because of the abundant horizontal corticocortical projections in areas 5 through 7 (16) and thereafter is imposed on the thalamus. To investigate the role of intracortical connectivity on synchrony, we performed multisite recordings from the suprasylvian cortex, using the same array of electrodes as for thalamic recordings. In control conditions (Fig. 4A, Intact), spontaneous spindle oscillations occurred at 8 to 9 Hz almost simultaneously in the eight leads, reflecting the synchrony recorded in the thalamus with intact cortex (Fig. 1).

After a deep coronal cut through the suprasylvian gyrus (Fig. 4A, Cut), cortex leads Cx4 and Cx5 showed diminished activity due to local damage, but spontaneous oscillations still occurred simultaneously in the other leads. To quantify the effect of disruption of intracortical connections, we calculated the averaged crosscorrelations between sites separated by increasing distances (Fig. 4B). Similar to thalamic recordings (Fig. 2), crosscorrelations showed a smooth decay with increased distance in the cortex. After the cut, a gap appeared in correlations 1-4 and 1-5 due to tissue damage, but the same correlation patterns were seen at distances of 5 mm and greater (17).

These results are consistent with a decisive role for corticothalamic projections in organizing the long-range synchrony and spatiotemporal patterns of oscillations generated in the thalamus. The natural consequence of thalamic synchrony is that the impact of thalamic output to the cortex is increased during this sleep oscillation. Whether this represents a mere consequence of the type of connectivity between cortex and thalamus subserving information processing or has in itself a precise physiological role is a question whose answer is still far from our reach.

![Fig. 3. Synchronized spindle sequences of closely located TC cells in the decorticated thalamus. (A) Couples of TC cells (designated TC1 and TC2) were intracellu

larily recorded at distances around or less than 1 mm (n = 5) from the VL nucleus. Spindles occurred at the same time in both cells (spontaneous activity at right). The rightmost sequence expanded below shows the synchrony of the intracellular events characteristic of spindling. Spindling-related IPSPs (n = 10) from TC1 were aligned, with the time of their onset as a zero time reference (dotted line). The intracellular recording from TC2 was aligned to the same reference, revealing the occurrence of IPSPs that were almost simultaneously with TC1. (B) TC cells were recorded simultaneously from the VL nucleus (TC1) and the LP nucleus (TC2), distant by 4 mm. Spindles occurring spontaneously in each cell showed no consistent temporal relation. The spindling sequence expanded below shows that the termination of a spindle in TC1 coincides with the beginning of a spindle in TC2. Alignment of IPSPs (n = 10) from TC1 compared with a flat line in TC2.

![Fig. 4. Synchrony of spindle oscillations is not determined by intracortical connectivity. (A) Multisite recordings were taken from a 1-mm depth in the suprasylvian (SS) gyrus, with a similar electrode array (Cx1 to Cx8) as described in Fig. 1. Spontaneous spindle sequences occurred nearly simultaneously in control conditions (Intact). A 3-mm-deep coronal section (Cut) of the SS gyrus (horizontal line between electrodes 8 and 7 in the scheme), crossing laterally from the lateral aspect of the marginal gyrus (M) to the medial aspect of the ectosylvian gyrus (ES), did not disrupt synchrony of oscillations. PC indicates postauricular gyrus. (B) Synchronization was evaluated by calculating crosscorrelograms between electrode Cx1 and each of the others. Correlograms from 15 consecutive spindle sequences were averaged before and after the cut. The value of the averaged correlogram at time zero was represented as a function of distance with respect to the first electrode. Averaged correlograms for each pair of electrodes were represented as surface plots for intact cortex (middle) and cortex after the cut (right). Correlation values were displayed with a gray scale ranging from −0.4 (black) to 1 (white; see grayscale bar). Secondary peaks around 120 ms indicate rhythmicity at 8 to 9 Hz.](image-url)
REFERENCES AND NOTES


3. Modeling studies have proposed a scenario to explain the absence of spindles in RE cells studied in vitro, based on the absence of neuromodulation in thalamic slices [A. Dostrovsky, D. Contreras, T. J. Sejnowski]. To ensure stability of intracellular recordings, we paralyzed the animals with halothane-ethanol (5 mg/kg intravenously) and artificially ventilated them, with control of the end-tidal CO2 concentration at around 3.7%. Further stability was obtained by performing cisternal drainage, bilateral pneumoencephalax, and hip suspension, and by filling the hole left by the trephination with a 4% agar solution. Body temperature was maintained at 37°C to 38°C. A constant state of deep anesthesia was obtained by additional doses of barbiturate and continuous monitoring of the electroencephalogram (EEG) from the contralateral hemisphere. A high-impedance amplifier with active bridge circuitry was used to record and inject current in the cells. The signals were recorded on an eight-channel tape with bandpass of 0.1 to 9 kHz and digitized off-line at 10 kHz for analysis and display.

4. Intracellular recordings in barbiturate-anesthetized cats have shown that, during spindles, the GABA-containing RE cells generate rhythmic spike-bursts within the frequency range of spindling, superimposed on a slowly rising and decaying depolarizing envelope (1). Spike-bursts of RE cells, particularly those in the rostral pole and rostrolateral sector of the nucleus, impose rhythmic IPSPs onto a large IPSPs and transmitted back to RE cells, where they generate AMPA (α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid) glutamatergic postsynaptic potentials (IPSPs) [T. Bai, M. von Krosigk, D. A. McCormick, *J. Physiol.* (London) **483**, 641 (1995)], and to neocortical cells, where glutamatergic EPSPs are at the basis of the spindle oscillations observable in the EEG [M. Steriade and M. Deschénes, in *Cellular Thalamic Mechanisms*, M. Berti, P. G. Spalluto, and R. Scalfaro, Eds. (Elsevier, Amsterdam, 1988), pp. 51-76].


7. The possibility that corticocortical connections, other than those disrupted by the cut in the suprasylvian gyrus, might account for the preserved synchrony of spindles is remote, because the same type of suprasylvian transection succeeded in immediately disrupting the synchrony of intracortically generated slow oscillation [F. Arzoca and M. Steriade, *J. Neurosci.* **15**, 4655 (1995)].

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