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NEW VISTAS ON THE MORPHOLOGY, CHEMICAL TRANSMITTERS AND PHYSIOLOGICAL ACTIONS OF THE ASCENDING BRAINSTEM RETICULAR SYSTEM

M. STERIADE

Laboratoire de Neurophysiologie, Département de Physiologie, Faculté de Médecine, Université Laval, Québec G1K 7P4, Canada

I would like to introduce this tribute to our teacher and friend, Giuseppe Moruzzi, by stating that the basic tenets of the ascending activating brainstem reticular concept (9, 10) are fully supported by the newest developments in neurosciences and that some of the questions raised in Moruzzi's studies led to fruitful research in the past few years.

The replacement of high-amplitude synchronized EEG rhythms by low-voltage fast waves upon brainstem reticular stimulation (10) is now recognized as a reliable indicator of states with intense activity of cerebral neurons. The old debate whether cell bodies or passing fibers were stimulated in the brainstem reticular core to induce EEG desynchronization is solved since chemical stimulation of the midbrain core helped to demonstrate that perikarya were indeed activated. The most effective site to elicit that EEG reaction corresponds to the area where an ascending arrow was placed in Fig. 3 of the pioneering paper by Moruzzi and Magoun (10). Moreover, single-cell recording in that upper brainstem field showed that midbrain reticular neurons are not only most active during EEG-desynchronized states, but also that their discharge rates reliably increase in advance of overt behavioral changes from resting to active states. Another idea of the 1949 paper (10), that of a thalamic mediation of the cortical EEG response to brainstem reticular stimulation, is now substantiated by the evidence that identified thalamocortical neurons are directly excited by stimulating the midbrain reticular core after chronic degeneration of passing fibers and that the excitability of those cortically-projecting thalamic neurons is dramatically enhanced during EEG-desynchronized behavioral states. Details of these studies that justify Moruzzi's major theoretical statements were discussed in recent reviews (17, 21).

The questions raised in the numerous studies that reflected the interest aroused by the discovery of an ascending activating reticular system have begun to be answered since 1980, due to the refinement of electrophysiological methods and the advent of elegant techniques that combine the tracing of pathways with the immunohistochemical identification of their transmitters. Here are some of these questions.

a) Which are the sources of brainstem cholinergic afferents to the thalamus? The facilitatory actions of brainstem reticular stimulation or natural arousal upon

synaptic transmission through sensory and motor thalamic nuclei have long been assumed to be mainly cholinergic in nature because those effects are partially sensitive to some cholinergic blockers and because iontophoretically applied acetylcholine (ACh) changes the burst responses of thalamic neurons into single-spike responses. This ACh-induced change in firing mode is much like the shift from bursting to tonic discharges seen by passing from the hyperpolarizing state of thalamocortical neurons during EEG synchronization into the tonic depolarization that characterizes these cells during EEG-desynchronized states (cf. 21).

However, the brainstem potentiating effect on the thalamic transmission awaited clarification of the morphological substrates since, with the exception of intralaminar and some medial thalamic nuclei for which there was evidence of brainstem reticular inputs, it appeared that there are no obvious anatomical pathways from the brainstem reticular formation to thalamic relay nuclear groups (5). Since the great majority of physiological studies have been conducted in cat, we used in this species a most effective retrograde tracer (horseradish peroxidase conjugated with wheat germ agglutinin, WGA-HRP) that we injected within the limits of all thalamic nuclei, and we combined the WGA-HRP processing with choline acetyltransferase (CAT) immunohistochemistry to reveal the sources of brainstem cholinergic projections to the thalamus (12, 22).

A connected question relates to the brainstem-forebrain circuits that underly the cholinergic activation of the cerebral cortex. The idea of a cholinergic nature of cortical activation was based on a multifold increase in ACh cortical output following brainstem reticular stimulation and during both EEG-desynchronized states of arousal and REM-sleep (cf. 6). As mentioned above, brainstem reticular stimulation directly excites thalamocortical neurons, but cortically-projecting thalamic cells use aspartate and/or glutamate as transmitter agent, not ACh. Recent data on projections from the brainstem reticular core to substantia innominata and adjacent structures of the same cholinergic family indicate that basal forebrain neurons with widespread cortical projections are the most likely candidates to mediate the cortical effect of brainstem reticular stimulation.

b) Which are the subtle cellular aspects of increased response readiness upon arousal, combined with the blockade of long-lasting and cyclic inhibitory periods that characterize quiet sleep, but associated with the preservation of inhibitory processes involved in discrimination? It was a time, during the 1960's and 1970's, when arousal was thought to be accompanied by a global blockade of inhibitory circuits and the increased excitability of thalamocortical neurons was entirely ascribed to disinhibition in the loop between the reticular thalamic (RE) and the cortically-projecting thalamic nuclei. This idea derived from the neglect or even denial, during the past two decades, of local-circuit inhibitory neurons and the belief that all thalamic inhibitory processes are attributable to the functions of the RE nucleus. It is now known that 20-30% of neurons in major thalamic nuclei are short-axoned and GABAergic (cf. 5, 17).

The idea of a complete blockade of inhibitory thalamic circuits was really embarrassing since, on an *a priori* ground, both processes of excitation and sculpturing

inhibition should be present during the brain-activated state of wakefulness, characterized by complex integrative tasks. It is now known that, contrary to the idea of an undifferentiated disinhibition, arousal as well as ACh not only facilitates the excitatory responses to an optimal stimulus, but also enhances stimulus-specific inhibitory influences on thalamic and cortical cells. The consequence of both manipulations (the change in behavioral state from sleep to arousal and ACh application) is an increased receptive field specificity and orientation selectivity (7, 14). That awakening is associated with relatively short but very effective periods of inhibition, which render the neuron unresponsive to synaptic or antidromic volleys, was earlier shown in recordings of pyramidal tract neurons of behaving primates, by using conditioning-testing volleys in afferent and recurrent collateral circuits during natural wake-sleep states (16). The role played by cholinergic brainstem reticular neurons in the selective blockade of longlasting inhibitions involved in the oscillatory mode and generated in thalamocortical neurons by RE neurons, without interferring, however, with the local inhibitory processes generated by intrinsic interneurons, was recently studied in our laboratories (18).

Some of these new results are briefly discussed below.

Thalamic projections of cholinergic and non-cholinergic brainstem reticular neurons

We found that all major sensory (medial geniculate-MG, lateral geniculate-LG, ventrobasal-VB), motor (ventroanterior-VA, ventrolateral-VL, ventromedial-VM), associational (mediodorsal-MD, pulvinar-PUL, lateral posterior-LP), limbic (anteromedial-AM, anteroventral-AV), intralaminar (centrum medianum-CM, parafasciular-PF, central lateral-CL, paracentral-PC), as well as the rostral, lateral and caudal sectors of the reticular thalamic sheet (RE), receive projections from the upper brainstem reticular formation (Fig. 1).

Specific relay (MG, LG, VB, VA-VL) nuclei receive less than 10% of their brainstem reticular afferents from the non-cholinergic central tegmental field (FTC) of the rostral midbrain. Instead, they receive 85% to 95% of the brainstem innervation from the peribrachial (PB) and laterodorsal tegmental (LDT) cholinergic nuclei in the caudal mesencephalon and at the midbrainpontine junction. The percentages of double-labeled (HRP-CAT) neurons from the total number of HRP-positive elements between the plane anterior 2 and posterior 2, where PB and LDT nuclei fully develop, are around 70% to 85% after WGA-HRP injections in various sensory and motor relay thalamic nuclei.

The amounts of HRP-positive and double-labeled brainstem reticular cells after injections in various districts of the RE nuclear complex are comparable to those detected after injections in specific relay nuclei.

Compared to relay nuclei, we found three to eight times more numerous HRP-labeled cells after injections in associational MD and PUL-LP nuclei, limbic AV-AM nuclei, nuclei with diffuse cortical projections (such as the rostral intralaminar

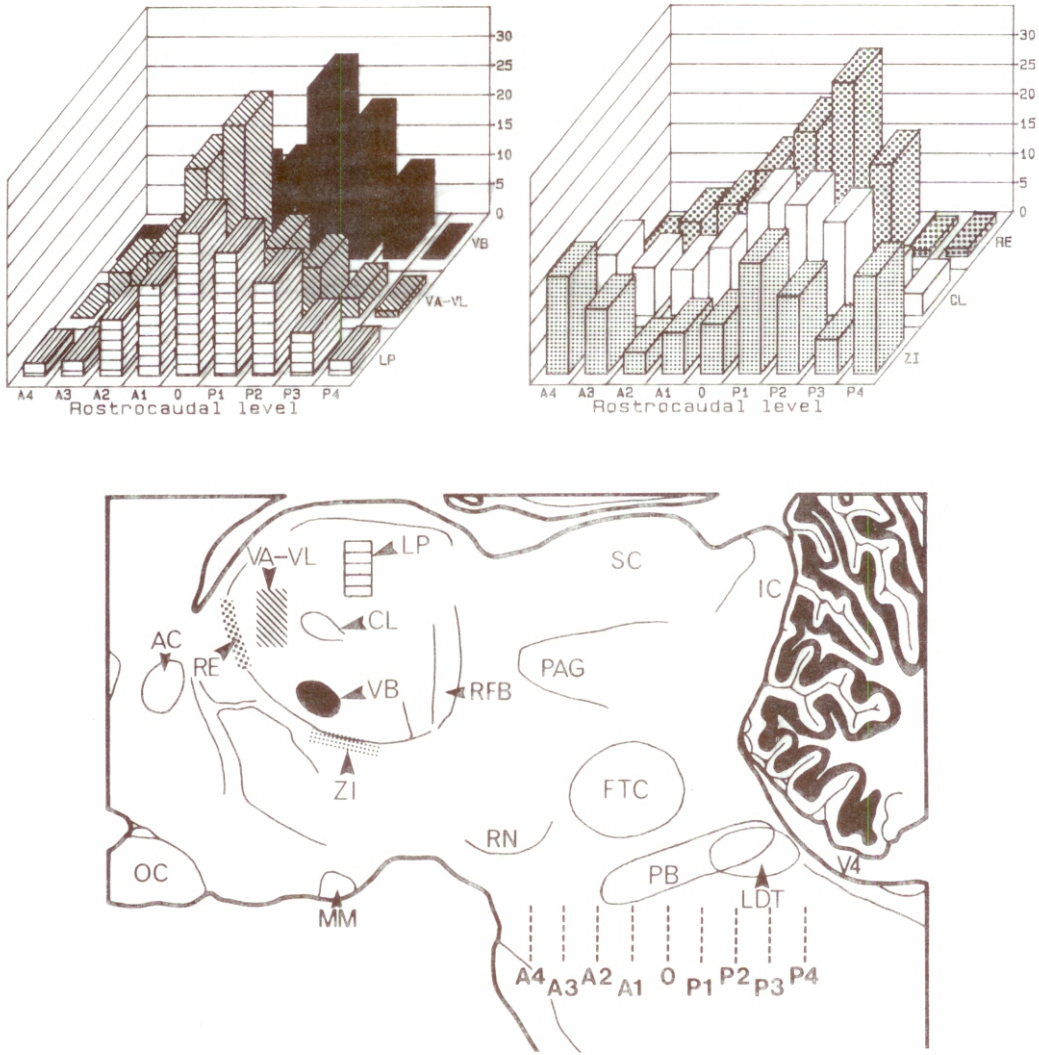

Fig. 1. — *Thalamic projections of brainstem reticular peribrachial (PB) and laterodorsal tegmental (LDT) nuclei in the cat.*

The parasagittal section shows some of the thalamic nuclei where WGA-HRP was injected and the brainstem territories where retrogradely labeled neurons were found: the central tegmental field (FTC), PB and LDT nuclei. Stereotaxic planes from anterior 4 to posterior 4 are indicated. The computer-generated graphs at top show the percentages (ordinates) of HRP-positive cells at various rostro-caudal levels (abscissae) from the total number of retrogradely labeled neurons in the upper brainstem reticular core. Description in text. Abbreviations other than thalamic and brainstem nuclei: AC, anterior commissure; IC, inferior colliculus; MM, medial mammillary nucleus; OC, optic chiasm; PAG, periaqueductal gray; RFB, retroflex bundle; RN, red nucleus; SC, superior colliculus; ZI, zona incerta. Modified fron Steriade *et al.* (22) and Paré *et al.* (12).

CL-PC wing and the VM nucleus that, in addition of relaying cerebellar fastigial impulses to the motor cortex, projects to layer I of widespread cortical areas), and the caudal intralaminar CM-PF complex. The striking labeling after WGA-HRP injections in associational and diffusely-projecting thalamic nuclei was mainly due to more massive projections from the non-cholinergic parts of the upper brainstem reticular formation.

Parallel experiments using the concurrent visualization of CAT immunohistochemistry and the retrograde transport after WGA-HRP injections in the primate thalamus showed that the associational MD and PUL-LP nuclei of *Macaca sylvana* receive a massive afferentation from the midbrain reticular formation, mostly from the cholinergic PB nucleus. Surprisingly, the crossed projection from the brainstem core to the primate PUL-LP thalamic nuclei is as important as the ipsilateral one (Fig. 2).

While the only sources of cholinergic projections to the majority of thalamic nuclei are brainstem PB and LDT nuclei, the AV-AM and especially the RE and MD thalamic nuclei in both cat and monkey also receive afferents from cholinergic neurons located in diagonal band nuclei and substantia innominata (23). This recent finding, combined with the evidence of direct brainstem-forebrain pathways, indicates that in any experimental design involving rostral brainstem reticular stimulation, one may drive cholinergic and non-cholinergic basal forebrain neurons that modulate the activity of RE, MD and, to a much lesser extent, AV-AM and VM thalamic nuclei.

Finally, after all thalamic injections, we found much more numerous HRP-labeled cells within the limits of cholinergic PB and LDT brainstem nuclei than in dorsal raphe nucleus and in locus coeruleus.

These results provide information on the structural substrate and cholinergic nature of enhanced synaptic transmission through thalamic relay nuclei upon brainstem reticular stimulation and natural arousal. Our data, however, leave open a series of questions that should be submitted to further investigation.

Firstly, which are the transmitter agents used by the noncholinergic brainstem reticular cells that were found labeled in the rostral midbrain FTC and in other parts of the upper brainstem core, outside the PB and LDT nuclei? Although some investigators have equated the brainstem reticular actions with those of ACh, the repeatedly reported failure of antagonizing completely the effects of brainstem reticular stimulation with various cholinergic blockers points to the complexity of transmitters in the ascending reticular projections. The co-localization of peptides in brainstem cholinergic neurons (24) and the still undisclosed transmitter (s) of neurons in the large FTC territory of the rostral midbrain reticular formation are some aspects of this complexity.

Secondly, what is the degree of collateralization of thalamopetal axons originating in the upper brainstem core? Our recent tendency was to replace the old concept of diffuseness and non-specificity of brainstem reticular projections by the idea of a focused neuronal network with respect to its input-output organization. Data force us to admit, however, that this specificity of a system previously

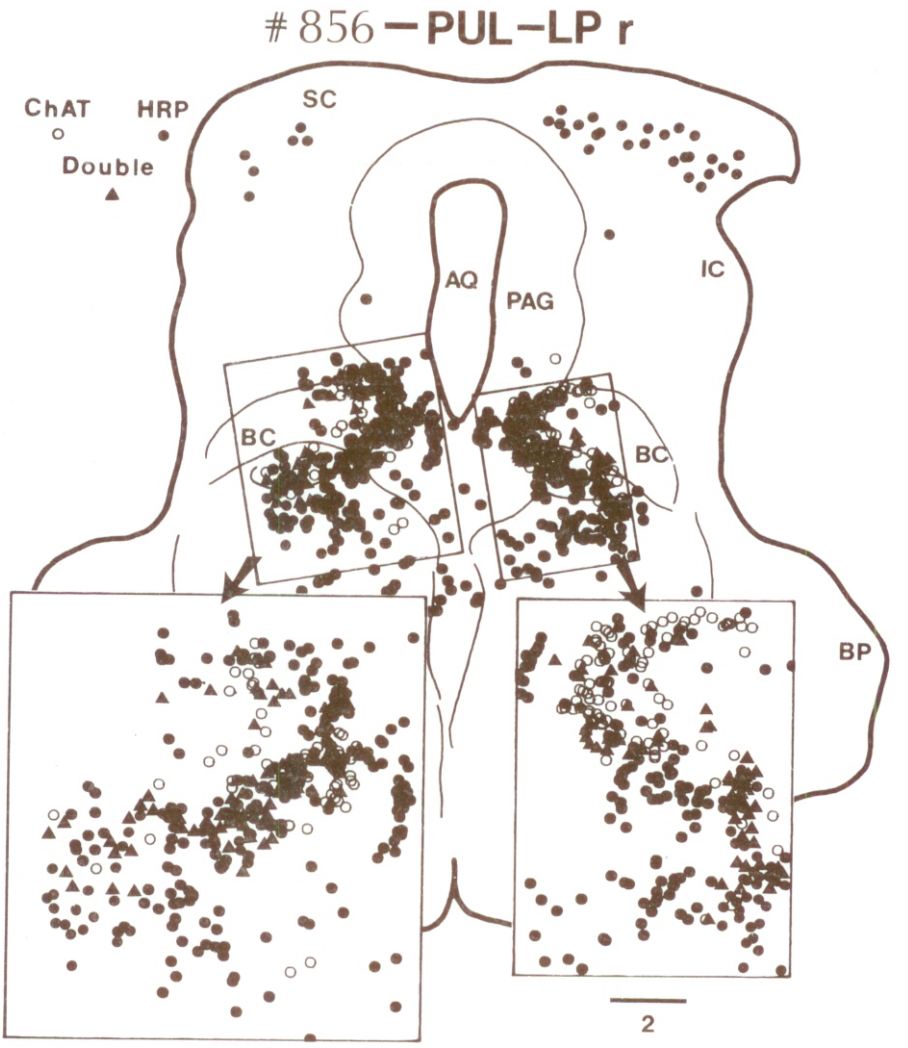

Fig. 2. — *Cholinergic and non-cholinergic brainstem reticular neurons projecting to the right PUL-LP associational thalamic nuclei in the macaque monkey.*

Localization of the three cell-types (CAT-positive, HRP-positive, ands double-labeled; see symbols at top left) made with a computer-assisted microscope. The areas delimitated by rectangles are shown below at a greater magnification. Abbreviations other than in Fig. 1: BC, brachium conjunctivum; BP, brachium pontis. From Steriade *et al.* (22).

regarded as non-specific has some limits. We analyzed the results in our experiments reported above and found that the percentages of double-labeled (HRP + CAT) neurons from the total number of CAT positive cells in PB and LDT brainstem nuclei are around 230% when all injected thalamic nuclei are considered. This result raises the possibility that individual axons of PB or LDT neurons may indeed branch to innervate distant and functionally different thalamic nuclei. Multi-

ple fluorescent tracers combined with CAT immunohistochemistry should be used to shed light on the collateralization of brainstem-thalamic cholinergic axons.

Involvement of brainstem-thalamic projections in the tonic activation and the blockade of synchronized oscillations in thalamocortical systems upon arousal.

A. The notion of direct excitation of thalamocortical neurons from the upper brainstem reticular formation or during natural arousal mainly results from extracellular recordings in unanesthetized preparations (cf. 17, 21). During the 1970's and even more recently, intracellular studies conducted under barbiturate anesthesia concluded that the midbrain reticular formation modulate indirectly the excitability of LG thalamic neurons through a process of disinhibition. This conclusion was based on the fact that midbrain reticular stimulation blocked the recurrent IPSPs that originate in the perigeniculate sector of the RE nucleus, without depolarizing directly LG neurons (cf. 15).

Recent intracellular studies in our laboratories, conducted on unanesthetized brainstem-transected preparations with lesions of trigemino-thalamic pain pathways, indicate however that midbrain reticular stimulation directly depolarizes LG thalamocortical neurons (2, 18). The early depolarization starts at 10-20 ms and lasts for about 150-200 ms, while a late depolarization appears with a latency of 1-2 s and lasts for up to several seconds (Fig. 3). The early depolarization is direct since circuitous pathways through the visual cortex were precluded by extensive cortical ablations. The latency of this reticular-induced early excitation of thalamocortical neurons is consistent with the quite slow conduction velocities of brainstem-thalamic axons (1). The cholinergic nature of the early depolarization is indicated by several lines of evidence: it was obtained by stimulating the PB brainstem cholinergic nucleus and it is still elicitable after depletion of monoamines in reserpine-treated preparations; and it is highly sensitive to very small doses of barbiturates (2 mg/kg), similarly to the barbiturate blockade of ACh effects (4). As to the very long-latency and long-lasting depolarization seen to Fig. 3, it may result from the release of peptides that are colocalized in brainstem cholinergic neurons or it may be due to still unknown transmitters used by reticular cells.

The direct brainstem-thalamic depolarizing effect is in keeping with the original formulation of the activating reticular system (10). Our new set of results indicates that the use of unanesthetized preparations is compulsory when investigating the directly excitatory effects of cholinergic brainstem reticular nuclei upon thalamocortical neurons. Probably the best condition for intracellular studies related to these aspects is the brainstem-transected preparation, either at a midpontine pretrigeminal level (cf. 9) or with a bulbo-spinal cut combined with lesions of sensory trigeminal nuclei. Such preparations have been successfully used both in the thalamus (see above) and in the cerebral cortex (11) to investigate intracellularly the arousing effects of brainstem reticular stimulation.

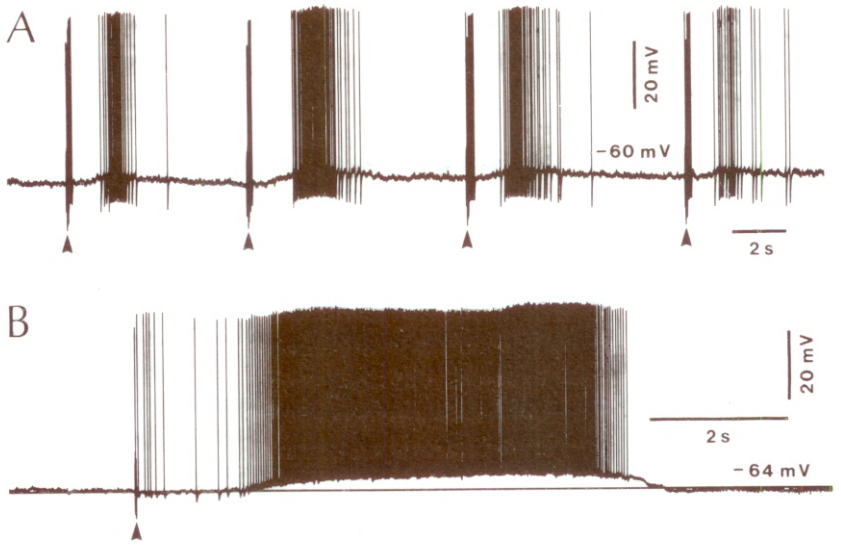

Fig. 3. — *Excitation of LG thalamocortical neurons by stimulating the brainstem reticular PB nucleus in the cat.*

Intracellular recordings in unanesthetized preparation with bulbo-spinal cut and deafferentation of trigemino-thalamic pathways; retina and visual cortex were also removed. A: 2 shocks to the PB nucleus (arrow heads) elicit a short-latency excitation followed by a prolonged (1.5 s-2.5 s) exicitation starting at a long (1-1.5 s) latency. B: expanded record showing in more detail the two components of the reticular-elicited exicitation. Modified fron Steriade and Deschênes (18).

B. The oscillatory mode, with a depressed transfer function, is the characteristic feature of the thalamus during EEG-synchronized sleep. Spindle oscillations are 7-14 Hz waves, grouped in sequences that recur periodically with a slow rhythm of 0.1-0.2 Hz (3, 17). The EEG spindles are stigmatic events of the transition between waking and sleep. It is now documented that spindle rhythms are generated in RE thalamic neurons that impose them upon target thalamocortical neurons. Recent data support this assumption.

First, the spike bursts of GABAergic RE neurons extend over a whole spindle sequence recorded focally by the same extracellular microelectrode and the intracellularly recorded spindles of RE cells occur on a slowly growing and decaying depolarization, whereas thalamocortical neurons simultaneously display long-lasting cyclic hyperpolarizations interrupted by brief rebounds (Fig. 4). Second, after thalamic transections or chemical lesions that deprive cortically-projecting thalamic nuclei from their RE afferents, spindles are abolished in the thalamic nuclei disconnected from the RE nucleus (19). The same absence of spindle oscillations was observed without any experimental manipulation in the only group of thalamic nuclei, AM-AV, that are naturally devoid of RE inputs; this absence of spindling is due to the network characteristics (lack of RE afferents) since AV-AM neurons possess the same intrinsic properties as other thalamic neurons (Fig. 5). Lastly, the RE nucleus disconnected by appropriate transections from its input sources

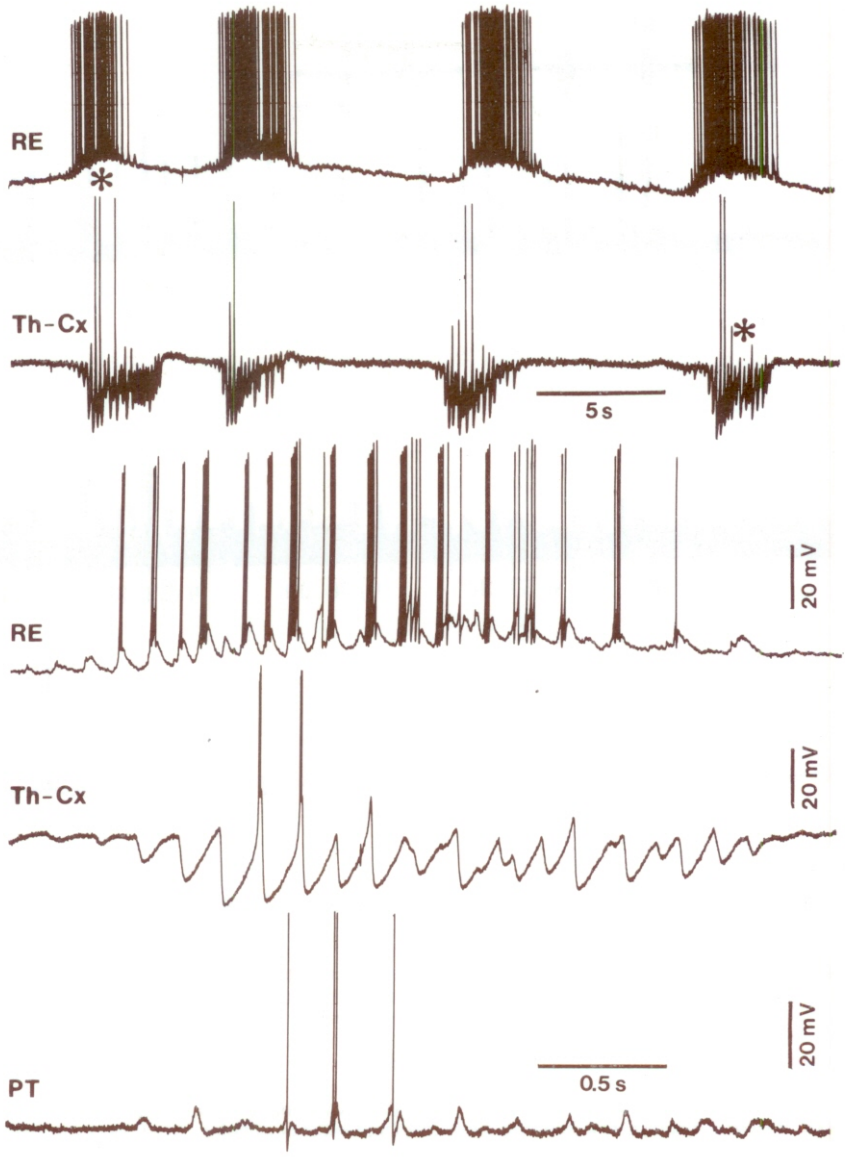

Fig. 4. — *Intracellular aspects of oscillatory activities in reticular thalamic (RE), thalamocortical (Th-Cx; from VL nucleus) and pyramidal tract (PT; from precruciate gyrus) neurons of cat under barbiturate anesthesia.*

The spindle sequences marked by asterisks in top traces of RE and Th-Cx neurons are depicted below at higher speed. Modified fron Steriade and Deschênes (18).

(thalamus and cerebral cortex) continues to oscillate within both (7-14 Hz and 0.1-0.2 Hz) frequencies of spindle rhythmicity (Fig. 6). All these date indicate that RE neurons are pacemakers of spindle oscillations.

The classical blockade of EEG spindling by brainstem reticular stimulation (10)

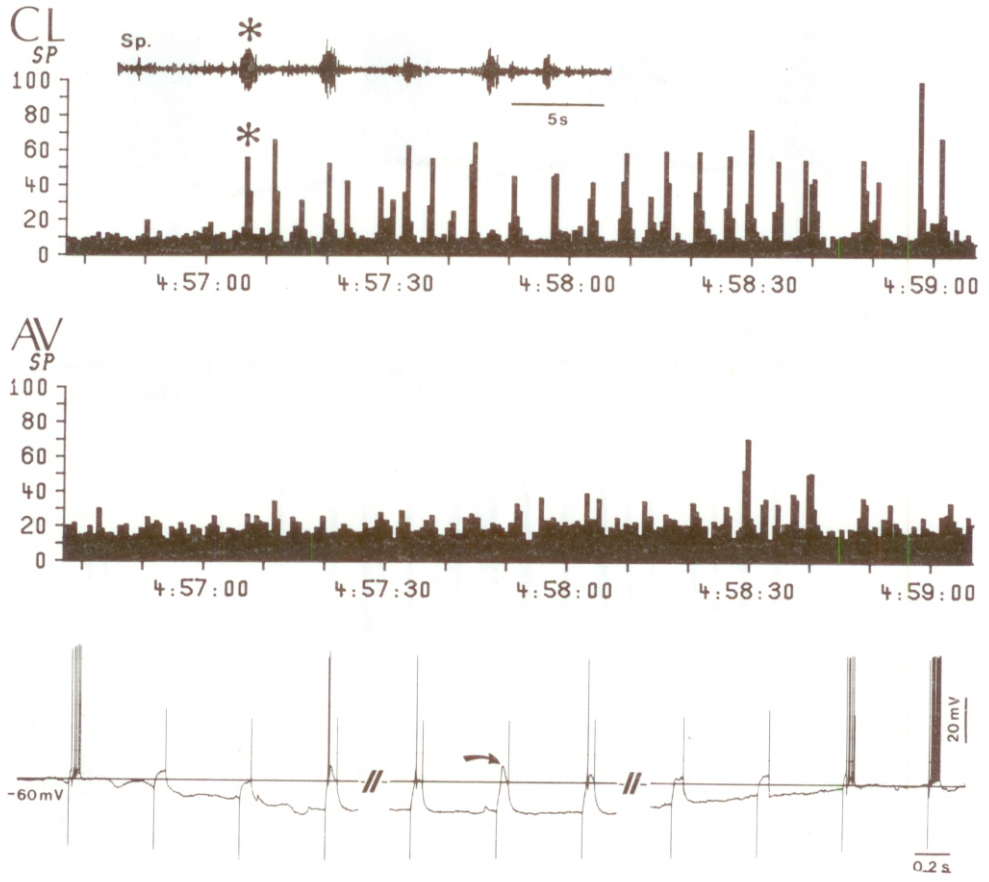

Fig. 5. — *Absence of spindle oscillations in cat's anterior thalamic nuclei, a group that is naturally devoid of inputs from the RE thalamic nucleus.*

A: preparation with intercollicular transection. Simultaneous recordings of focal waves in intralaminar CL and in AV thalamic nuclei. Abscissae indicate real time. Computer-generated graphs represent amplitudes of spindle (SP) waves, filtered at 7-14 Hz. Asterisk in CL trace indicates the first spindle sequence and corresponds to the asterisk-marked sequence in the inset depicting an ink-written recording at higher speed. B: preparation under barbiturate anesthesia. Effect of membrane potential on firing mode of an AM thalamic cell. Tonic firing induced by a depolarizing pulse at rest (—60 mV) developed into a low-threshold spike and spike bursts under steady hyperpolarization when the membrane potential reached —72 mV; recovery of tonic mode at right. Oblique arrow indicates a low-threshold spike in isolation. Modified from Paré *et al.* (13).

results from the blockade of spindle oscillations in thalamocortical neurons (Fig. 7 B). However, the origin of this effect should be searched at the very site of spindle genesis, the RE nucleus. Indeed, short pulse-trains applied to the midbrain reticular core in the region of the cholinergic PB nucleus prevent the occurrence of spindles and effectively block ongoing spindle sequences (Fig. 7 A). The hyperpolarization that is reponsible for the blockade of spindles in RE cells follows a direct depolarization of RE cells. While the transmitter responsible for the early excitation of RE neurons is not yet elucidated, the hyperpolarization is cholinergic

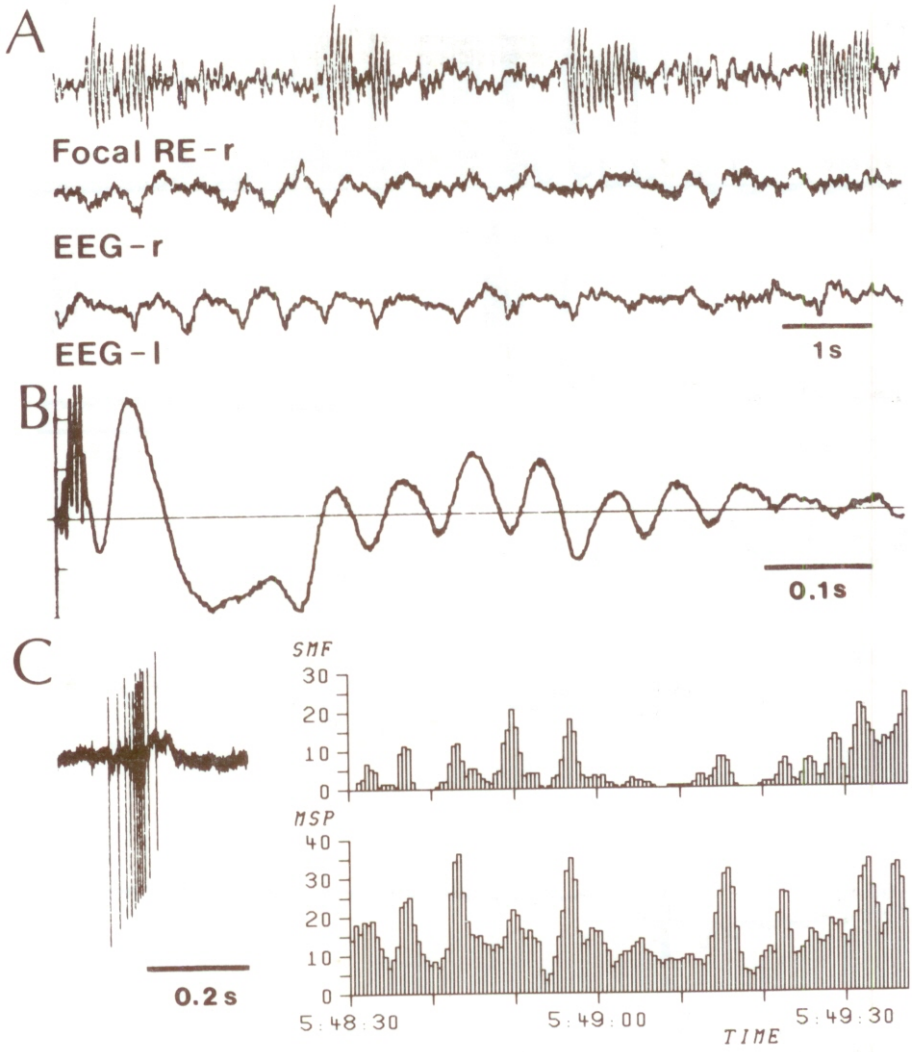

Fig. 6. — *Spindle oscillations in the deafferented RE thalamic nucleus of cat.*

Acutely prepared animals with rostral brainstem transections. The rostral pole of RE nucleus was isolated from its thalamic and cortical inputs by bilateral transections in the rostral thalamus and corona radiata (see histology of such preparations in ref. 18). A: spindle sequences in the RE isolated nucleus contrast with absence of spindles in right and left cortical EEG. B: evoked spindle oscillations in the deafferented RE nucleus by stimulating the white matter overlying the caudate nucleus (50 averaged traces). C: slow rhythm of spindle sequences and related burst oscillations of deafferented RE neurons. At left, a spike burst of a RE cell. At right, computer-made graph showing the sequential mean frequency (SMF) of this neuron and the normalized amplitudes of focal waves filtered for spindles, recorded simultaneously through the same microelectrode (MSP). Abscissa indicates real time. Modified from Steriade *et al.* (20).

in nature since it is blocked by scopolamine. The hyperpolarization induced by PB stimulation in Fig. 7A was associated with a 40%-50% increase in membrane conductance, probably to K ions (8).

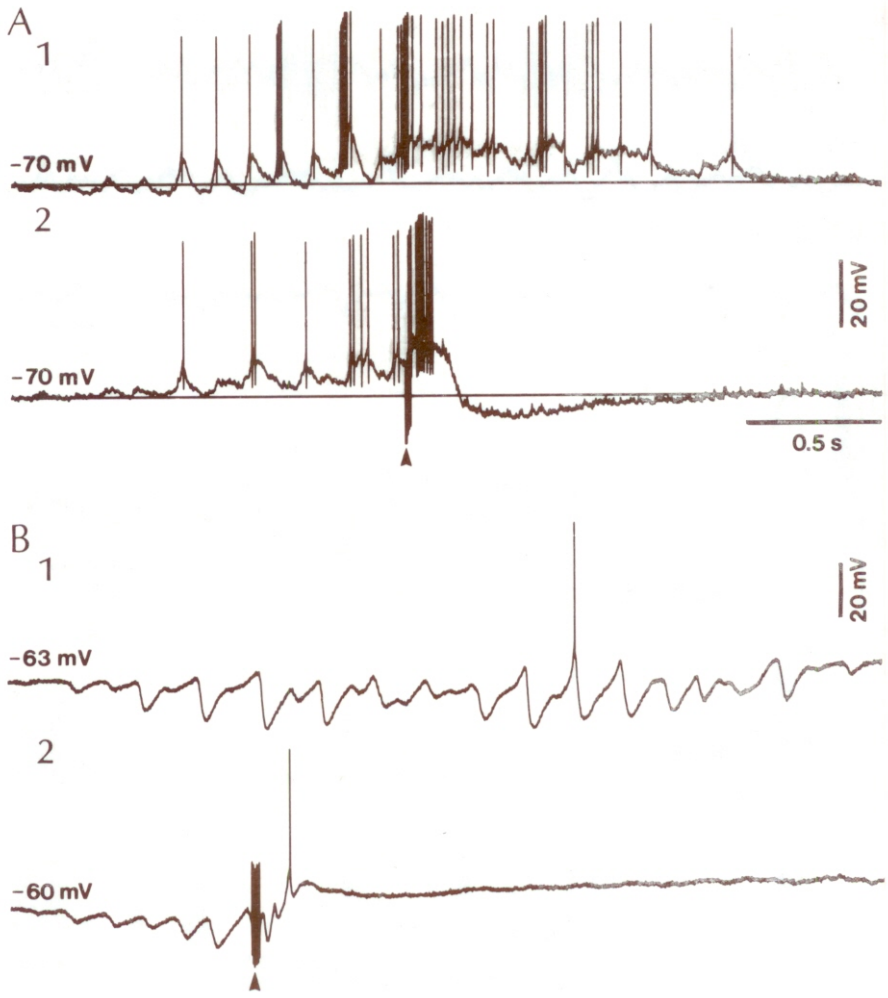

Fig. 7. — *Intracellular aspects of the spindle blockage in a neuron of the perigeniculate part of the RE nuclear complex and in a thalamocortical LG cell of the cat.*

A: a perigeniculate cell. B: thalamocortical LG cell. In both A and B, spontaneous spindle sequence (1) and its blockage by a brief pulse-train to the PB brainstem reticular nucleus (arrow heads in 2). Modified from Steriade and Deschênes (18).

I must emphasize that this hyperpolarizing effect of midbrain reticular stimulation is exerted upon RE neurons but not on local-circuit inhibitory cells intrinsic to each thalamic nucleus. Indeed, a conditioning pulse-train to the midbrain reticular core selectively blocks the late part of the long-lasting (>100 ms) hyperpolarization in thalamocortical neurons (due to a K current), but leaves intact the early, short-lasting (<40 ms), Cl-dependent IPSP (see Fig. 28 C in ref. 17 and Fig. 12 C in ref. 18). Indirect evidence that the IPSPs generated by local interneurons are relatively short in duration, as compared to those generated by RE cells,

comes from intracellular recordings of thalamocortical cells disconnected from the other GABAergic source, the RE nucleus (19).

Many questions remain to be solved in the future. One of them relates to the functional significance of spindles: are the rhythmic rebound bursts just epiphenomena that are de-inactivated by the preceding long hyperpolarizations of thalamocortical neurons or do they have a functional role in preventing the metabolic inertia that would result if the thalamic neurons would be hyperpolarized for the tens of minutes or even hours that they spend in EEG-synchronized sleep? It is also possible that the spindle-related spike bursts in thalamocortical axons create conditions for increased synaptic efficacy in cortical circuits and favor the consolidation of information storage during the waking state. This can be tested experimentally. Another fascinating field of research in the future is the formal identification of local-circuit inhibitory cells and the investigation of their behavior during changes in the states of vigilance. Presently we infer their enhanced activity upon natural arousal or stimulation of brainstem reticular cholinergic nuclei by determining that thalamocortical neurons exhibit an increased effectiveness of inhibitory processes involved in discrimination during waking (see *b* in the introduction). As yet, there is no information about a completely (morphologically, immunohistochemically and electrophysiologically) identified short-axoned GABAergic cells in the thalamus and cerebral cortex *in vivo*. We must now rush into this problem with a modern armamentarium to record directly such elements and to understand their role in the center-surround antagonism and other feature detection properties of neurons during the waking state.

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REFERENCES

1. Ahlsén, G. Brain stem neurones with differential projection to functional subregions of the dorsal lateral geniculate complex in the cat. *Neuroscience*, **12**: 817-838, 1984.
2. Deschênes, M., Hu, B. and Steriade, M. The effect of mesencephalic reticular stimulation on relay neurons of the dorsal lateral geniculate nucleus. *Soc. Neurosci. Abstr.*, **12**: 854, 1986.
3. Deschênes, M., Paradis, M., Roy, J. P. and Steriade, M. Electrophysiology of neurons of lateral thalamic nuclei in cat: resting properties and burst discharges. *J. Neurophysiol.*, **51**: 1196-1219, 1984.
4. Eysel, V. T., Pape, H. C. and Van Schayck, R. Exicitatory and differential disinhibitory actions of acetylcholine in the lateral geniculate nucleus of the cat. *J. Physiol., Lond.*, **370**: 233-254, 1986.
5. Jones. E. G. *The Thalamus*. New York, Plenum, 935 pp., 1985.
6. Krnjević, K. Chemical nature of synaptic transmission in vertebrates. *Physiol. Rev.*, **54**: 318-540, 1974.

7. LIVINGSTONE, M. S. and HUBEL, D. H. Effects of sleep and arousal on the processing of visual information in the cat. *Nature, Lond.*, **291**: 554-551, 1981.
8. MCCORMICK, D. A. and PRINCE, D. A. ACh induces burst firing in thalamic reticular neurones by activating a K conductance. *Nature Lond.*, **319**: 402-405, 1986.
9. MORUZZI, G. The sleep-waking cycle. *Ergebn. Physiol.*, **64**: 1-165, 1972.
10. MORUZZI G. and MAGOUN, H. W. Brain stem reticular formation and activation of the EEG. *Electroenceph. clin. Neurophysiol.*, **1**: 455-473, 1949.
11. OSHIMA, T. Intracortical organization of arousal as a model of dynamic neuronal processes that may involve a set for movements. Pp. 287-300. in DESMEDT, J. E. (Ed.), *Motor Control Mechanisms in Health and Disease*, New York, Raven Press. 1983.
12. PARÉ, D., SMITH, Y., PARENT, A. and STERIADE, M. Projections of upper brainstem cholinergic and non-cholinergic neurons of cat to intralaminar and reticular thalamic nuclei. *Neuroscience*, **25:** 69-86, 1988.
13. PARÉ, D., STERIADE, M., DESCHÊNES, M. and OAKSON, G. Physiological properties of anterior thalamic nuclei, a group devoid of inputs from the reticular thalamic nucleus. *J. Neurophysiol.*, **57:** 1669-1685, 1987.
14. SILLITO, A. M., KEMP, J. A. and BERARDI, N. The cholinergic influence on the function of the cat dorsal lateral geniculate nucleus (dLGN). *Brain Res.*, **280**: 299-307, 1983.
15. SINGER, W. Control of thalamic transmission by corticofugal and ascending reticular pathways in the visual system. *Physiol. Rev.*, **57**: 386-420, 1977.
16. STERIADE, M. and DESCHÊNES, M. Inhibitory processes and interneuronal apparatus in motor cortex during sleep and waking. II Recurrent and afferent inhibition of pyramidal tract neurons. *J. Neurophysiol.*, **37**: 1093-1113, 1974.
17. STERIADE, M. and DESCHÊNES, M. The thalamus as a neuronal oscillator. *Brain Res. Rev.*, **8**: 1-63, 1984.
18. STERIADE, M. and DESCHÊNES, M. Intrathalamic and brainstem-thalamic networks involved in resting and alert states. Pp. 51-76. In: BENTIVOGLIO, M. and SPREAFICO, R. (Eds.) *Cellular Thalamic Mechanisms*. Amsterdam, Elsevier, 1988.
19. STERIADE, M., DESCHÊNES, M., DOMICH, L. and MULLE, C. Abolition of spindle oscillations in thalamic neurons disconnected from nucleus reticularis thalami. *J. Neurophysiol.*, **54**: 1473-1497, 1985.
20. STERIADE, M., DOMICH, L., OAKSON, G. and DESCHÊNES. M. The deafferented reticular thalamic nucleus generates spindle rhythmicity. *J. Neurophysiol.*, **57**: 260-273, 1987.
21. STERIADE, M. and LLINÁS, R. R. The functional states of the thalamus and the associated neuronal interplay. *Physiol. Rev.*, **68**: in press, 1988.
22. STERIADE, M., PARÉ, D., PARENT, A. and SMITH, Y. Projections of cholinergic and non-cholinergic neurons of the brainstem core to relay and associational thalamic nuclei in cat and monkey. *Neuroscience*, **25:** 47-67, 1988.
23. STERIADE, M., PARENT, A., PARÉ, D. and SMITH, Y. Cholinergic and non-cholinergic neurons of cat basal forebrain project to reticular and mediodorsal thalamic nuclei. *Brain Res.*, **408**: 372-376, 1987.
24. VINCENT, S. R., SATOH, K., ARMSTRONG, D. M. PANULA, P., VALE, W. and FIBIGER, H. C. Neuropeptides and NADPH-diaphorase activity in the ascending cholinergic reticular system of the rat. *Neuroscience*, **17**: 167-182, 1986.