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Theta-like Activity in the Limbic Cortex In Vitro

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KONOPACKI, J. *Theta-like activity in the limbic cortex in vitro.* NEUROSCI BIOBEHAV REV **22**(2), 311–323, 1998. The generation of EEG theta rhythm in the mammalian limbic cortex is a prime example of rhythmic activity that involves central mechanisms of oscillations and synchrony. This EEG pattern has been extensively studied since 1938, when Jung and Kornmuller (28) (Eine methodik der ableitung lokalisierter potential schwankingen aus subcorticalen hirnyebieten, Arch. Psychiat. Neruenkr. 109 (1938) 1–30) demonstrated the first theta recordings in the hippocampal formation of rabbits. In 1986 we demonstrated for the first time that bath perfusion of hippocampal slices with the cholinergic agonist, carbachol, resulted in theta-like oscillations. Since this initial demonstration of in vitro theta-like activity, we have carried out a number of experiments in an attempt to answer the following question: what are the similarities between cholinergic-induced in vitro theta-like activity and theta rhythm which naturally occurs in the in vivo preparation. Thus far, our studies have provided strong evidence that theta-like activity recorded in vitro shares many of the physiological and pharmacological properties of theta rhythm observed in vivo. © 1998 Elsevier Science Ltd All rights reserved.

Theta rhythm Limbic cortex In vitro Cholinergic receptors GABAergic receptors

INTRODUCTION

THETA RHYTHM (rhythmical slow activity, RSA) is the largest (1–2 mV), most prominent, and best synchronized (3–12 Hz) electroencephalogram (EEG) generated by the mammalian brain. Commonly, theta activity has been associated with the hippocampal formation (HPC) since it is one of the most conspicuous activities recorded in this structure (10,12,47,59). However, a number of in vivo reports have revealed that the HPC is not the only limbic cortical region involved in the production of theta activity. Theta oscillations have also been recorded from the entorhinal cortex (EC) and the cingulate cortex (CC) in freely behaving or anesthetized animals (2,13,18,44,53).

It is my intent in this review to demonstrate that the limbic cortex mechanisms underlying the production of oscillation and synchrony, can also be successfully investigated in complete isolation from the extrinsic input (i.e. in the in vitro maintained brain slice preparation obtained from the HPC and EC of rats and cats). Interestingly, more than 15 years ago Lynch and Schubert (50) pointed out that one of the differences in the electrophysiology of the in vitro and in vivo maintained limbic cortex ''is that the synchronous slow waves characteristic of the hippocampus are not to be found in vitro''. The results of the experiments presented in this review demonstrate that rhythmic slow waves (theta-like activity) are also present under certain conditions in vitro. In addition, they provide evidence that in many aspects the in vitro recorded theta-like oscillations are similar to the physiological and pharmacological properties of in vivo recorded theta rhythm.

The idea of recording the HPC theta rhythm in vitro dates back to the early 1970s, when Bland made the first in vitro observations of theta-like oscillations in Per Andersen's laboratory in Oslo, Norway. Fifteen years later, we began the systematic study of in vitro carbachol-induced theta-like activity with the use of the HPC and EC slices obtained from rats and cats. In the beginning, I collaborated with Bland and MacIver in Roth's laboratory (The University of Calgary). From 1989 on, I have been studying the in vitro recorded theta-like activity with my present team in the Department of Neurobiology at The University of Lodz.

Ten years ago, in 1986, we documented for the first time that the perfusion of hippocampal slices with carbachol (CCH) resulted in the production of theta-like slow waves (Figs. 1 and 2, (51)). We also observed the in vitro theta-like activity in response to bath perfusion of acetylcholine and eserine (Fig. 1, (30,31)). The cholinergic induced EEG activity was found to be reversible after 10–40 min of washout with artificial cerebrospinal fluid (ACSF). It ranged in frequency from 3 to 12 Hz with amplitudes of 0.2–2.0 mV (Fig. 2), and typically appeared in trains, lasting 1–10 s.

After this initial demonstration of theta-like oscillations in rat hippocampal slices, the basic question arose regarding the similarities between the cholinergic-induced in vitro theta-like activity and the theta rhythm occurring in the in vivo preparations. Further experiments were designed specifically to answer this question.

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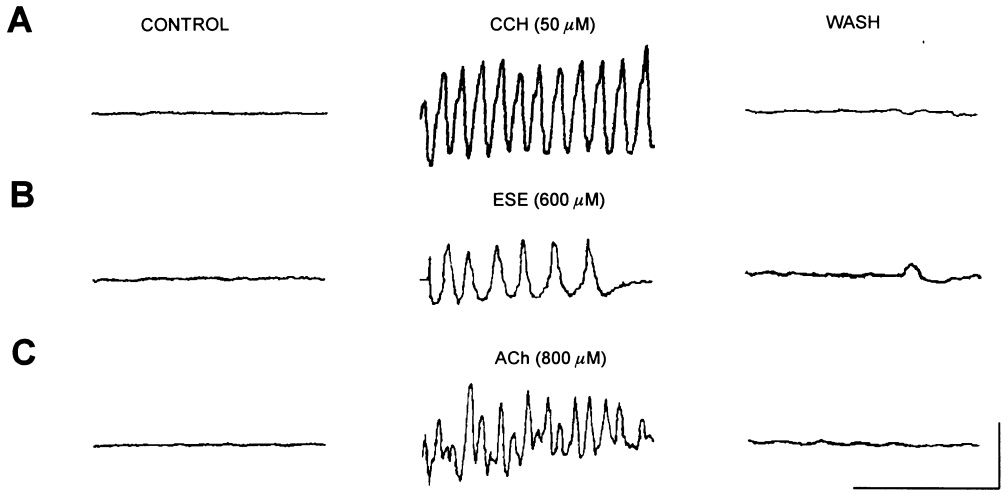

FIG. 1. Comparison of slow wave activity recorded from the molecular layer of the dentate gyrus after perfusion: carbachol (CCH, 50 μM), eserine (ESE, 600 μM) and acetylcholine (ACh, 800 μM). In vitro theta-like activity was usually reversed within a 60-min wash with artificial cerebro-spinal fluid (WASH). Calibration: 1 s and 200 μV.

INTRAHIPPOCAMPAL GENERATORS AND PHARMACOLOGICAL PROFILE OF THE IN VITRO RECORDED THETA-LIKE ACTIVITY

In the first series of experiments we demonstrated that, as is the case for the cholinergically-mediated type 2 theta in the rat, CCH-induced in vitro theta-like oscillations can also be antagonized by the muscarinic blocker, atropine sulphate, but not by the nicotinic antagonist, *d*-tubocurarine (Fig. 3, (30)). We also obtained similar results in experiments performed with the use of the cat HPC slice preparation (35).

The next experiments addressed the problem of generators of theta, localized in the HPC. The earlier in vivo studies suggested that neurons in the CA1 area of the HPC generated the currents underlying the theta field potential (25). Subsequent detailed topographic investigations performed in vivo reported two theta amplitude maxima, one in the stratum oriens of the CA1 area and another in the stratum moleculare of the dentate gyrus (DG) (8,9,61). Our detailed mapping study and evaluation of amplitude profiles of the in vitro recorded theta-like activity (32) supported previous in vivo studies. These results indicated that synaptic potentials both in the CA1 and DG areas were capable of independent theta generation, as proposed by the two generator hypothesis (8,10). In addition, using the model of the transected slice preparation (Fig. 4), in which the CA1 and DG regions were completely anatomically separated, we demonstrated that both the CA1

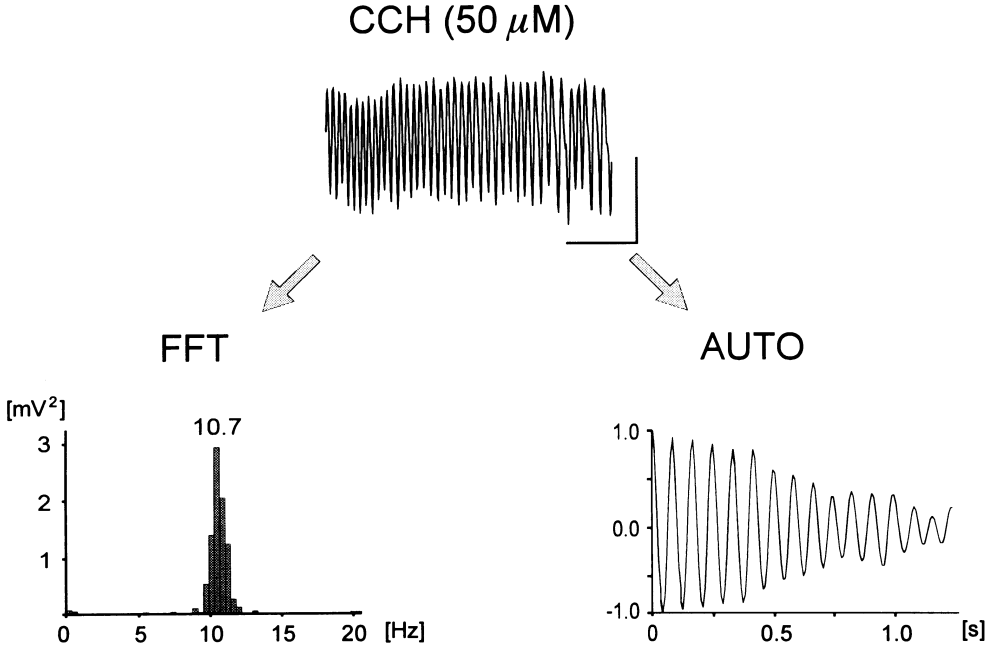

FIG. 2. Analogue example, power frequency (FFT) and autocorrelation (AUTO) analysis of theta-like activity recorded in the region of CA3 pyramidal cells in the presence of carbachol (50 μM).

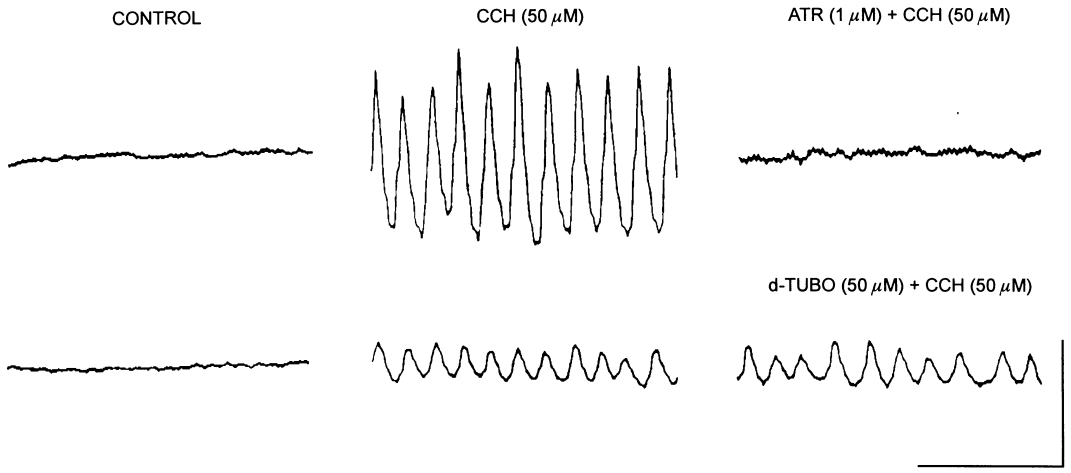

FIG. 3. Theta-like activity recorded from two separate experiments on different slices. Carbachol (CCH, 50 μM)-induced theta-like activity was antagonized by atropine sulphate (ATR, 1 μM), but resistant to *d*-tubocurarine (D-TUBO, 50 μM). Calibration: 1 s and 200 μV.

and DG regions were capable of independent generation of theta-like oscillations in the presence of continuous cholinergic stimulation (perfusion with CCH, Fig. 5A–C, (29)). This finding was the first in vitro observation supporting the two generator hypothesis. Further physiological findings concerning the in vitro CA1 and DG theta-like activity were consistent with numerous earlier in vivo reports suggesting that the generator producing larger HPC type 2 theta was localized in the DG region (10,58,61). We also demonstrated in vitro that when the CA1 and DG generators were anatomically separated, they could independently generate theta-like oscillations of different amplitude, as shown in Fig. 5B.

The results of experiments conducted with the use of transected slices also revealed that integrity of the laminar, trisynaptic hippocampal circuit was not required for the generation of theta-like oscillations. Furthermore, pharmacological profiles for theta-like activity recorded from the isolated CA1 and DG area supported earlier in vivo findings that muscarinic receptors mediate this EEG response (10,12,40): both CA1 and DG theta-like oscillations recorded in vitro were antagonized by a muscarinic blocker, atropine sulphate, and were found to be completely resistant to the nicotinic antagonist, *d*-tubocurarine (Fig. 5C).

The transected slice technique was also found to be very useful in determining whether other regions of the HPC were capable of independent theta generation. Historically, Petsche and Stumpf (55) were the first to record theta in the CA3 region of the hippocampus proper in vivo. This observation was supported later by Buzsáki et al. (15) and Feder and Ranck (19). Using our transected slices technique, we demonstrated later that CCH-induced theta-like activity could be recorded from the isolated population of CA3c pyramidal cells (32).

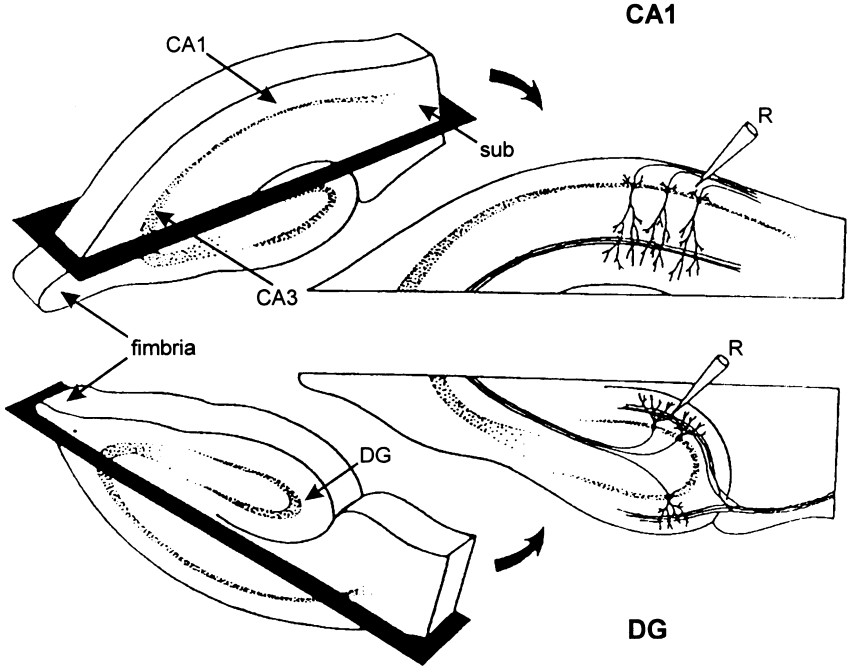

FIG. 4. The preparation of CA1 and DG-trans-slices of the rat hippocampal formation. Recording electrodes (R) were placed close to the cell body layers of CA1 or DG areas to record theta-like field potentials.

Summing up, our studies utilizing transected slices provide strong evidence that there are in fact three anatomically separated intrahippocampal generators of cholinergic-induced theta-like oscillations, one localized in the basal part of the CA1 neurons (stratum oriens), the other in the stratum moleculare of the dorsal blade of the dentate gyrus, and a third in the CA3c region of the hilus. Experiments performed on the transected slice preparation revealed that these generators could operate independently of one another.

POSTNATAL DEVELOPMENT OF THETA-LIKE ACTIVITY RECORDED IN VITRO

In the next stage of our in vitro study we analysed the postnatal development of CCH-induced theta-like activity and compared it with the pattern of development of spontaneous theta, described earlier in neonatal rats. Leblanc and Bland (42) demonstrated that type 2 theta appeared in rats around 10 days of age during voluntary movements and

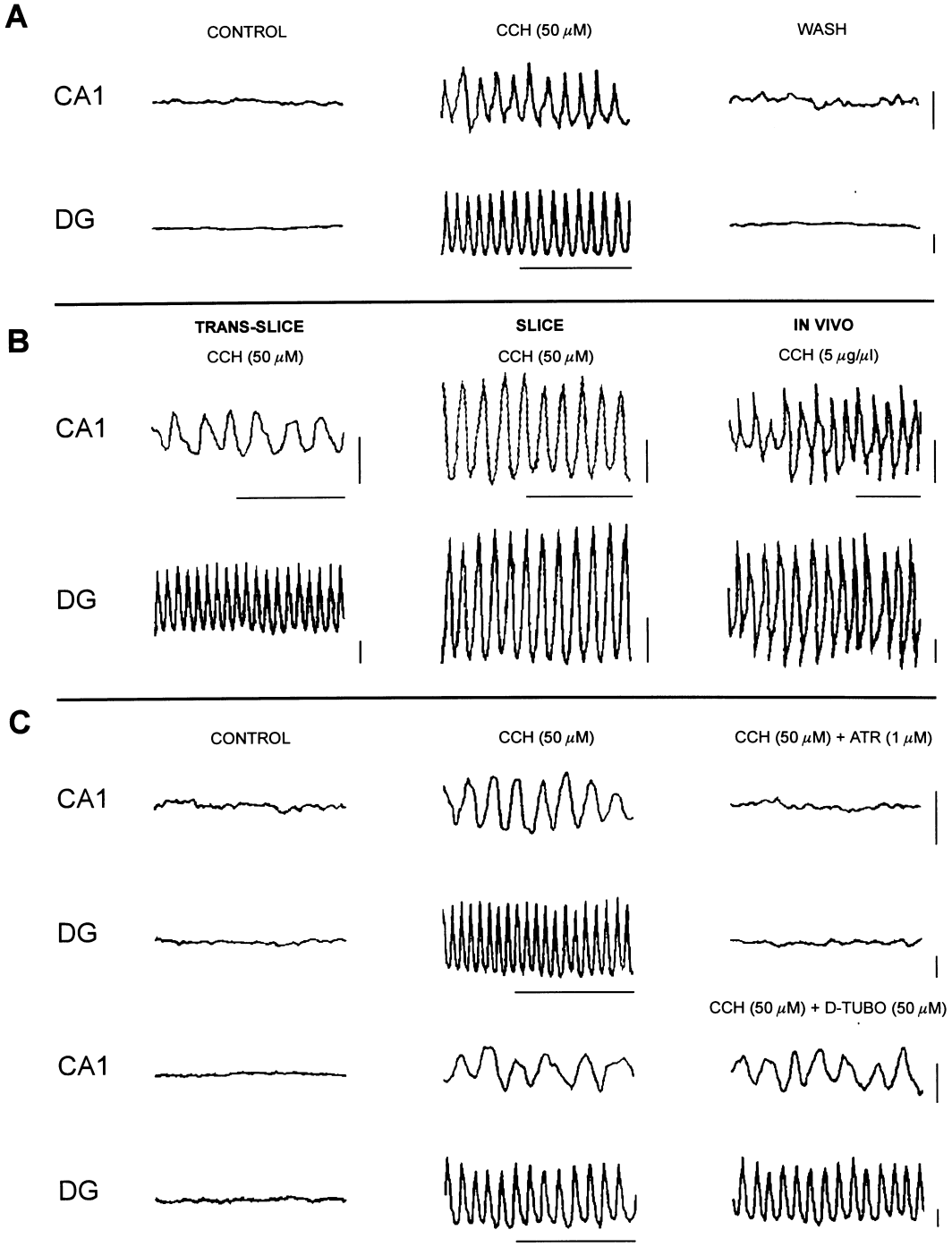

FIG. 5. Carbachol-induced theta-like activity recorded in the hippocampal trans-slice preparations. (A) Carbachol (CCH, 50 μM)-induced theta-like activity both in the CA1 and DG trans-slices. The CCH effect was reversed within 15–60 min. of wash with artificial cerebro-spinal fluid (WASH). (B) Comparison of CCH-induced theta-like activity recorded from the CA1 and DG areas in the hippocampal trans-slices, intact slices and slices from anesthetized rats (in vivo). (C) CCH-induced theta-like activity from both the CA1 and DG area was antagonized by 1 μM of atropine (ATR), but unaffected by 50 μM of *d*-tubocurarine (D-TUBO). Calibration for A, B and C: 1 s and 200 μV.

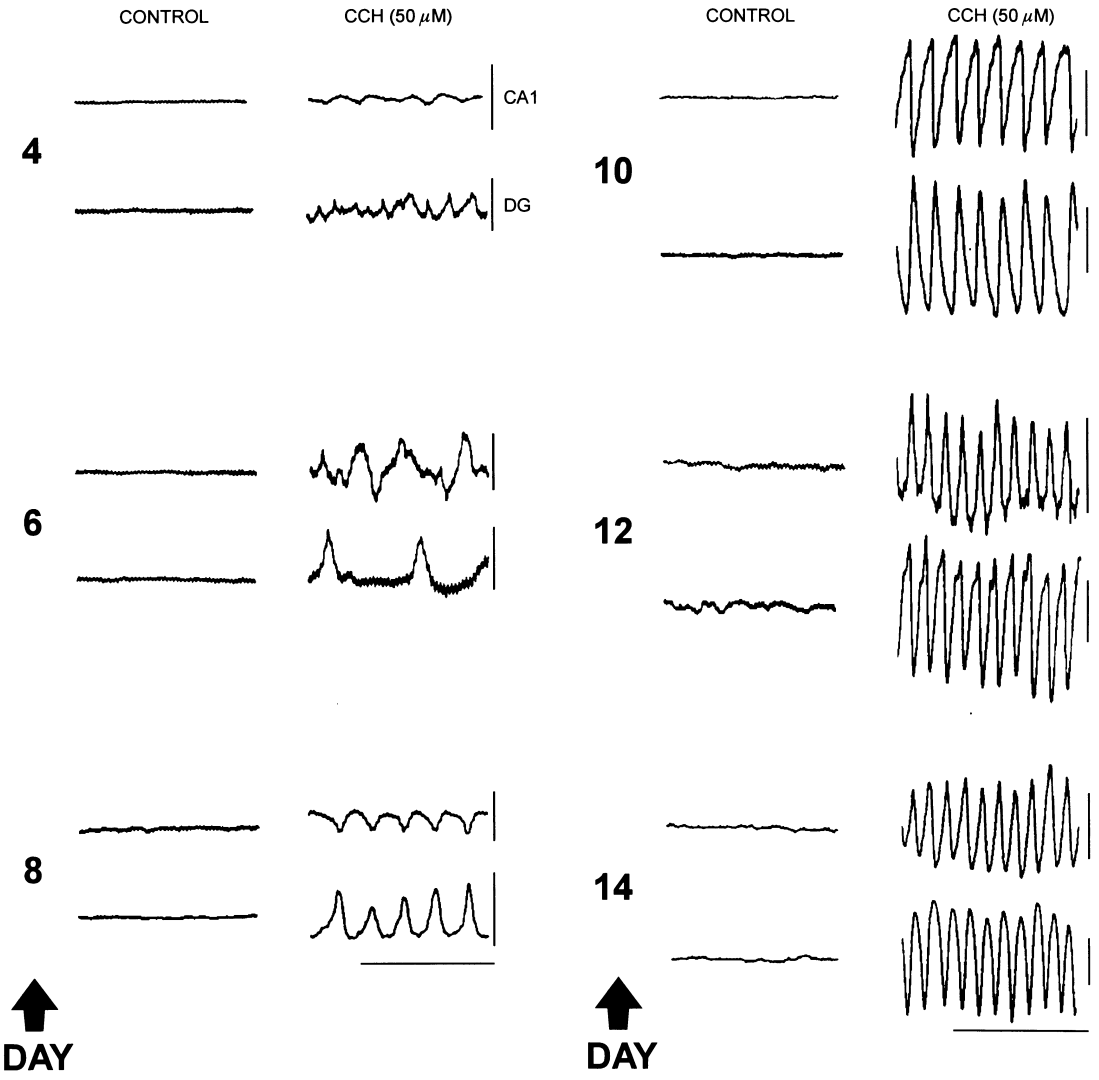

FIG. 6. Development of carbachol (CCH, 50 μM)-induced in vitro theta-like activity in the CA1 and DG regions of the hippocampal slices. At 4 and 6 days of age, perfusion of slices with CCH-induced irregular short-latency activity. Regular theta-like trains were induced in 8-day old slices. From 8 days onward an increase in frequency and amplitude was observed. Calibration: 1 s and 200 μV.

during rapid eye movement (REM) sleep and then increased in amplitude and frequency to the value typically seen in adult animals. Our in vitro experiments conducted on slice preparations obtained from neonatal (4, 6, 8, 10, 12, 14 days of age) and mature rats supported this observation (Fig. 6, (33)). Despite the difference in the time course of neurogenesis between CA1 and DG regions (5), CCH-induced theta-like activity was observed in these two areas at about the same time (8–10 days after birth). At around 14 days of age, it reached the frequency and amplitude typical for rhythmical slow activity observed during CCH perfusion in slices delivered from adult rats (33).

CELLULAR BASIS OF THETA-LIKE ACTIVITY RECORDED IN VITRO

The advantages of the in vitro brain slice preparation for intracellular recordings and pharmacological manipulations are well documented (50). In the next stage of our studies we investigated cellular correlates of CCH-induced theta-like activity. Intracellular recordings were made in the CA1, CA3, and DG regions prior to, during, and after the application of CCH. More than 50% of cells tested were related to the extracellular theta-like activity. They exhibited clear membrane potential oscillations (MPOs, 5–28 mV) and multiple spike discharges occurring close to the peak positivity (Fig. 7). MPOs were always phase locked with extracellularly recorded theta-like field potentials and disappeared when extracellular theta-like oscillations were no longer observed (11). Similar in vitro observations were also noted by other authors (6,23,45,52). Neural mechanisms responsible for in vitro observed MPOs still remain an open question. An argument that MPOs arise from intrinsic membrane properties is based on the observation that these oscillations persist during the blockade of synaptic transmission by low calcium, low sodium and tetrodotoxin (TTX) (45). On the other hand, MacVicar and Tse (52) demonstrated that the application of TTX or inorganic calcium channel blockers abolished CCH-induced MPOs in the CA3 region of HPC slices. Future research must be focused at determining the contributions of intrinsic membrane properties and/or synaptic inputs in generation of

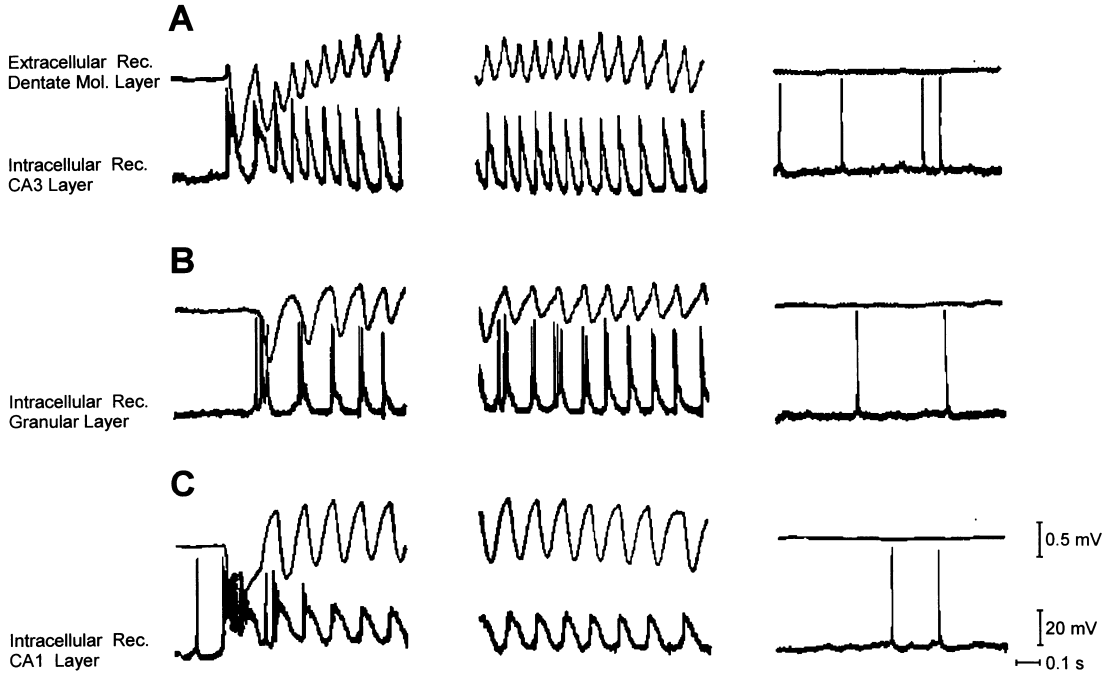

FIG. 7. Membrane potential oscillations (MPOs) and accompanying spike discharges in cells related with extracellular theta-like activity. (A) The three panels were continuous recordings, from left to right. Note that the intracellular oscillations were large ($>$ 25 mV) enough that the successive spike discharges in each burst were attenuated. (B) An example of the dentate layer cell recording with smaller membrane potential oscillations, and less of a reduction in the number and height of successive spike discharges. (C) An example of the CA1 layer cell recordings with large amplitude membrane potential oscillations (28 mV) and inactivation of spike discharges.

MPOs (see Ref. (12), for a proposed model). It should be emphasized that MPOs (intracellular theta rhythm) and rhythmic spike discharges are also observed in vivo in phasic ''theta-on'' and ''theta-off'' cells during extracellularly recorded theta (4,12,20,22,34,43,54).

The above findings clearly demonstrated that CCH-induced in vitro theta-like activity has a strong cellular basis which closely resembles neuronal mechanisms responsible for the appearance of the in vivo theta rhythm. In addition, the model of the in vitro recorded theta-like activity is particularly valuable for studying cellular processes underlying type 2 theta, offering all the advantages concomitant with the slice preparation.

GABAERGIC/CHOLINERGIC INTERACTION IN THE PRODUCTION OF THE IN VITRO THETA-LIKE ACTIVITY

There is accumulating evidence for a GABAergic involvement in the neural mechanisms responsible for the generation of the hippocampal formation theta rhythm. It has been histochemically demonstrated that approximately 30% of the fibres forming the septo-hippocampal projection are GABAergic (1,3,46). In addition, the HPC has been reported to contain a significant amount of glutamic acid decarboxylase (GAD) immunoreactive cells (i.e. the cells which possess GABA synthesizing enzyme, (56)). Recently, Cobb et al. (16) have demonstrated that specific activation of GABAergic interneurons is capable of modulating the frequency of discharges of theta-related cells. It has also been recently demonstrated in vivo that intrahippocampal and intraseptal microinjections of muscimol, a GABA-A-ergic agonist, reversibly abolished theta field potentials and the hippocampal cell discharges (12,57). This muscimol effect was antagonized by bicuculline, a GABA-A antagonist (57). It was also demonstrated that only combined intrahippocampal injections of carbachol and bicuculline or picrotoxin (a GABA-A antagonist) were capable of producing trains of theta rhythm during the procaine suppression of the medial septum in urethanized rats (17,27). The authors suggested that the HPC type 2 theta resulted from a dynamic interaction between the cholinergic and GABAergic systems (57). This was precisely what we observed in vitro (Fig. 8, (38)): CCH at low concentrations (25 μM) never induced theta-like oscillations. The overall level of activation of the hippocampal neuronal network was probably insufficient for theta-like activity to appear. When the same concentration of CCH was perfused simultaneously with bicuculline (25 μM), well-synchronized theta-like oscillations were observed. By blocking GABA-A receptors, bicuculline reduced hippocampal inhibition, and this diminution of GABAergic inhibition together with the subthreshold excitation of the hippocampal cholinergic network, produced the level of activity required for generation of theta-like oscillations. Further disinhibition of the hippocampal neuronal network by 100 μM bicuculline resulted in a pronounced increase in the amplitude of in vitro recorded theta-like activity (Fig. 8D).

In another set of experiments we provided additional evidence supporting a GABAergic/cholinergic interaction in mechanisms responsible for production of theta-like activity (38). Muscimol, which diminishes overall hippocampal excitation by increasing the level of GABAergic inhibition, resulted in the abolition of carbachol/bicuculline-induced theta-like activity (Fig. 9). A similar effect was also produced by atropine sulphate. By blocking hippocampal

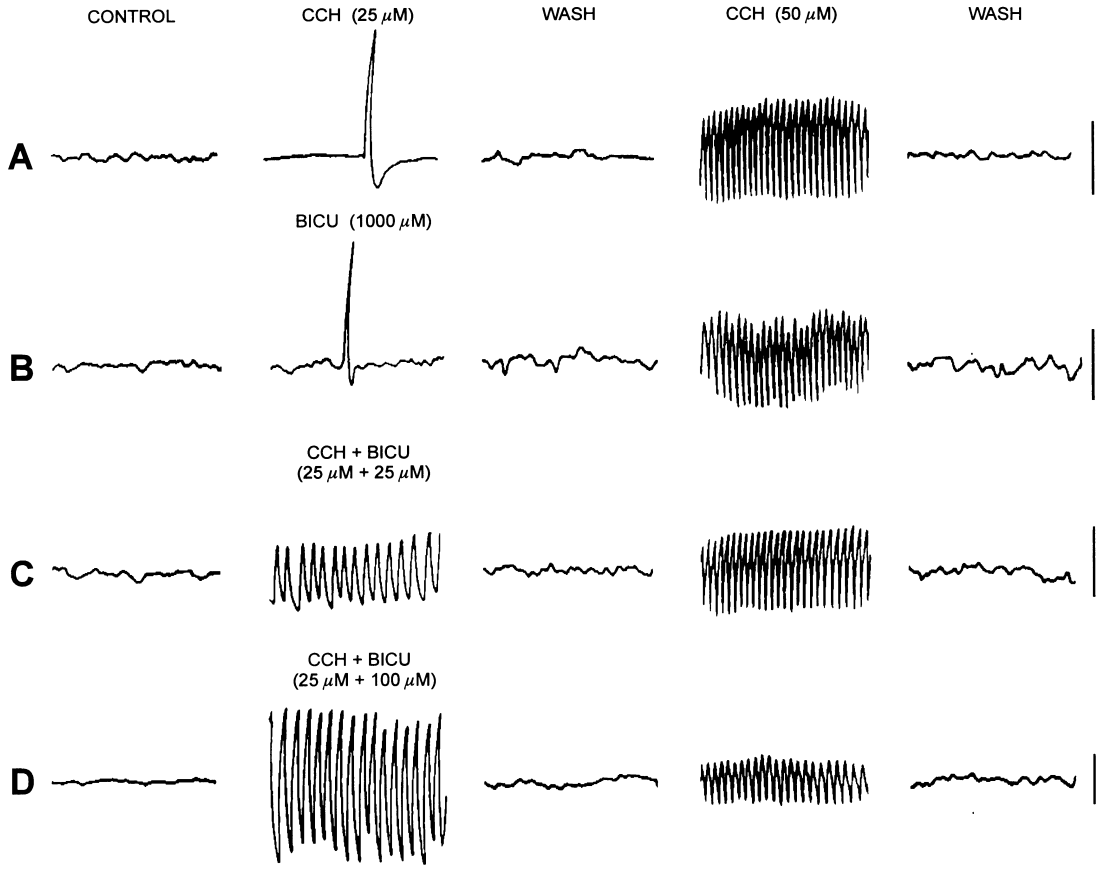

FIG. 8. Cholinergic/GABAergic interaction in the generation of theta-like activity in hippocampal slices. (A,B) These traces show a lack of rhythmical oscillations after the perfusion of a low concentration (25 μM) of carbachol (CCH) and high concentration (1000 μM) of bicuculline (BICU). Note that the slices tested responded with theta-like slow waves to 50–100 μM of CCH (CCH 50 μM). (C) When 25 μM of CCH was perfused in the presence of 25 μM BICU, theta-like oscillations could be observed. (D) These traces show an increase in amplitude of CCH + BICU-induced theta-like activity (vs. theta-like oscillations induced by 25 μM CCH + 25 μM BICU) in the presence of 100 μM of BICU. The induced field potentials were usually reversal after 20–60 min of wash with cerebro-spinal fluid (WASH). Calibration for A, B, C and D: 1 s and 500 μV.

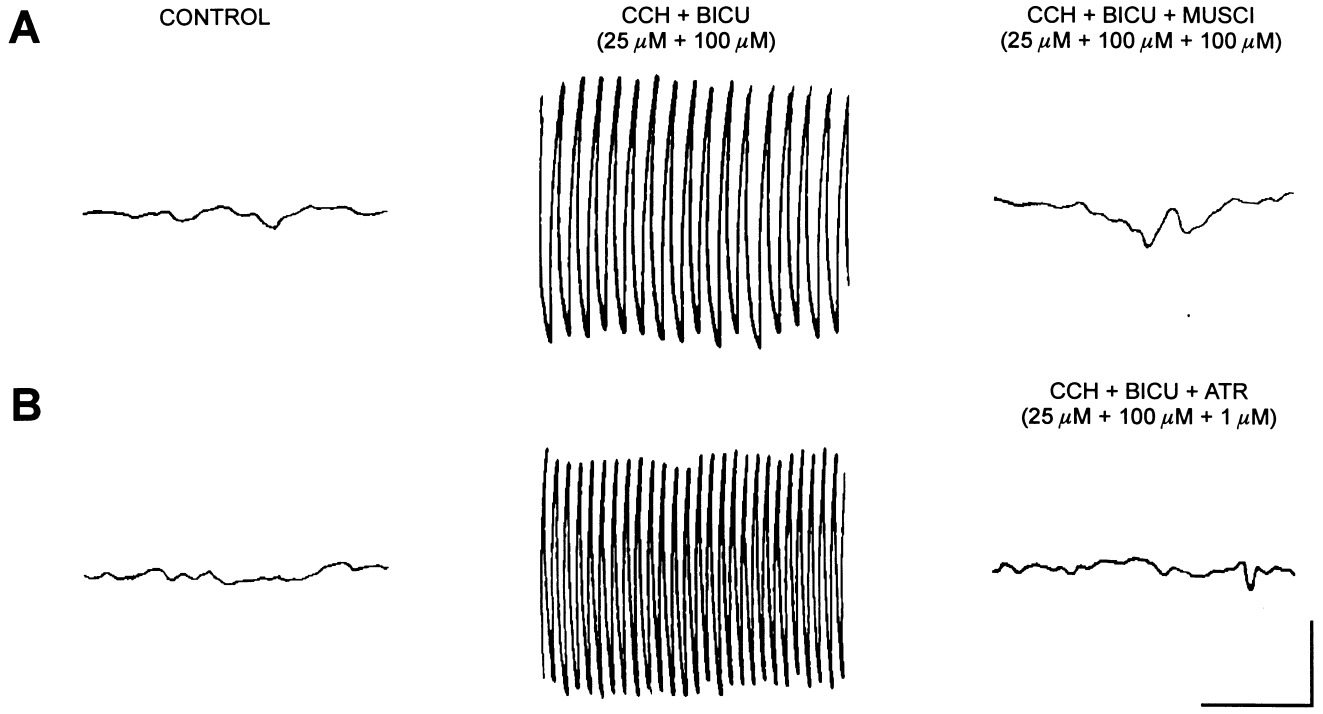

FIG. 9. The effect of muscimol (MUSCI) and atropine sulphate (ATR) on carbachol/bicuculline (CCH, 25 μM + BICU, 100 μM)-induced theta-like activity. Both MUSCI (100 μM) and ATR (1 μM) antagonized the induced theta-like activity. Calibration: 1 s and 500 μV.

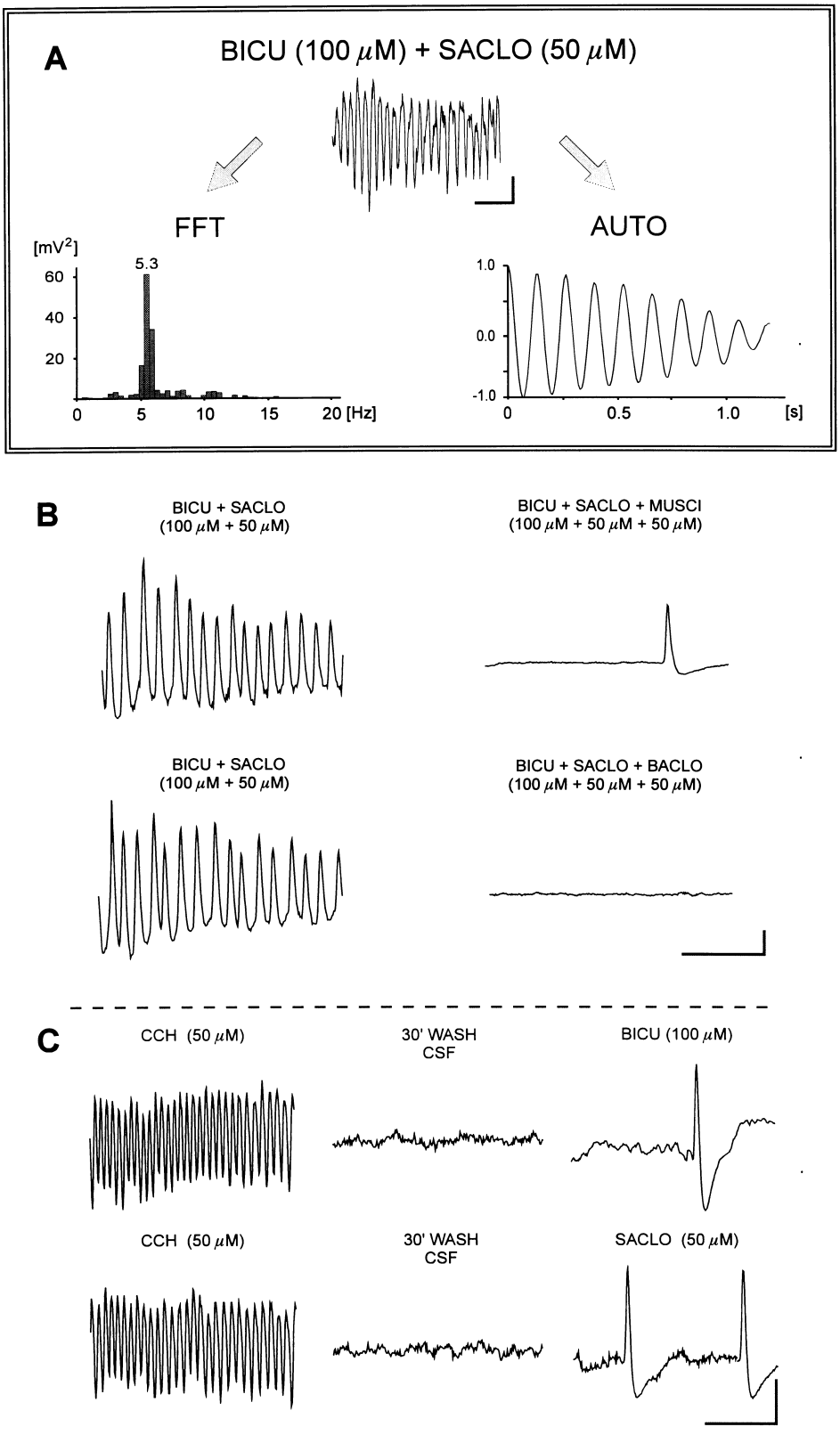

FIG. 10. Bicuculline/2-hydroxysaclophen (BICU, 100 μM + SACLO, 50 μM)-induced theta-like activity in the hippocampal slice and the effect of muscimol (MUSCI, 50 μM) and baclophen (BACLO, 50 μM). (A) Analogue example, power frequency (FFT), and autocorrelation (AUTO) analysis of theta-like oscillations recorded in the region of CA3 pyramidal cells in the presence of bicuculline and 2-hydroxysaclophen. (B) The in vitro induced theta-like activity was antagonized both by muscimol and baclophen. (C) The hippocampal slices which responded with theta-like oscillations in control (perfusion of 50 μM carbachol; CCH, 50 μM) did not manifest rhythmical slow waves when perfused either with bicuculline or 2-hydroxysaclophen: only epileptic discharges were observed. Calibration: for A, B, and C: 1 s and 200 μV.

muscarinic receptors this agent decreased the overall level of cholinergic excitation (Fig. 9).

Thus far we have presented evidence regarding theta-like oscillations resulting from the cholinergic excitation of the HPC neuronal network or resulting from simultaneous cholinergic stimulation and GABA-Aergic disinhibition. The question arises whether strong diminution of GABAergic inhibition per se is capable of producing a level of the HPC excitation essential for theta-like activity to appear. This idea has recently been tested in our laboratory. The HPC slice preparations were perfused with different concentrations of bicuculline and the GABA-B antagonist, 2-hydroxysaclophen (2HS). Well-synchronized theta-like oscillations were observed only in response to the

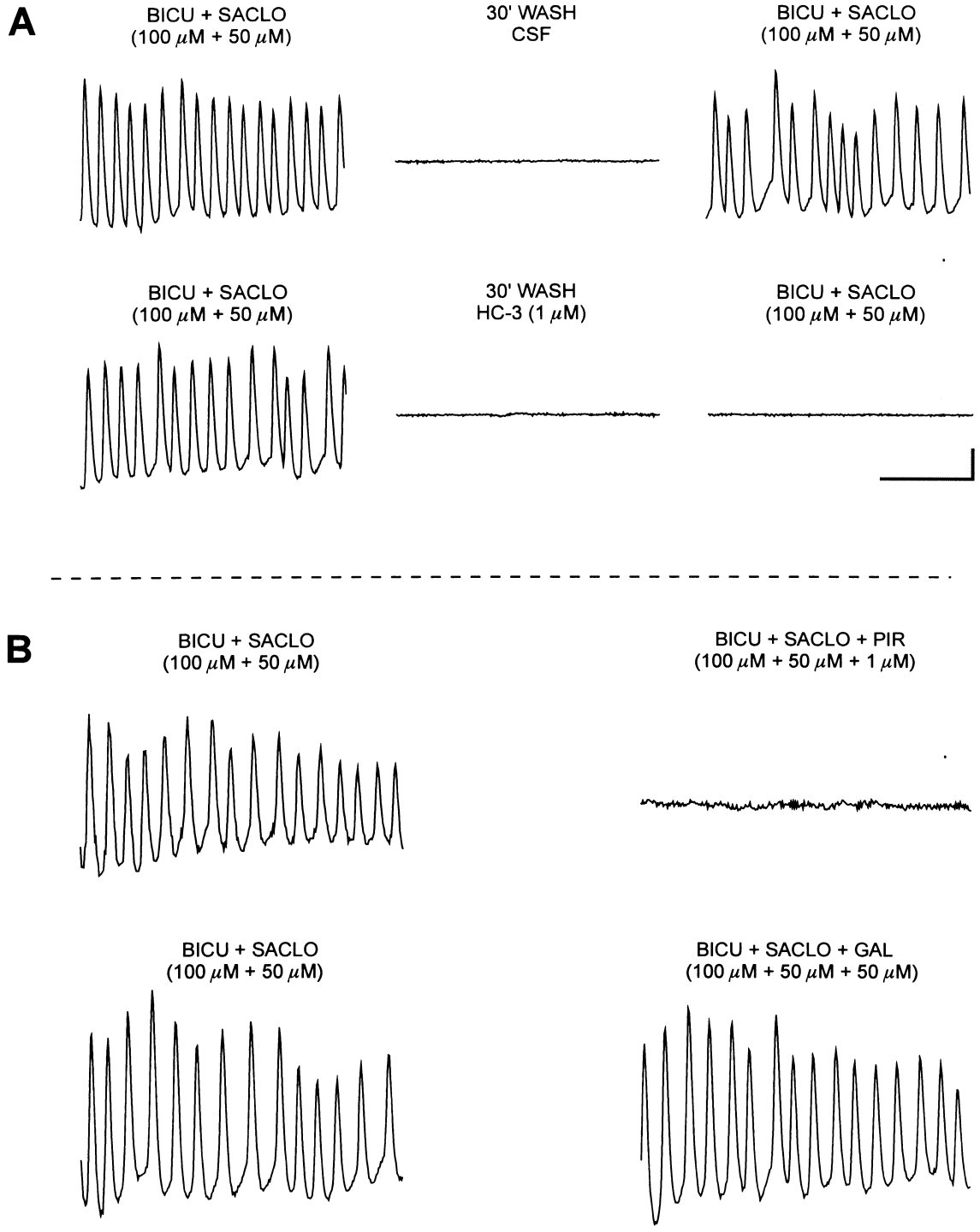

FIG. 11. Bicuculline/2-hydroxysaclophen (BICU, 100 μM + SACLO, 50 μM)-induced theta-like activity and the effect of hemicholinum (HC-3, 1 μM), pirenzepine (PIR, 1 μM) and gallamine (GAL, 50 μM). (A) BICU + SACLO-induced theta-like activity was reversed after 10–30 min wash with artificial cerebro-spinal fluid (CSF) or CSF containing HC-3. Note that a wash with CSF alone did not prevent the appearance of theta-like activity after a secondary bath perfusion of BICU + SACLO. (B) BICU + SACLO-induced theta-like activity was antagonized by pirenzepine (PIR) but was resistant to perfusion with gallamine (GAL). Calibration for A and B: 1 s and 200 μV.

simultaneous perfusion of 100 μM bicuculline and 100 μM 2-hydroxysaclophen in approximately 50% of the experiments performed (Fig. 10A, (39)). Both muscimol and baclophen were found to be effective in antagonizing bicuculline/2-hydroxysaclophen-induced oscillations (Fig. 10B). The bath perfusion of HPC slices with bicuculline or 2-hydroxysaclophen produced only seizure activity (Fig. 10C). Bicuculline/2-hydroxysaclophen-induced theta-like activity is the first in vitro evidence demonstrating that specific levels of excitation of hippocampal neurons required for theta to appear can also be produced by the strong diminution of GABA-A and GABA-B inhibition.

In the next series of experiments we extended our observations concerning the pharmacological profile of bicuculline/2-hydroxysaclophen-induced theta-like activity. The in vitro induced response was studied in the presence of hemicholinum-3 (HC-3; the agent that blocks choline transport across the membrane, thus diminishing acetylcholine content in the slices; (7),(21)), and the cholinergic M1 and M2 receptor antagonists, pirenzepine and gallamine, respectively. The slices pretreated for 30 min with hemicholinum were found to be completely resistant to bicuculline and 2-hydroxysaclophen when these agents were added to the bath (Fig. 11A). As is shown in Fig. 11B, bicuculline/2-hydroxysaclophen-induced theta-like oscillations were also antagonized by the M1 blocker, pirenzepine. Gallamine, was completely ineffective in abolishing previously induced theta-like oscillations (Fig. 11B). These results provide evidence which strongly suggest that bicuculline/2-hydroxysaclophen-induced theta-like activity also has a significant cholinergic M1 involvement (39).

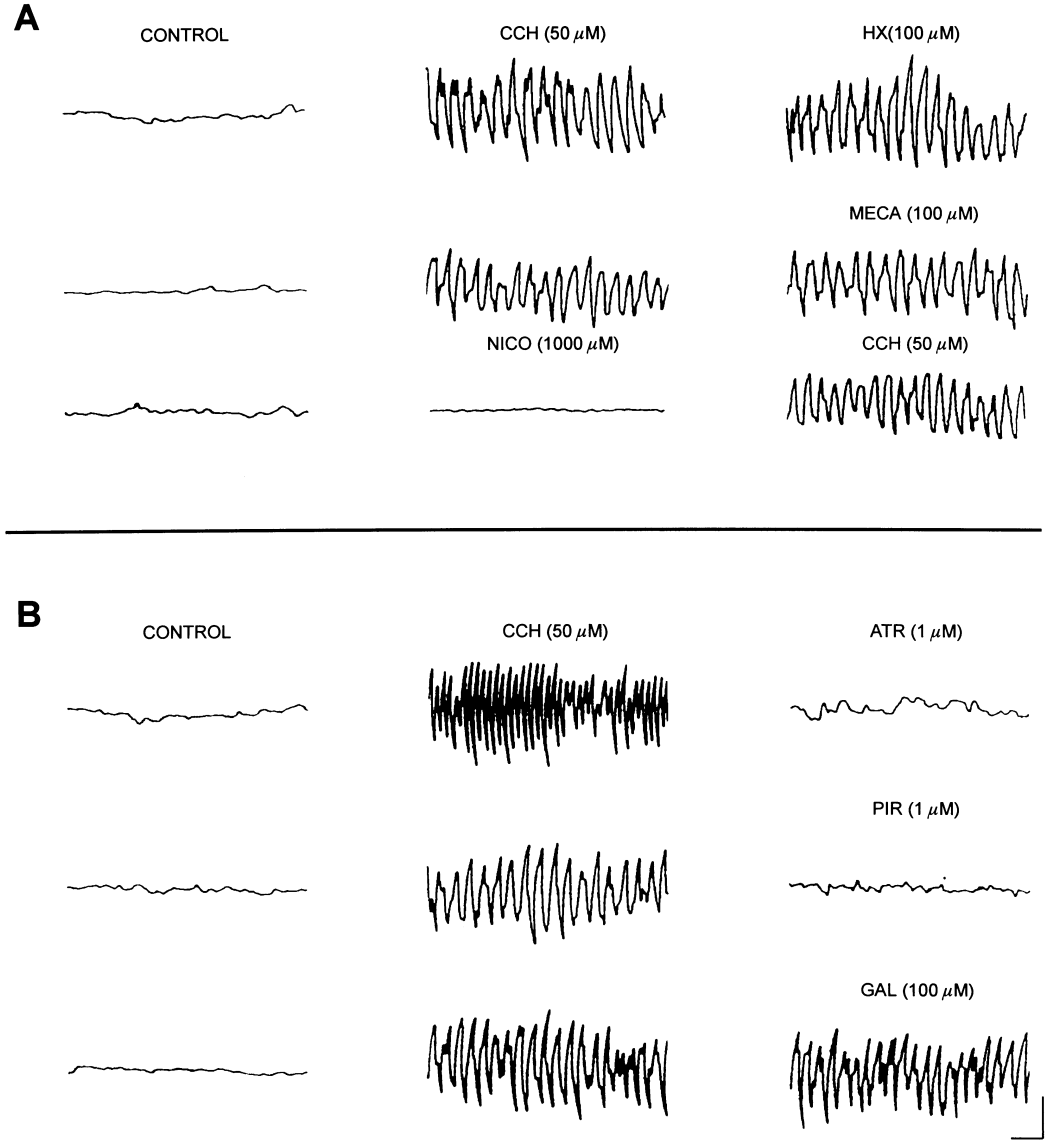

FIG. 12. Representative examples of carbachol (CCH, 50 μM)-induced theta-like activity in the cat medial entorhinal cortex slice. (A) CCH-induced theta-like activity recorded from three separate experiments on different slices. The recordings show the lack of antagonism of CCH-induced theta-like slow waves by hexamethonium (HX, 100 μM) and mecamylamine (MECA, 100 μM). The bottom recording shows the ineffectiveness of nicotine (NICO, 1000 μM) in inducing theta-like rhythm. However, when the same preparations were perfused with CCH, theta-like activity could be observed. (B) CCH-induced theta-like slow waves were antagonized by a classic muscarinic blocker, atropine sulphate (ATR, 1 μM), by M1 receptor antagonist, pirenzepine (PIR, 1 μM), but were unaffected by M2 receptor antagonist, gallamine (GAL, 100 μM). Calibration for A and B: 1 s and 200 μV

THETA-LIKE ACTIVITY RECORDED FROM ENTORHINAL CORTEX SLICE PREPARATIONS

Increasing attention has been paid to the role of the EC in mechanisms responsible for the generation of theta rhythm. The EC is the main source of afferents to the HPC and receives strong multisynaptic projections from the Ammon's horn field of the hippocampus (47,62). The medial part of the EC has been postulated to play a role in the generation of HPC theta (53,60). In addition, the EC per se, was suggested to be a source of the in vivo recorded theta rhythm (2,18,24,53). This suggestion was strongly supported by experiments we recently conducted on medial EC slice preparations obtained from rats and cats (34,36,37). Specifically, we demonstrated that in the in vitro conditions (i.e., deafferentiation from the hippocampal formation and medial septum) the EC neuronal network was capable of producing theta-like activity when CCH was added to the bath (Fig. 12A,B). Three lines of evidence demonstrate that CCH-induced theta-like oscillations were mediated by muscarinic (M1) receptors (Fig. 12A,B): (a) nicotine perfusion did not induce rhythmic slow waveforms; (b) cholinergically induced theta-like activity is antagonized by atropine sulphate and pirenzepine (the M1 receptor blocker) but not by gallamine (the M2 receptor antagonist); (c) hexamethonium and mecamylamine (the nicotinic antagonists) have been found to be ineffective in blocking cholinergic-induced theta-like activity.

SUMMARY AND CONCLUSION

The in vitro studies discussed up to now have focussed on two limbic cortex preparations: slices obtained from the HPC and EC. One can hypothesize that theta-like field potential could also be induced in other regions of the brain maintained in vitro. Indeed, just recently Lukatch and MacIver (49) demonstrated theta-like activity in coronal neocortical slices perfused with CCH and bicuculine. However, the experiments we have performed recently on slices obtained from the medial septum, posterior hypothalamus and brain stem do not provide further confirmation of this hypothesis. Many more in vitro experiments with the use of brain slices dissected in different planes remain to be done.

The experiments we have been conducting for the last 10 years on slice preparations from the HPC and EC demonstrate that a number of properties of the in vivo recorded theta rhythm can be successfully studied in vitro. Specifically: (1) the frequency and amplitude of the in vitro recorded theta-like activity ranges in the frequency and amplitude of the in vivo theta rhythm; (2) the time course analysis reveals that, as is the case for spontaneous theta in the rat, CCH-induced theta-like activity appears typically in short trains; (3) the pharmacological profile shows that both in vivo theta rhythm and in vitro recorded theta-like activity are muscarinically mediated; (4) both rhythms have the same locus of the amplitude maxima, suggesting an overlapping topography of the intrinsic hippocampal generators; (5) the pattern of development of in vitro theta-like activity closely resembles postnatal development of the in vivo theta rhythm; (6) both the in vivo theta rhythm and in vitro induced theta-like activity are accompanied by MPOs of ''theta-on'' and ''theta-off'' cells; (7) furthermore, both the production of the in vivo theta and in vitro theta-like activity require a dynamic balance between cholinergic and GABAergic systems.

These coincidences in properties of the in vivo and in vitro recorded rhythmic slow activity lead to a general conclusion that the generation of theta in both these preparations share common mechanisms.

One more issue should be addressed. The known ability of CCH to induce epileptiform activity (when administered in an appropriate concentration) would suggest that theta-like activity also has an epileptiform component. The theoretical implication of this suggestion would be that theta-like activity reflects the physiological and pharmacological properties of epileptiform discharges. Does it really?

(1) The typical intracellular correlate of the interictal epileptiform activity is the paroxysmal depolarization shift (PDS) (14). We have never observed a typical PDS in cells during extracellularly recorded in vitro theta-like activity. Instead, in a number of intracellularly recorded theta-related cells, MPOs and multiple spike discharges developed. In some intracellularly recorded cells (''theta-on'') an initial depolarizing shift with spike discharges was observed only at the onset of extracellular theta-like oscillations. However, the other cells (''theta-off'') manifested a hyperpolarizing shift at the onset of in vitro theta-like activity.

(2) The amplitude of epileptiform discharges was usually 5–10 times higher than the amplitude of the in vivo theta and in vitro theta-like activity and the frequency was typically lower than the range for in vivo theta and in vitro theta-like activity (3–12 Hz).

(3) Although some brain regions are recognized as epileptogenic, generally epileptiform activity is not restricted to specific regions of the brain (except cerebellum). Theta-like activity, in contrast, was observed only in the neocortex, HPC and EC, regions known to produce physiological theta in vivo.

(4) In contrast to in vivo theta and in vitro recorded theta-like oscillations, in vivo and in vitro recorded epileptiform discharges can be induced at all stages of postnatal brain development and even prenatally (26).

(5) While the appearance of the in vivo theta and in vitro theta-like activity results from cholinergic excitation and simultaneous GABAergic disinhibition, both in vivo and in vitro epileptiform discharges appear mainly in response to disinhibition of the GABAergic system (14). In addition, in contrast to theta-like activity, epileptiform discharges can also be mediated by NMDA type glutamate receptors (14,48). Hence, the epilepsy is usually successfully abolished by glutamate receptor antagonists and GABA agonists but not by the muscarinic receptor blockers, atropine or scopolamine.

(6) It is known that orthodromic stimulation of CA1 afferent fibres in vitro normally gives one population spike when recorded extracellularly from the pyramidal cell body layer. The bath perfusion of HPC slices with CCH at concentrations sufficient to induce theta-like activity does not change this pattern of the evoked response. However, GABAergic antagonists (penicillin, picrotoxin, bicuculline), which are used to induce epilepsy, typically produce three to 10 population spikes, as an effect of disinhibition of pyramidal cells (41).

In conclusion, the answer to the question asked above is that the in vitro induced theta-like activity does not reflect the physiological and pharmacological properties of the epileptiform discharges. Since it has much more in common

with the naturally occurring theta than with epilepsy, we have adapted the term ''theta-like'' activity.

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