NMDA Receptor-Dependent Periodic Oscillations in Cultured Spinal Cord Networks

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INTRODUCTION

The mechanisms driving the spontaneous activity of neuronal ensembles and their generation of spatiotemporal spike and burst patterns are difficult to study quantitatively in vivo because the simultaneous monitoring of neurons in small ensembles is technically extremely difficult (Bragin et al. 2000; McNaughton et al. 1983). However, neuronal networks grown in culture provide simpler systems in which a quasi monolayer architecture can be coupled to planar microelectrode arrays that allow ensemble recording over long periods of time. We used murine spinal cord networks growing on such microelectrode arrays (Droge et al. 1986; Gross 1994) to obtain long-term, multisite recording of spontaneous and pharmacologically modified activity (Fig. 1). The chemical environment can be controlled with precision, and specific activity states can be maintained and investigated for many hours, a time period usually not achievable in vivo. Like in vivo networks, cultured networks exhibit multiple synaptic driving forces resulting in complex spike and burst patterns. Therefore, this in vitro system offers the opportunity to investigate basic cellular and ensemble mechanisms underlying spontaneous activity.

In mammalian development, there is a short period during which neuronal networks are connected by purely excitatory synapses (Habets et al. 1987; Jackson et al. 1982). Throughout this developmental window, or when inhibitory synapses are blocked in more mature tissue, networks exhibit bursts of action potentials which are roughly synchronized across the population. These synchronous population bursts are proposed to be important in pruning and sculpting neuronal circuits during development (Tosney and Landmesser 1985). However, in the absence of inhibitory transmission, the mechanisms that serve to terminate bursts are unclear.

Application of inhibitory neurotransmitter antagonists, resulting in disinhibition of cultured networks, reliably induces oscillatory behavior consisting of bursts of action potentials concomitant with intracellular Ca2+ oscillations (Layrie et al. 1993; Rhoades and Gross 1994, Robinson et al. 1993; Wallen and Grillner 1987; Wang and Grunein 1997). Similar results have also been obtained by increasing excitability with ionic manipulations such as low Mg2+ or increased extracellular K+.

Fictive locomotion can be elicited in intact spinal cord preparations with burst patterns alternating between the right and left sides of the cord by application of serotonin (5-HT), N-methyl-D-aspartate (NMDA), 5-HT and NMDA in combination, or elevated extracellular K+ (Bracci et al. 1998; MacLean et al.

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1998; Wallen and Grillner 1987). These studies have shown that inhibitory conductances are not essential for rhythmogenesis, but it remains unclear as to the relative contributions of cellular versus network properties in the production of rhythmic motor output.

To study burst patterns in excitatory-only coupled networks, we pharmacologically reduced the inhibitory and excitatory neurotransmitter systems that drive the spontaneous activity in cultured murine spinal cord networks to one dominated by NMDA receptor activation, a situation reminiscent of that found during the embryonic/early postnatal period (Scheetz and Constantine-Paton 1994). The resulting activity (termed “NMDAONLY”) is characterized by a highly regular burst oscillation, as evidenced by the low coefficient of variation [(± SD/mean) *100] values for population burst variables, burst synchronization among units in the network, and a stationary burst rate of 21.0 ± 2.0 bursts per minute (bpm; mean ± SD, n = 16 cultures) that is independent of the initial activity state. Blocking NMDA receptors in the presence of bicuculline (BCC) and strychnine (STR), leaving the AMPA/kainate glutamate receptor subtypes as the sole driving force, did not produce network oscillations with the same level of precision as the NMDAONLY activity (n = 6). It appears that the NMDA receptor is uniquely suited for the production of the most stable burst oscillations.

We explored burst termination mechanisms with potential contribution to the NMDAONLY activity. These include after-hyperpolarization (AHP), receptor desensitization, and depression of neurotransmitter release (O’Donovan 1999). Blocking both AHP and NMDA receptor desensitization did not affect established NMDAONLY oscillations. Synaptic depression, possibly resulting from exhaustion of the readily releasable pool (RRP) of excitatory neurotransmitter vesicles, has been observed in disinhibited whole spinal cord and spinal cord slices (Bracci et al. 1996a; Streit 1993). CA3 population activity can be dominated by vesicle depletion and the time to refill the RRP (Staley et al. 1998). Our results indicate that strong synaptic depression caused by the depletion of the RRP could serve as burst termination mechanism during NMDAONLY activity, with the time required to refill the pool setting the period of the oscillation.

METHODS

Cell culture

The techniques used to fabricate and prepare microelectrode arrays (MEAs) have been described elsewhere (Gross 1979; Gross and Kowalski 1991; Gross et al. 1985). The electrode conductor pattern consisted of a central 0.8-mm² recording matrix of 64 microelectrodes (Gross 1994). Dissociated tissue cultures were prepared according to the basic method established by Ransom et al. (1977). Spinal cord tissues were harvested from embryonic day 14 – 15 Hsd:ICR mice. The tissue was dissociated enzymatically and mechanically, then seeded at a density of 0.2–0.5 × 10⁶ cells/cm² onto MEA surfaces (Gross 1994; Gross and Kowalski 1991). Cultures were incubated at 37°C in a 10% CO₂ atmosphere until ready for use, generally 3 wk to 3 mo after seeding. Cells media was replenished twice a week with minimal essential medium (MEM) containing 10% horse serum. Spontaneous activity started at approximately one week in the form of random spiking and stabilized in terms of coordinated spike and burst pattern by 15 days in vitro. The age of cultures used in this series of experiments ranged from 18 to 113 days in vitro. Such networks can remain spontaneously active and pharmacologically responsive for more than 6 mo (Gross 1994).

Drugs and solutions

All drug applications were made to a constant volume (1,000–1,500 μl) experimental bath in a consecutive manner. Thus, all drugs for a particular pharmacological treatment (BCC/STR/NBQX for example) were in the experimental bath simultaneously (see Fig. 6). All stock solutions were made on the day of use. Concentrations were calculated to minimize volume additions to the experimental bath. Apamin, atropine, BCC, CaCl₂, charybdotoxin, curare, Evan’s blue, glycine, KCl, MgCl₂, norepinephrine, and STR were purchased from Sigma Chemical (St. Louis, MO). APV, haloperidol, L-733,060, MCPG, NBQX, and SCH 50911 were purchased from Tocris Cookson (Ballwin, MD). Carbenoxolone was purchased from ICN (Costa Mesa, CA). Methysergide maleate was obtained from RBI (Natick, MA).
Extracellular recording procedures and data analysis

MEAs were placed in constant-bath recording chambers (Gross 1994; Gross and Schwalm 1994) and maintained at 37°C on a microscope stage. The pH was maintained at 7.4 with a continuous stream of filtered, humidified, 10% CO$_2$. Stainless steel chamber components were sterilized via autoclaving before each experiment. The normal bath solution consisted of a 50:50 mixture of fresh MEM and conditioned MEM with 10% horse serum supplement. The basal ionic concentrations for all experiments were (in mM) 0.8 Mg$^{2+}$, 1.3 Ca$^{2+}$, and 5.4 K$^+$.

Neuronal activity was recorded with a two-stage, 64-channel amplifier system (Plexon, Dallas, TX), and digitized simultaneously via a Dell 410 workstation (spike analysis) and a Masscomp 5700 computer (burst analysis). Total system gain used was normally 12 K. Spike identification and separation was accomplished with a template-matching algorithm (Plexon) in real time to provide single-unit spike rate data. In addition, whole channel (multiple-units/channel) data were analyzed off-line using custom programs for burst recognition and analysis. Burst patterns derived from spike integration ($\tau = 200$ ms) provided a high signal-to-noise feature extraction that has been shown to reveal modes of neuronal network behavior (Gross et al. 1994). From this approach, burst rate, duration, and interburst interval were readily quantified from individual recording sites. All et al. (1994). From this approach, burst rate, duration, and interburst interval were readily quantified from individual recording sites. All data presented are based on quantification of whole-channel burst data. In addition, whole channel (multiple-units/channel) data were analyzed off-line using custom programs for burst recognition and analysis. Burst patterns derived from spike integration ($\tau = 200$ ms) provided a high signal-to-noise feature extraction that has been shown to reveal modes of neuronal network behavior (Gross et al. 1994). From this approach, burst rate, duration, and interburst interval were readily quantified from individual recording sites. All data presented are based on quantification of whole-channel burst parameters, except for Figs. 5C and 10, B and D. The power spectra in these figures were calculated from spike data, and reveal prominent peaks at 0.37 Hz, corresponding to the period of $2.9 \pm 0.3$ s obtained from the whole-channel burst data. This confirms that the burst events are an integrated phenomenon, reflecting the ensemble dynamics of a neuronal population. Detailed analysis of the firing of individual neuronal units during their participation in the network burst events may yield insights into the mechanisms underlying the precise oscillation we characterize. However, the precision and culture-to-culture reproducibility of the phenomenon is captured by the burst analysis performed here.

Statistics

Statistical significance was determined using two-sample Student’s $t$-test with $P < 0.05$ considered as significant. To quantify the periodicity of bursting, as well as the synchronizaton of the neuronal population participating in each burst event, we calculated the coefficients of variation over time and across the network after 15- to 30-min stabilization periods to allow the networks to reach a steady state in their activity after pharmacological manipulation. Figure 2 summarizes the calculation of CVs. CV$_{time}$ reflects the periodic behavior of the activity pattern (Bracci et al. 1996a). CV$_{network}$ reflects the synchronization between different neurons. CV$_{time}$ was obtained from minute means of each channel by averaging over the experimental episode. The episode CVs per channel then were averaged to yield temporal mean networks. CV$_{network}$ was obtained by averaging values in 60-s bins, followed by another average across channels that yielded a CV$_{network}$ for each minute. These CVs were averaged for each experimental episode. The CVs were calculated for different burst variables: burst rate (BR), burst duration (BD), and interburst interval (IBI) during different experimental episodes, (spontaneous, partial disinhibition with BCC, and NMDA$_{ONLY}$). Large CVs imply a wide range of variability in the activity of the networks across both time and the neurons recorded. Hence, if a population was synchronized, but fluctuated together, low CV$_{network}$ and high CV$_{time}$ were obtained. Conversely, a nonsynchronized network with several regular (periodic) patterns yielded high CV$_{network}$ with low CV$_{time}$.

RESULTS

In their original medium (native state), spinal cord networks typically exhibited multiple patterns of activity (Fig. 3A). Disinhibition with the GABA$_A$ receptor antagonist BCC (40 $\mu$M) elicited robust bursting activity that was synchronized across the network (Fig. 3B). However, under BCC, the temporal variation in the burst period was still high. Further disinhibition by blocking glycine receptors with 1 $\mu$M STR did not reduce the variability of the burst period. When AMPA/kainate receptors were subsequently blocked with 10 $\mu$M 2,3-dioxo-6-nitro-1,2,3,4-tetrahydrobenzoquinoline-7-sulphonamide (NBQX), the networks were entrained to one common, highly periodic burst pattern activity (Fig. 3C). This unique activity state persisted for up to 12 h without change in regularity (Fig. 3D).

Data presented in this report were obtained from 16 separate cultures. In a subset of eight experiments, the oscillations began almost immediately after addition of BCC/STR/NBQX with a period of $2.8 \pm 0.2$ (SD) s, suggesting some common underlying control mechanism. This oscillation period was 2.8-3 s obtained...
associated with high spatial and temporal burst pattern regularity. The eight remaining networks established longer burst periods under NBQX (4.3–3.8 s), with less regularity of the bursts, suggesting that additional inhibitory mechanisms such as GABA\(_B\) receptor inhibition of vesicle release (Isaacson and Hille 1997) might have prevented the establishment of the unique 2.8-s oscillation. Indeed, the addition of 50 \(\mu M\) SCH 50911 (a soluble GABA\(_B\) antagonist) decreased the burst period in five of eight networks to 3.0 ± 0.3 s. In the three remaining networks, the application of 40 \(\mu M\) norepinephrine (NE) in addition to the preceding four compounds, promptly led to the adjustment of the burst oscillation to a regular, periodic burst period of 2.8 ± 0.2 s. NE is known to affect both NMDA receptor desensitization and the slow burst AHP, two other potentially inhibitory mechanisms (Legendre et al. 1993; Madison and Nicoll 1986; Tong and Jahr 1994; Tong et al. 1995). It is important to emphasize that SCH 50911 and/or NE had no effect when they were added after the NMDA\(_{ONLY}\) oscillation was established. These results indicate that GABA\(_B\) receptor-mediated inhibition of neurotransmitter release or mechanisms sensitive to NE were sometimes sufficient to prevent the characteristic NMDA\(_{ONLY}\) pattern from developing, but were not necessary for its maintenance. It is also important to note that the low CVs characterizing the NMDA\(_{ONLY}\) activity pattern were not obtained if the network burst rate following BCC/STR/NBQX was lower than 17 bpm. Thus, the eight cultures that required SCH or SCH/NE to lower their oscillation period into the 2.8 ± 0.2-s range had significantly higher CVs for each of the burst parameters before the additional pharmacological treatment.

The mean periods with associated SDs of all three pharmacological manipulations (BCC/STR/NBQX, BCC/STR/NBQX/SCH, and BCC/STR/NBQX/SCH/NE) were not significantly different (\(P > 0.05\), t-test for 2 samples), and thus data from all 16 experiments were pooled for subsequent analysis. To quantify the periodicity of the bursting, as well as the synchronization of the neuronal population participating in each burst event, we calculated the coefficients of variation for

\[ CV = \frac{\text{SD}}{\text{Mean}} \times 100 \]

FIG. 3. A–C: simultaneous spike trains from 15 discriminated neurons during different experimental episodes (25-s samples). A: spontaneous native activity displaying tonic and phasic firing with occasional coordinated bursting. B: 40 \(\mu M\) bicuculline transforms the activity into a bursting pattern that is coordinated across neurons but with a high degree of variability in the interburst intervals (IBI) and burst durations (BD). C: N-methyl-D-aspartate only (NMDA\(_{ONLY}\)) activity consists of a synchronized periodic burst pattern. In many cases, the phase relationships between neurons remained stable for hours. D: the long-term stability of the NMDA\(_{ONLY}\) burst oscillation is demonstrated with chart recorder trace of integrated activity (τ = 0.7 s) from a single channel at 5 min and 12 h after NBQX application.
several burst variables over time and across the network. All calculations were done with binned data (60 s means). The results of the CV calculations for three different burst variables: burst rate (BR), burst duration (BD), and interburst interval (IBI), under three different conditions (spontaneous, disinhibited with 40 μM BCC, and under NMDA ONLY), are summarized in Fig. 4. During native conditions, the CVs are large, implying a wide range of variability in the activity of the networks across time and between the neurons recorded. BCC (40 μM) reliably reduced the CVs of all three burst parameters, showing that disinhibition has a stabilizing effect on network oscillations. However, reducing the synaptic driving forces to one mediated through the NMDA receptor only, produced CVtime of 2.6–5% (Fig. 4A) and entrained virtually all recorded neurons (n = 678, 16 experiments), as evidenced by the global CVnetwork for BR of 2.8%. The dependency of the oscillation on the NMDA receptor was demonstrated with 40–100 μM APV, which abolished activity in all cases (n = 7).

Comparing the CVs from the experimental episodes of the eight experiments in which the precise NMDA ONLY oscillation was not established immediately after BCC/STR/NBQX, but before addition of either the GABA A antagonist SCH50911 or SCH50911 and NE to the CVs of the six experiments under AMPA ONLY conditions, we found that there was no significant difference. In all eight of these NMDA ONLY experiments, the BR was below 17 bpm after addition of the BCC/STR/NBQX cocktail. Manipulations to maximize neurotransmitter release and prevent NMDA receptor desensitization always increased the BR, indicating that certain inhibitory constraints may be emphasized to a greater extent in some networks. This is an interesting observation in its own right, and may speak to the different homeostatic mechanisms employed by developing neuronal networks to ensure that spontaneous activity falls within an appropriate dynamic range. Burst rates under AMPA ONLY conditions ranged from 13 to 28. None of the pharmacological manipulations we attempted under AMPA ONLY conditions produced the low CVs distinguishing the NMDA ONLY activity (Fig. 5, A and B). Supplementation of the BCC/STR/APV treatment with SCH50911 and NE had some minor effects on BR and structure, but did not significantly enhance the precision of the oscillation. In two experiments, we blocked AMPA receptor desensitization with cyclothiazide after adding BCC/STR/APV. In both cases, a rapid and large increase in tonic spiking ensued followed by complete cessation of network activity. This activity inhibition could possibly have been caused by a tonic depolarization of membrane potential produced by the longer open time of the AMPA channel. There was no combination of pharmacology we tried that reproduced the extreme precision of the NMDA ONLY oscillation under AMPA ONLY conditions.

Figure 5C compares the power spectra calculated from the spike trains of 106 neurons from 14 different NMDA ONLY experiments to those of 81 neurons from six different AMPA ONLY experiments. The dotted lines represent 95% confidence intervals, and clearly show that the two pharmacological conditions are distinct in their effects on network oscillations. These results indicate that the NMDA synapse is uniquely suited to provide extremely regular population burst oscillations.

Figure 6 illustrates the evolution of activity with sequential addition of BCC, STR, and NBQX to the culture bath, culminating in the NMDA ONLY activity pattern. The period of spontaneous activity has low rates of bursting and spiking. Addition of 40 μM BCC produces an increase in both activity variables within 5 min of application. However, the minute-to-minute variation in both variables is still quite large. Addition of 1 μM STR to remove the second set of inhibitory circuits elicits a further increase in burst and spike rates accompanied by an increase in the temporal variability. The subsequent application of 10 μM NBQX resulted in a decrease in both burst and spike rates from the totally disinhibited activity. Both measures stabilized at near constant levels after about 20 min. The 30 min following establishment of stable NMDA ONLY activity had CVtime for BR, BD, and IBI of 2.1, 4.1, and 2.9%, respectively. The dependence of the stationary activity on NMDA receptor mediated events is shown by the application of 100 μM APV at 412 min, which resulted in a loss of all bursting within 10 min.

During NMDA ONLY activity, spinal cord networks consistently oscillated within a very narrow range of BRs. This activity was apparently independent of network age or neuronal density, as the 16 cultures from which the data were gathered ranged in age from 18 to 113 days in vitro and were seeded at concentrations of 0.2–0.5 × 106 cells/ml. Averaging BRs from all 178 channels resulted in a mean global BR of 21.0 ± 2.0 (SD) bpm. For each channel, the NMDA ONLY BR
was essentially independent of the initial (native) BR. The distribution of BRs for all 16 cultures (178 channels) under three different conditions is shown in Fig. 7. Native activity (Fig. 7A), prior to any pharmacological additions, ranged from 3 to 27 bpm. When BCC (40 μM) was added to block GABA<sub>A</sub>-mediated inhibition, the BR distribution was broadened, ranging from 3 to 36 bpm (Fig. 7B). A peak in the distribution at 12–15 bpm indicates that the disinhibited network state has some preferential activity modes, though the typical BCC response varies between cultures. Figure 7C, which shows the NMDA<sub>ONLY</sub> activity distributed from 18 to 24 bpm, demonstrates the reliability of expression of the oscillation in all cultures (n = 16).

Mechanisms controlling burst oscillations

The possible mechanisms that contribute to the unique characteristics of the NMDA<sub>ONLY</sub> activity were explored with a battery of pharmacological agents summarized in Table 1. These agents may be roughly divided into compounds that affect neurotransmitter release, compounds that affect receptor desensitization, compounds that affect burst and spike AHP, and antagonists of neurotransmitter receptors.

COMPOUNDS AFFECTING NEUROTRANSMITTER RELEASE. As previously described, when the main synaptic driving force had been reduced to NMDA<sub>ONLY</sub> and the network activity had already stabilized to a highly periodic BR of 21.0 ± 2.0 bpm,
the GABA<sub>B</sub> receptor antagonist SCH 50911 (50 μM) had no effect. However, in eight experiments, the combination of BCC/STR/NBQX resulted in a BR of less than 17 bpm. The variability in the burst parameters were also significantly higher than in the eight experiments that responded with precise burst oscillations immediately after application of NBQX. In 5 of 8 of these cultures, the effect of SCH50911 was to increase the BR to 18–24 bpm and to establish a highly periodic pattern of activity. Thus it appears in our preparation, inhibition of neurotransmitter release through activation of GABAB receptors by endogenous GABA is sometimes sufficient to prevent the characteristic NMDA<sub>ONLY</sub> pattern of activity from developing. These network specific effects may reflect fluctuations in network structure that are revealed by the pharmacological manipulations.

In three experiments, after NMDA<sub>ONLY</sub> activity had been established, we titrated the Ca<sup>2+</sup> concentration from 1.3 to 8.0 mM (Fig. 8). The initial Ca<sup>2+</sup> increase to 3 mM caused a consistent decrease in both the BR and BD. Further increases in Ca<sup>2+</sup> suppressed mean BDs from 600 ms at 3 mM Ca<sup>2+</sup> to 300 ms at 8 mM Ca<sup>2+</sup>, but did not affect the BR significantly. At all elevated Ca<sup>2+</sup> concentrations, the precision of the pre-existing NMDA<sub>ONLY</sub> oscillation was lessened. In two of these experiments, we subsequently raised K<sup>+</sup> concentrations from 1.3 to 8.0 mM caused a consistent decrease in both the BR and BD. Further increases in K<sup>+</sup> increased both the level of neuronal excitability and the level of Ca<sup>2+</sup> influx at the presynaptic terminal. The effect of elevated K<sup>+</sup> under these conditions was to increase the BR, consistent with an increase in neuronal excitability (Fig. 8). After the extensive pharmacological manipulations, it is of significance that the network responded to elevated K<sup>+</sup> concentrations in a predictable manner (Rhoades and Gross 1994).

The contribution of metabotropic glutamate receptors (mGluR) to neurotransmitter release was examined with the nonselective group I/II antagonist MCPG (200 μM). The compound was without measurable effect in five experiments, indicating that mGluR activation was not a significant factor in the control of glutamate release in our cultures. This finding is in accord with those of von Gersdorff et al. (1997), who showed that mGluR activation apparently contributes to only about 10% of the EPSC depression induced by afferent stimulation at the calyx of Held in the rat brain stem.

Titrating the extracellular Mg<sup>2+</sup> from the normal 0.8 mM to a maximum of 6 mM after establishment of NMDA<sub>ONLY</sub> activity resulted in a dose-dependent reduction in the BR without affecting the BD except at the higher concentrations immediately prior to network failure (Fig. 9). Like Ca<sup>2+</sup>, Mg<sup>2+</sup> has multiple sites of action. It inhibits neurotransmitter release and blocks the NMDA channel in a voltage-dependent fashion. Increasing the concentration of Mg<sup>2+</sup> raises the threshold for relief of the voltage-dependent blockade. Mg<sup>2+</sup> is also implicated in suppression of spontaneous activity by charge screening of voltage-sensitive Na<sup>+</sup> channels (Guth and Drescher 1990).

**COMPOUNDS AFFECTING RECEPTOR DESENSITIZATION.** NMDA receptors undergo different forms of desensitization that could potentially contribute to the activity pattern. Glycine-dependent desensitization of NMDA receptor-mediated currents has been reported in cultured hippocampal neurons (Mayer et al. 1989; Vyklicky et al. 1990). Both groups found that 3 μM glycine was sufficient to alleviate a strong depression of such currents. In addition, the NMDA receptor undergoes a Ca<sup>2+</sup>-dependent form of desensitization that is mediated by the phosphatase calcineurin (Legendre et al. 1993; Tong and Jahr 1994; Tong et al. 1995). To test the hypothesis that glycine-dependent NMDA receptor desensitization influenced the neuronal network activity under NMDA<sub>ONLY</sub> conditions, we added 10 μM glycine to counteract desensitization (n = 3). The glycine had no measurable effect, indicating that glycine-dependent desensitization did not play a role in generating NMDA<sub>ONLY</sub> oscillations.

Raman et al. (1996) showed that NE increases PKA activity through a β-adrenergic dependent process, which is sufficient to counteract the phosphatase actions of calcineurin and prevent NMDA receptor desensitization. In three experiments, application of 40 μM NE increased BRs and stabilized IBI at NMDA<sub>ONLY</sub> levels. When NE was applied after establishment.

**FIG. 6.** Changes in spontaneous spike rate (○) and burst rate (●) induced by sequential addition of 40 μM bicuculline (BCC), 1 μM strychnine (STR), 10 μM NBQX, and 100 μM APV. Each symbol represents the mean of 27 neurons (spike rate) and 14 channels (burst rate). ▼, times of drug application. Spontaneous activity increases within 3 min of bicuculline application at 170 min. Strychnine application at 270 min reduces activity in both bursting and spiking, accompanied by an increase in temporal variability. Blocking AMPA receptors with NBQX at 360 min reduces both bursting and spiking to levels intermediate to BCC and STR. Note the greatly reduced activity fluctuation within 20 min after NBQX application. APV abolishes all bursting and most spiking within 10 min of application, demonstrating the dependence of the activity on the NMDA receptor.
of a stable NMDA\textsubscript{ONLY} pattern, it was without effect. However, NE also inhibits the slow AHP (sAHP) that may serve to terminate bursting (Madison and Nicoll 1986). Therefore it is unclear whether the effects produced by NE were a result of blocking receptor desensitization or the sAHP. In either case, the NMDA\textsubscript{ONLY} pattern of activity, once established, was not dependent on a mechanism sensitive to NE.

COMPOUNDS AFFECTING SHP. Action potentials in many excitatory cells are followed by a prolonged AHP that modulates repetitive firing. Apamin has been shown to inhibit the Ca\textsuperscript{2+}-dependent S(K) current that is responsible for this AHP (Sah and McLachlan 1992). In our experiments, 1 \( \mu \)M apamin (\( n = 4 \)) increased BRs if it was applied prior to blocking AMPA/kainate receptors (Fig. 8). When apamin was applied after the NMDA\textsubscript{ONLY} activity was established (\( n = 3 \)), it was without effect. This indicates that the apamin-sensitive AHP does not affect NMDA\textsubscript{ONLY} oscillations.

A transient AHP was identified in hippocampal slices (Alger and Williamson 1988) that was sensitive to charybdotoxin (ChTX), indicating its mediation by B(K)\textsubscript{1} channels. We performed experiments with 20 nM ChTX before (\( n = 3 \)) and after (\( n = 3 \)) network activity was reduced to NMDA\textsubscript{ONLY}. ChTX increased BRs when it was applied before blockade of AMPA/kainate receptors (Fig. 8), but was without effect when applied after NBQX. These results indicate that the Ca\textsuperscript{2+}-activated B(K) channel does not contribute substantially to NMDA\textsubscript{ONLY} oscillations.

NEUROTRANSMITTER RECEPTOR ANTAGONISTS. After the NMDA\textsubscript{ONLY} activity was established, we used atropine (muscarinic receptor antagonist, 1–30 \( \mu \)M, \( n = 3 \)), curare (nicotinic receptor antagonist, 10–20 \( \mu \)M, \( n = 3 \)), haloperidol (dopamine receptor antagonist, 2 nM, \( n = 2 \)), methysergide (5-HT\textsubscript{1}/2 receptor antagonist, 20 \( \mu \)M, \( n = 2 \)), Evan’s blue (P2X receptor antagonist, 50 \( \mu \)M, \( n = 2 \)), and L-733,060 (tachykinin receptor antagonist, 2 nM, \( n = 2 \)). None of these compounds had measurable effects on previously established NMDA\textsubscript{ONLY} oscillations.

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carbenoxolone (50–100 μM, n = 3). There was no measurable effect on the NMDA ONLY activity, indicating that gap junction coupling played no significant role in these oscillations. ZD7288 (50 μM, n = 3) was used to test for the contribution of the hyperpolarization-activated cationic conductance (Ih) to NMDA ONLY activity. This agent was also ineffective.

PRE-VERSUS POSTSYNAPTIC CONTROL MECHANISMS. The addition of 20–50 μM NMDA to the experimental culture medium after the NMDA ONLY activity was established resulted in both increased spike production and a disruption of the periodic nature of the activity (Fig. 10, n = 2). CV time for BR was 58% in one network and 71% in the other, indicating that the regular oscillations were no longer present. The disruption of the pattern can be demonstrated in the spike frequency domain with Fourier analysis of spike intervals from the same identified units. Figure 9, B and D, reveals a drastic alteration in the spike interval structure. Whereas the NMDA ONLY activity peaks at 0.34 Hz (B), the addition of NMDA to the medium (D) obliterates the interval organization.

The NMDA receptor channel possesses a unique voltage-dependent Mg2+ block that has been shown to induce oscillations in several preparations (Hu and Bourque 1999; Rioult-Pedotti 1997; Wallen and Grillner 1987). This oscillation is elicited by NMDA receptor activation in the presence of physiological levels of Mg2+ and is apparently due to the negative slope in the current-voltage relation of the NMDA synapse. Wallen and Grillner (1987) showed that NMDA application produced TTX-resistant oscillations in membrane potential, indicating an intrinsic cellular property. Because bath application of NMDA directly activates the receptors, independent of vesicle release, and essentially uncouples the NMDA synapses from presynaptic influences, the loss of regular oscillations strongly suggests that the periodicity under NMDA ONLY conditions is not induced at the receptor level only.
DISCUSSION

Independent of spontaneous activity or age, 16 spinal cord cultures were entrained to a remarkably stable, highly periodic burst pattern of 21.0 ± 2.0 bpm under NMDA ONLY conditions. This pattern of activity persisted for up to 12 h (maximum observation time, Fig. 3D), and more than 98% of all recorded neurons participated (40–85 neurons per experiment). NMDA receptor activation was necessary for generation of this unique, highly periodic activity pattern as it was abolished by 40–100 μM APV. However, tonic NMDA receptor activation was not sufficient to maintain the periodicity, implying that control of the period may originate at the presynaptic level. Additionally, disinhibition with BCC and STR and blockade of NMDA receptors with APV (leaving only the AMPA/kainate synapse as the sole driving force) did not produce the characteristic oscillation.

Mechanisms underlying intrinsic burst generation have been explored in several different cell types (Azouz et al. 1996; Ballerini et al. 1999; Bracci et al. 1996b; Llinas 1988; Streit 1993; Traub et al. 1994). Generally, these investigations have analyzed burst phenomena one cell at a time, although population studies using Ca\(^{2+}\) imaging (Lawrie et al. 1993; Robinson et al. 1993; Wang and Gruenstein 1997) or extracellular field potentials (Staley et al. 1998) have provided insights into network bursting. Acutely isolated intact spinal cords, acute spinal cord slices, and organotypic slice preparations have been explored in several different cell types (Azouz et al. 1996; Ballerini et al. 1999; Bracci et al. 1996b; Llinas 1988; Streit 1993; Traub et al. 1994). Generally, these investigations have analyzed burst phenomena one cell at a time, although population studies using Ca\(^{2+}\) imaging (Lawrie et al. 1993; Robinson et al. 1993; Wang and Gruenstein 1997) or extracellular field potentials (Staley et al. 1998) have provided insights into network bursting. Acutely isolated intact spinal cords, acute spinal cord slices, and organotypic slice preparations have been explored in several different cell types (Azouz et al. 1996; Ballerini et al. 1999; Bracci et al. 1996b; Llinas 1988; Streit 1993; Traub et al. 1994). Generally, these investigations have analyzed burst phenomena one cell at a time, although population studies using Ca\(^{2+}\) imaging (Lawrie et al. 1993; Robinson et al. 1993; Wang and Gruenstein 1997) or extracellular field potentials (Staley et al. 1998) have provided insights into network bursting. Acutely isolated intact spinal cords, acute spinal cord slices, and organotypic slice preparations have been explored in several different cell types (Azouz et al. 1996; Ballerini et al. 1999; Bracci et al. 1996b; Llinas 1988; Streit 1993; Traub et al. 1994). Generally, these investigations have analyzed burst phenomena one cell at a time, although population studies using Ca\(^{2+}\) imaging (Lawrie et al. 1993; Robinson et al. 1993; Wang and Gruenstein 1997) or extracellular field potentials (Staley et al. 1998) have provided insights into network bursting. Acutely isolated intact spinal cords, acute spinal cord slices, and organotypic slice preparations have been.
used to study the mechanisms of fictive locomotion and putative central pattern generators. For example, elevated extracellular K\(^+\) resulted in increased neuronal excitability, leading to rhythmic, synchronized oscillations in organotypic rat spinal cord slices (Ballerini et al. 1999). These oscillations were network dependent as they were blocked by TTX and low-Ca\(^{2+}\)/high-Mg\(^{2+}\) solutions. Comparable oscillations were also seen in isolated spinal cord preparations (Bracci et al. 1998).

Ballerini et al. (1999) reported in one experiment a persistent, network-dependent, rhythmic burst oscillation in ventral horn interneurons with a period of 2.8 ± 1.5 s under elevated (6–7 mM) extracellular K\(^+\) (a period close to the 2.9 ± 0.3 s that we observed during NMDA\(_{\text{ONLY}}\) activity). Thus, the oscillation rate of the NMDA\(_{\text{ONLY}}\) activity is not unique to the dissociated cell culture condition. However, this is the first report of an oscillation characterized not only by remarkable temporal and spatial stability of all burst parameters within individual experiments but also by high interexperiment reproducibility with networks that varied widely in age and cell density. This suggests the NMDA\(_{\text{ONLY}}\) network state may be unmasking a fundamental cellular mechanism rather than a circuit specific network property.

CA3 network activity can be dominated by strong synaptic depression presumably induced by depletion of a finite supply of releasable glutamate (Staley et al. 1998). They suggested that the period of the population bursts was determined by the rate of refilling of this pool. Recent investigations have provided insights into the dynamics of neurotransmitter vesicle pools (Goda and Stevens 1998; Ryan et al. 1993, 1996). The RRP in central neurons has been shown to contain from 5 to 20 vesicles (Do brunz and Stevens 1997; Stevens and Tsujimoto 1995). This pool refills with a time constant of 5–12 s (Rosenmund and Stevens 1996). High-frequency stimulation of presynaptic terminals with trains of 100–300 Hz significantly enhances the rate of refilling when compared with square wave depolarizing input (Wang and Kaczmarek 1998). Stevens and Wesseling (1998) reported that the synaptic recovery period was reduced from 6 to 3 s when focal hyperosmotic conditions were paired with presynaptic 10-Hz stimulation. The recovery time for CA1 synapses depleted by 10-Hz stimulation in hippocampal slices was 2.8 ± 2.0 s (Dobrunz and Stevens 1997), a time remarkably similar to our NMDA\(_{\text{ONLY}}\) period. By comparison, the NMDA\(_{\text{ONLY}}\) bursts in our studies produced a long-lasting depolarization that is necessary to support action potential burst firing in cultured hippocampal neurons. These results all highlight the unique relationship of the NMDA receptor to intracellular Ca\(^{2+}\) dynamics. Hence, NMDA receptor-dependent Ca\(^{2+}\) influx is likely to influence the character of the burst generated, which, in turn, influences the degree of vesicle depletion at the presynaptic terminal.

Preliminary results of Ca\(^{2+}\) imaging experiments performed under three different conditions (NMDA\(_{\text{ONLY}}\), partial disinhibition with BCC, and AMPA\(_{\text{ONLY}}\)) indicate that intracellular Ca\(^{2+}\) oscillations occur with the same frequency and precision under NMDA\(_{\text{ONLY}}\) conditions as the extracellularly recorded burst oscillations. The baseline level of intracellular Ca\(^{2+}\) during NMDA\(_{\text{ONLY}}\) appears to be significantly elevated when compared with the other two conditions. This is possible evidence for the NMDA\(_{\text{ONLY}}\) condition being particularly efficacious in affecting intracellular Ca\(^{2+}\) dynamics. This heightened Ca\(^{2+}\) concentration could in turn promote maximal vesicle release during the active phase of each oscillation.

In the lamprey, NMDA application induces a robust fictive swimming rhythm which is dependent on NMDA-induced Ca\(^{2+}\) currents and Ca\(^{2+}\)-dependent K\(^+\) currents in pacemaker cells (Brodin et al. 1991). Rat spinal neurons exhibit membrane potential oscillations in response to NMDA application which are TTX resistant, but dependent on serotonin (Hochman et al. 1994a,b; MacLean et al. 1998). These membrane potential oscillations have been hypothetized to contribute to the phasic population activity occurring during fictive locomotion, allowing the expression of a precise oscillation period by filtering temporally dispersed synaptic activity (Hochman et al. 1994b). While our experiments certainly do not preclude this mechanism from contributing to the oscillatory nature of the NMDA\(_{\text{ONLY}}\) activity, disruption of the periodicity of preexisting oscillations by application of NMDA indicates that the receptor alone is not sufficient to drive the bursting with great precision.

Staley et al. (1998) speculated that depletion of the excitatory neurotransmitter vesicle pool might be necessary for burst termination, with other mechanisms such as inhibitory conductances and AHP acting to modulate the postsynaptic effect of glutamate. It is of interest that early in postnatal development, GABA application depolarizes neurons (Ben-Ari et al. 1997; Menedez de la Prada and Sanchez-Andres 1999). During this period, bursting patterns of coordinated activity occur (Habets et al. 1987; Jackson et al. 1982). This coordinated activity selectively activates subsets of synapses and functions as an important mechanism for sculpting circuitry that is preserved in the adult animal (Landmesser and Pilar 1978; Tosney and Landmesser 1985). During the period when GABA is depolarizing, mechanisms other than fast synaptic inhibition must serve to terminate bursting. Strong synaptic depression induced
by vesicle depletion would allow the coordination of phasic activity between recurrently connected neurons, permitting the expression of fundamental motor patterns such as the respiratory rhythm prior to establishment of mature synaptic circuitry.

The dependence of the NMDA_{ONLY} oscillation on such a mechanism might be explored with compounds that affect the rate of vesicular recycling, such as bafilomycin (Cousin and Nicholls 1997). Quantification of miniature excitatory postsynaptic potentials occurring immediately prior to and after a burst event could give a direct measure of the amount of vesicle depletion caused by a burst and provide information on the refilling rate of the releasable vesicle pool. Initial results from Ca^{2+} imaging studies indicate that intracellular Ca^{2+} concentrations are tonically elevated during the NMDA_{ONLY} condition and that Ca^{2+} oscillations occur with the same frequency and precision as the burst events.

Few neuronal systems can be forced into a specific dynamic state with high reliability and remain entrained for many hours. The availability of such a stable dynamic system provides a tool for the study of structure/function relationships controlling network behavior, excitotoxicity, and qualitative assessment of functional synaptic deficits, as well as therapeutic measures designed to restore synaptic efficacy. In any case, NMDA_{ONLY} activity represents a simplification of synaptic driving forces, which will allow the study of excitatory-coupled network dynamics and basic burst mechanisms, providing insight into the complex interactions of cellular and network properties.

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