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Recovery of NMDA receptor currents from MK-801 blockade is accelerated by Mg\(^{2+}\) and memantine under conditions of agonist exposure

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**Abstract**

MK-801 is a use-dependent NMDA receptor open channel blocker with a very slow off-rate. These properties can be exploited to ‘pre-block’ a population of NMDARs, such as synaptic ones, enabling the selective activation of a different population, such as extrasynaptic NMDARs. However, the usefulness of this approach is dependent on the stability of MK-801 blockade after washout. We have revisited this issue, and confirm that recovery of NMDAR currents from MK-801 blockade is enhanced by channel opening by NMDA, and find that it is further increased when Mg\(^{2+}\) is also present. In the presence of Mg\(^{2+}\), 50% recovery from MK-801 blockade is achieved after 10' of 100 \(\mu\)M NMDA, or 30' of 15 \(\mu\)M NMDA exposure. In Mg\(^{2+}\)-free medium, NMDA-induced MK-801 dissociation was found to be much slower. Memantine, another PCP-site antagonist, could substitute for Mg\(^{2+}\) in accelerating the unblock of MK-801 in the presence of NMDA. This suggests a model whereby, upon dissociation from its binding site in the pore, MK-801 is able to re-bind in a process antagonized by Mg\(^{2+}\) or another PCP-site antagonist. Finally we show that even when all NMDARs are pre-blocked by MK-801, incubation of neurons with 100 \(\mu\)M NMDA in the presence of Mg\(^{2+}\) for 2.5 h triggers sufficient unblocking to kill >80% of neurons. We conclude that while synaptic MK-801 ‘pre-block’ protocols are useful for pharmacologically assessing synaptic vs. extrasynaptic contributions to NMDAR currents, or studying short-term effects, it is problematic to use this technique to attempt to study the effects of long-term selective extrasynaptic NMDAR activation.

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**1. Introduction**

MK-801 (dizocilpine), a compound originally characterised as an anti-convulsant drug, is a potent NMDAR antagonist (Wong et al., 1986). MK-801 binds selectively and with high affinity to NMDARs when they are in their open state (Huttner and Bean, 1988) and as such is referred to as a use-dependent or open-channel blocker.

Early electrophysiological and ligand binding studies revealed that the blockade of NMDARs by MK-801 persisted long after the drug had been washed out (Huttner and Bean, 1988; Reynolds and Miller, 1988). This unusual property meant that MK-801 blockade of NMDARs is highly stable and could be regarded as “irreversible” over the timescourse of many experiments, leading to it being used to “permanently” block a sub-population of NMDARs in order to study a separate population of non-blocked NMDARs. An example of such use is in the study of synaptic and extrasynaptic NMDARs (Hardingham et al., 2002; Tovar and Westbrook, 1999). Differential signalling by the neuroprotective phasic activation of synaptic NMDARs compared to the deleterious tonic activation of extrasynaptic NMDARs, is a topic of ongoing interest (Bordji et al., 2010; Dick and Bading, 2010; Hardingham and Bading, 2002, 2010; Ivanov et al., 2006; Leveille et al., 2008; Milnerwood et al., 2010; Okamoto et al., 2009; Papadia et al., 2008; Soriano et al., 2009; Tu et al., 2010; Wahl et al., 2009; Zhang et al., 2007).

In order to selectively activate extrasynaptic NMDARs, synaptic NMDARs must first be pre-blocked by, for example, driving synaptic activity in the presence of MK-801, leaving extrasynaptic NMDARs unaffected. Following washout, MK-801 mediated block of synaptic NMDARs persists, enabling the selective activation of extrasynaptic NMDARs simply by bath-applying an NMDAR agonist (Bengtson et al., 2008; Hardingham et al., 2002). The same technique has also been employed to other ends, such as the analysis of recovery of synaptic currents as an indicator of NMDAR diffusion from extrasynaptic to synaptic sites (Tovar and Westbrook, 2002).

While the stability of the MK-801 blockade means that it can be relied upon to largely persist for the timescourse of short-term...
experiments, it is important to define precisely how persistent MK-801 blockade is. For example, a recent study involved an attempt to selectively activate extrasynaptic NMDARs for 150 min by relying on the MK-801 mediated pre-block of synaptic NMDARs remaining over this time period (Wroge et al., 2012). However, it is clear, even from early experiments, that MK-801 blockade is not irreversible and moreover, that its stability depends on the activation state of the receptor. In particular, dissociation of MK-801 from the NMDAR is increased when the receptor is in the open state: it was observed originally that recovery from MK-801 blockade could be accelerated by NMDA, i.e. that recovery is use-dependent (Huettner and Bean, 1988). However, in that particular study the authors reported a time constant for recovery of 92 ± 106 min (mean ± SD) reflecting the fact that recovery was observed in several cells but not others, the reason for which is unclear. Others also reported observing use-dependent recovery from MK-801 blockade using techniques such as radio-ligand binding and Ca²⁺ imaging (Reynolds and Miller, 1988; Yuzaki et al., 1990). However, Ca²⁺ imaging experiments are indirect indicators of NMDAR current and ligand binding assays often involve the use of membrane preparations that are by definition not at physiological membrane potential. Another issue that physiological conditions its voltage-dependent unbinding is the fact that recovery was observed in several cells but not others, the reason for which is unclear. Others also reported observing use-dependent recovery from MK-801 blockade using techniques such as radio-ligand binding and Ca²⁺ imaging (Reynolds and Miller, 1988; Yuzaki et al., 1990). However, we wanted to determine the influence of Mg²⁺ on the use-dependent recovery of NMDAR currents from MK-801. Mg²⁺ also binds the pore of the NMDAR, and under physiological conditions its voltage-dependent unbinding is essential for full channel activity. Moreover, Mg²⁺ has been reported to inhibit the binding of radiolabelled forms of MK-801 (Hubbard et al., 1989; Reynolds and Miller, 1988) suggestive of mutually antagonistic binding. Here we have revisited the issue of the stability of MK-801 blockade, focussing in particular on the extent to which NMDAR currents recover from MK-801 blockade under conditions of agonist exposure, both in the presence and absence of extracellular Mg²⁺.

2. Material and methods

2.1. Neuronal culture and assessment of cell death

Cortical rat neurons were cultured as described (Al-Mubarak et al., 2009; Soriano et al., 2009) at a density of between 9 and 13 × 10⁴ neurons per cm² from E12 rats with Neurobasal A growth medium supplemented with B27 (Invitrogen, Paisley, UK). Stimulations of cultured neurons were done in most cases after a culture period of 8–11 days during which neurons develop a network of processes, express functional NMDA-type and AMPA/kainate-type glutamate receptors, and form synaptic contacts (Padapai et al., 2008). To elicit an excitotoxic insult, neurons were first placed overnight into a minimal defined medium (Padapai et al., 2005) containing 10% MEM (Invitrogen), 90% Salt-Glucose-Glycine (SGG) medium (Badling et al., 1993); SGG: 114 mM NaCl, 0.219% NaHCO₃, 5.292 mM KCl, 1 mM MgCl₂, 2 mM CaCl₂, 10 mM HEPES, 1 mM Glycine, 30 mM Glucose, 0.5 mM sodium pyruvate, 0.1% Phenol Red; osmolarity 325 mosm/l, (Padapai et al., 2005)). NMDA and MK-801 were from Tocris Bioscience, Bristol, UK. To assess cell death, neurons were fixed and subjected to DAPI staining and cell death quantified by counting (blind) the number of shrunken, pyknotic nuclei as a percentage of the total.

2.2. Electrophysiological recording and analysis of MK-801 unblocking

Whole-cell NMDA-evoked currents in cultured rat cortical neurons were recorded using an Axopatch 200B amplifier (Molecular Devices) using patch-pipettes made from thick-walled borosilicate glass with a tip resistance of 4–8 MΩ, which were filled with an ‘internal’ solution that contained (in mM) potassium gluconate 141, NaCl 2.5, HEPES 10, EGTA 11; pH 7.3 with KOH. Experiments were conducted at room temperature (18–21 °C) in a Mg²⁺-free external/ACSF solution containing (in mM): NaCl 150, KCl 2.8, HEPES 10, CaCl₂ 2, glucose 10, EDTA 0.01; pH 7.3 with NaOH. Tetrodotoxin (300 nM) was included to block action potential-driven excitatory postsynaptic events. Whole-cell NMDA currents were elicited by bath perfusion of NMDA (100 µM, unless otherwise stated) in the presence of glycine (100 µM). Access resistances were monitored and, recordings where this changed by > 20% were discarded. Neurons were voltage-clamped at −60 mV. Currents were filtered at 2 kHz and digitized at 5 kHz via a BNC-2090A/PCI-6251 DAQ board interface (National Instruments, Austin, TX) and analysed using WinWdware software (Dr John Dempster, University of Strathclyde, Glasgow, UK). To pre-block all NMDARs, neurons were exposed to 100 µM NMDA in the presence of MK-801 (10 µM) except in Fig. 4b where 500 nM was used. The washout protocols for Figs. 1 and 2 involved constant perfusion of the neurons with media of different compositions (see legends). The washout protocol for Fig. 3 involved the transfer of coverslips containing neurons sequentially through 5 wells containing fresh medium (‘multi-well wash’). The washout protocols for Fig. 4 involved the multi-well wash but also a ‘one-well’ wash protocol whereby the neurons were washed with 5 sequential fresh medium changes within the same well. In Figs. 1 and 2, absolute measurements of MK-801 unblocking were determined by comparing whole-cell NMDA currents pre- and post-MK-801 blockade in a single neuron. In Fig. 3, the level of unblocking was estimated by comparing whole-cell currents post-washout to NMDAR currents in parallel sister coverslips that had not been subjected to MK-801 pre-blockade.

2.3. Induction of excitotoxicity

An approach similar to those previously reported was employed (Soriano et al., 2006). To induce neuronal death, neurons were exposed to NMDA (100 µM). To terminate NMDA activation MK-801 (10 µM) was added at the desired time point. Exposure to excitotoxic concentrations of NMDA or glutamate leads to neurons displaying swollen cell bodies and pyknotic nuclei with small irregular chromatin inclusions. Such characteristics are indicative of necrotic, as opposed to apoptotic, cell death (Marti et al., 2012). Assessment of cell death was made 24 h after exposure to NMDA by calculating the ratio of 4’, 6-diamidino-2-phenylindole-stained pyknotic nuclei as a percentage of the total nuclei.

3. Results and discussion

Whole-cell NMDAR currents were recorded at −60 mV prior to blockade of all NMDARs by the application of NMDA in the presence of MK-801. After MK-801 wash-out, the % recovery of NMDAR currents from MK-801 blockade was studied after 10 min exposure to various conditions. Consistent with previous studies, MK-801 blockade was stable in normal Mg²⁺-free ACSF: only 7% recovery was observed (Fig. 1a). Original studies showed that recovery from MK-801 blockade could be accelerated by NMDA (Huettner and Bean, 1988), i.e. that recovery is use-dependent. However, as stated in the Introduction, the large standard deviation for recovery time reflected the fact that recovery was observed in several cells but not others (potentially due to incomplete washout of MK-801). Others have also reported use-dependent recovery using techniques such as radio-ligand binding and Ca²⁺ imaging (Reynolds and Miller, 1988; Yuzaki et al., 1990). We observed that 10 min exposure to 100 µM NMDA promoted an approximate 20% recovery of NMDAR currents from MK-801 blockade (Fig. 1a), consistent with (Yuzaki et al., 1990) but contrary to the ligand binding study (Reynolds and Miller, 1988).

We next turned our attention to the influence of Mg²⁺ on the dissociation of MK-801 from NMDARs. Ligand binding studies have suggested that Mg²⁺ may accelerate its dissociation (Reynolds and Miller, 1988), however other studies (employing Ca²⁺ imaging approaches) have found no effect of Mg²⁺ (Yuzaki et al., 1990). We observed that 10 min exposure in 1 mM Mg²⁺-containing ACSF failed to promote appreciable recovery of NMDAR currents from MK-801 blockade (Fig. 1b), consistent with (Yuzaki et al., 1990) but contrary to the ligand binding study (Reynolds and Miller, 1988). We next investigated the effect of Mg²⁺ on NMDA-induced recovery from MK-801 blockade. Interestingly, Mg²⁺ strongly increased the level of MK-801 unblock in the presence of NMDA: 10 min exposure to 100 µM NMDA + 1 mM MgCl₂ led to recovery of around 50% of the original whole-cell NMDAR current (Fig. 1b). Thus, a combination of the channel in an open activated state, together with Mg²⁺, promotes recovery of NMDAR currents from MK-801 blockade. This is consistent with the long-held notion that MK-801 dissociation is only possible from an open NMDAR. However the effect of Mg²⁺ suggests a model whereby either Mg²⁺ promotes...
MK-801 dissociation or that, upon dissociation from its binding site in the pore, MK-801 is able to re-bind in a process antagonized by Mg$^{2+}$. The effect of Mg$^{2+}$ also raises the possibility that other NMDAR antagonists that act at this site could also promote the loss of MK-801 from an open receptor. We investigated this by replacing Mg$^{2+}$ in our MK-801 dissociation experiments with memantine, another "PCP site" antagonist. As in previous experiments, all NMDARs were pre-blocked by the application of NMDA in the presence of MK-801. After MK-801 wash-out, the % recovery of NMDAR currents from MK-801 blockade was studied after 9 min exposure to NMDA (+ memantine, followed by an additional minute to permit washout of memantine (which dissociates quickly from the NMDAR unlike MK-801 (Chen and Lipton, 1997; Parsons et al., 1995)). We found that, as was the case with Mg$^{2+}$ and in the presence of NMDA, memantine accelerated the recovery of NMDAR currents from MK-801 blockade (Fig. 1c). We conclude that when

**Fig. 1.** Both Mg$^{2+}$ and memantine accelerate recovery from MK-801 blockade of NMDARs in the presence of agonist (NMDA). A) Confirmation of agonist-dependent dissociation of MK-801 from NMDARs. Whole-cell NMDAR currents evoked by 100 µM NMDA were recorded, after which all NMDARs were blocked by co-application of NMDA + MK-801 (MK). Neurons were then held at -60 mV and continuously perfused for 10 min in ACSF ± NMDA (zero Mg$^{2+}$), after which whole-cell currents were once again recorded and expressed as a % of the original current. *p < 0.05, Student unpaired t-test (n = 8 Con, n = 9 NMDA). Examples traces are shown to the right. Scale bar = 5 s (x-axis), 200 pA (y-axis) here and throughout Fig. 1. B) Agonist-dependent recovery of NMDAR currents from MK-801 blockade is accelerated by Mg$^{2+}$. Neurons were subjected to exactly the same procedure as (A) except that the 10 min incubation period ± NMDA was carried out in Mg$^{2+}$-containing ACSF (1 mM MgCl$_2$). Dotted line shows the NMDA-induced unblocking level in the absence of Mg$^{2+}$. *p < 0.05, Student unpaired t-test (n = 7 Con, n = 8 NMDA). C) Agonist-dependent recovery of NMDAR currents from MK-801 blockade is accelerated by the antagonist memantine. Where indicated, memantine (Mem, 10 µM) was included in the 10 min recovery solution. *p < 0.05, Student unpaired t-test (n = 7 Con, n = 8 NMDA, n = 10 NMDA + memantine).

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MK-801 has dissociated from its site in the pore, that there is a finite chance that it rebinds its site rather than leave the pore entirely and further, that the effect of enhanced MK-801 unblock in the presence of either Mg$^{2+}$ or memantine is due to these channel blockers preventing the re-binding of MK-801.

The effect of Mg$^{2+}$ on NMDA-induced unblocking of the NMDAR can be visualized in real time by studying the effect of repeated applications of NMDA/Mg$^{2+}$ on NMDAR current in neurons pre-blocked by MK-801 (Fig. 2). Nine periods of 10 s exposures to 100 μM NMDA in zero Mg$^{2+}$ promotes some use-dependent recovery from MK-801 blockade, compared to ACSF alone (Fig. 2a,b). Because Mg$^{2+}$ is absent, the incremental increases in NMDAR currents as MK-801 dissociates can be visualized. In contrast, when this experiment was repeated in the presence of Mg$^{2+}$, the repeated NMDA applications did not elicit measurable currents because under voltage clamp at -60 mV, Mg$^{2+}$ blocks NMDARs even when they are free of MK-801. However, the extent of the recovery from MK-801 blockade becomes apparent when whole-cell currents are measured in the absence of Mg$^{2+}$: a 30% recovery from the MK-801 block was observed (Fig. 2c).

We next studied the influence of NMDA plus Mg$^{2+}$ on recovery of NMDAR currents from MK-801 blockade in unclamped neurons in culture. All NMDARs were pre-blocked by the addition of 100 μM NMDA + 10 μM MK-801 for 3 min, followed by five medium changes to remove MK-801, which involved transferring the coverslips sequentially along a row of 5 wells containing fresh medium. NMDA + Mg$^{2+}$ was then added to the neurons for either 30 min or 150 min, after which cells were patched and whole-cell currents recorded. We used a low, non-toxic concentration of NMDA (15 μM) because, even though this would likely promote a lower level of use-dependent unblocking, we wanted to ensure that the neurons would not die if MK-801 dissociated from a substantial proportion of NMDARs. We found that, after 30 min of exposure to 15 μM NMDA in the presence of Mg$^{2+}$, NMDAR currents had recovered to around half of that in control (non-pre-blocked) cells (Fig. 3a). After 150 min, currents were not significantly different from control.

**Fig. 2.** Illustration of the influence of repeated applications of NMDA + Mg$^{2+}$ on recovery from MK-801 blockade. Example traces further illustrating the agonist and Mg$^{2+}$-dependent recovery of NMDAR currents from MK-801 blockade. Following MK-801 pre-block of NMDAR currents, neurons were subjected to either a period of washout in ACSF + Mg$^{2+}$ (A) or to 9 × 10 s applications of NMDA + Mg$^{2+}$ (B, C), after which whole-cell currents were measured and the % recovery calculated. Scale bars refer to 25 s (x axis) and 400 pA (y axis). NM = NMDA; MK = MK-801; AC = ACSF.

**Fig. 3.** Studying the recovery of NMDAR currents from MK-801 in unclamped neurons. A) Where indicated, all NMDARs were pre-blocked by the addition of 100 μM NMDA + 10 μM MK-801. After extensive washing in which coverslips from all groups including those without pre-block were transferred 5 times into fresh media, the neurons were incubated for 30 min in Mg$^{2+}$-containing medium in the presence of a sub-toxic dose of NMDA (15 μM). After this period, NMDAR whole-cell currents were measured as previously. Currents were compared to levels recorded in neurons treated identically except that they were not subjected to MK-801 pre-block. *p < 0.05, Student unpaired t-test (n = 7 in all conditions). B) Neurons were treated as in (A) except that the incubation/washout period was for 150 min. *p < 0.05, Student unpaired t-test (n = 7 in all conditions).
that washing in multiple wells was potentially more thorough and because, while washing within the same well was easiest, we felt indicated, to 100 M
Where performed, washout involved 5 sequential fresh medium changes within the well
NMDARs were again pre-blocked by the addition of MK-801 for 150 min, after which all NMDARs were re-blocked by the addition of MK-801. 24 h after the commencement of the experiment, cells were fixed and cell death analysed.

This result indicates that if the above experiment was performed with toxic NMDA concentration, that sufficient unblocking of the NMDAR would take place to kill neurons. To study this, all NMDARs were again pre-blocked by the addition of 100 μM NMDA + 10 μM MK-801 for 10 min (Fig. 4a). Washout involved either five fresh medium changes within the same well (‘one-well’ washing), or the transfer of coverslips containing the neurons sequentially through a row of wells each containing fresh medium (‘multi-well’ washing). Different washout approaches were used because, while washing within the same well was easiest, we felt that washing in multiple wells was potentially more thorough and mirrored the electrophysiology experiments exactly. Following washout, NMDA was applied at 100 μM in the presence of Mg2+ for 150 min, after which more MK-801 was added (to terminate NMDA-induced activity). Cell death was assessed 24 h later to determine whether the period of NMDA/Mg2+ incubation was sufficient to cause enough dissociation of MK-801 from NMDARs to promote NMDAR-dependent cell death. Unlike in previous experiments, we did not compare NMDA/Mg2+ incubation to NMDA/zero Mg2+. This is because, while there would be less MK-801 unblocking in the absence of Mg2+, this smaller number of unblocked channels would pass more current than if Mg2+ were present, making it difficult to interpret any differences in levels of cell death in the presence vs. absence of Mg2+. We observed that in neurons where NMDARs were pre-blocked and MK-801 washout involved their transfer through five wells of fresh medium, a 150 min exposure of 100 μM NMDA/Mg2+ promoted NMDAR-dependent death in around 80% of neurons (Fig. 4a).

Thus, following pre-block of all NMDARs and after the thorough ‘multi-well’ wash procedure, MK-801 unblocks sufficiently in the presence of NMDA and Mg2+ over 150 min to kill neurons. Importantly, significant NMDA-induced cell death was not observed in the ‘one-well’ washing protocol, suggesting that this protocol may be less effective at removing all MK-801. Since MK-801 has a reported Kd of 3–30 nM (Berman and Murray, 1996; Reynolds and Miller, 1988; Wong et al., 1986), functionally relevant concentrations of MK-801 could remain even when washing leaves as little as 0.1% of the starting concentration (10 μM) behind. We reasoned that the ‘one-well’ washing protocol may be sufficient if the initial concentration of MK-801 used was reduced from 10 μM to a still-effective, but lower concentration. Thus, we repeated the experiment, using MK-801 to pre-block at 500 nM, rather than 10 μM (Fig. 4b). Under these conditions, MK-801 still effectively blocked NMDAR currents (data not shown) and prevented excitotoxicity when left in the well (Fig. 3b) but this time the ‘one-well’ washout protocol was effective in removing excess MK-801, and excitotoxicity due to MK-801 unblock was clearly observed (Fig. 4b). Collectively these experiments highlight how difficult thorough MK-801 wash-out is to achieve, potentially leading to erroneous neuroprotective effects if washout is imperfect. That said, if washout is thorough, it is clear that when all NMDARs are pre-blocked, MK-801 unblocking from NMDARs under conditions of agonist exposure occurs sufficiently over a 150 min timescale to cause cell death.

As stated in the Introduction, the very slow off-rate of MK-801 has been exploited to use-dependently selectively pre-block synaptic NMDARs, enabling the selective activation of extrasynaptic NMDARs following MK-801 washout. Tovar and Westbrook were among the first to use MK-801 to isolate extrasynaptic NMDARs (Tovar and Westbrook, 1999). Using autaptic micro-island cultures, they could stimulate action potential firing by brief depolarization of the neuron, resulting in an autaptic EPSC due to the trans-synaptic activation of synaptic AMPA and NMDARs. By stimulating autaptic EPSCs in the presence of MK-801, the authors were able to exploit the use-dependency of MK-801 to selectively block those NMDARs activated by the stimulation protocol. In other words, synaptic, but not extrasynaptic NMDARs became progressively blocked over the course of multiple stimulations. In order to selectively activate extrasynaptic NMDARs they exploited the very slow off-rate of MK-801: following open channel blockade of synaptic NMDARs, MK-801 was removed from the recording medium, leaving synaptic NMDARs blocked. Under these conditions, bath application of NMDA simply results in the activation of extrasynaptic NMDARs (Tovar and Westbrook, 1999). By combining this approach with other pharmacological tools the authors reported some differences in NMDAR subunit composition at synaptic vs. extrasynaptic locations (Tovar and Westbrook, 1999).
Other variations on this approach have been employed to selectively activate extrasynaptic NMDARs, using different initial methods to promote selective synaptic NMDAR stimulation. Examples include inducing action potential bursting in neuronal cultures with the GABA\(_A\) receptor antagonist bicuculline (Hardingham et al., 2002). We used this technique to show that selective chronic activation of extrasynaptic NMDARs results in rapid (seconds time-scale) perturbation of mitochondrial membrane potential, an early event in excitotoxicity which precedes and predicts cell death (Hardingham et al., 2002). Similar protocols have also used MK-801 with concurrent synaptic stimulation to isolate the extrasynaptic NMDA receptor pool in brain slices (Harris and Pettit, 2007).

An alternative to the bicuculline method is simply to allow spontaneous quantal release of glutamate to activate synaptic NMDARs by including TTX and zero Mg\(^{2+}\) blockade too literally.

Activation of extrasynaptic NMDARs results in rapid (seconds time-scale) perturbation of mitochondrial membrane potential, an early event in excitotoxicity which precedes and predicts cell death (Hardingham et al., 2002). Similar protocols have also used MK-801 with concurrent synaptic stimulation to isolate the extrasynaptic NMDA receptor pool in brain slices (Harris and Pettit, 2007).

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