POTASSIUM CURRENTS IN ISOLATED CA1 NEURONS OF THE RAT AFTER KINDLING EPILEPTOGENESIS

M. VREUGDENHIL* and W. J. WADMAN
Institute for Neurobiology, Faculty of Biology, University of Amsterdam, Kruislaan 320, 1098 SM Amsterdam, The Netherlands

Abstract—Daily tetanic stimulation of the Schaffer collaterals generates an epileptogenic focus in area CA1 of the rat hippocampus, ultimately leading to generalized tonic-clonic convulsions (kindling). Potassium currents were measured under voltage-clamp conditions in pyramidal neurons, acutely dissociated from the focus of fully kindled rats, one day and six weeks after the last generalized seizure. Their amplitude, kinetics, voltage dependence and calcium dependence were compared with controls. With Ca²⁺ influx blocked by 0.5 mM Ni²⁺, the sustained current (delayed rectifier) and the transient current (A-current) were not different after kindling. Calcium influx evoked an additional fast transient current component. This transient calcium-dependent current component was increased by 154%, but only immediately after the seizure. A second, slow calcium-dependent potassium current component was dependent on the intracellular calcium level, set by the pipette as well as on calcium influx. The peak amplitude of this slow calcium-dependent current was under optimal calcium conditions not different after kindling, but we found indications that either calcium homeostasis or the calcium sensitivity of the potassium channels was affected by the kindling process.

In contrast to the previously described enhancement of calcium current, kindling epileptogenesis did not change the total potassium current amplitude. The minor changes that were observed can be related either to changes in calcium current or to changes in intracellular calcium homeostasis.

In the kindling model of epileptogenesis, daily tetanization of an afferent pathway ultimately creates an epileptic focus in the stimulated area, with enhanced excitability and seizure susceptibility. In area CA1 of the rat hippocampus, about 25 tetanic stimulations of the Schaffer collateral/commissural fibres are sufficient to evoke generalized tonic-clonic seizures. Once the epileptic focus is established, this state of enhanced excitability persists for several months.

Neuronal excitability is determined by the specific set of voltage- and calcium-dependent ion conductances. Potassium currents play an important role in action potential repolarization and frequency adaptation, and they determine resting potential and firing rate. Even small changes in potassium conductance will affect neuronal excitability, and suppression of potassium currents can evoke epileptiform activity, as is shown in several acute models of epilepsy. The increased propensity of burst firing of CA1 pyramidal neurons, observed after kindling, could result from a reduced calcium-dependent potassium current.

In previous studies we have established that kindling epileptogenesis in the CA1 area is associated with an enhancement of high-voltage-activated (HVA) calcium current. We now want to assess whether this increase is specific for the calcium current or just part of a general increase in ion conductances. To this end, we firstly investigated the strictly voltage-dependent potassium currents after kindling.

CA1 pyramidal neurons were acutely isolated from the focal area of fully kindled rats and compared with cells from matched controls using the whole-cell voltage-clamp technique. In a first attempt to distinguish possible immediate effects of seizures from long-lasting changes, we measured the current one day as well as six weeks after the last of at least seven generalized seizures.

*To whom correspondence should be addressed.

Abbreviations: 4-AP, 4-aminopyridine; [Ca²⁺], intracellular free calcium concentration; CL, long-term control group; CS, short-term control group; EGTA, ethylene-glycol-bis(β-aminoethylether)-N,N,N',N'-tetraacetate; HEPES, N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid; HVA, high-voltage-activated; IₖA, A-current-like potassium current; IₖCa,f, fast calcium-dependent potassium current; IₖCa,s, slow calcium-dependent potassium current; IₖD, delayed rectifying potassium current; KS, short-term kindled group; LVA, low-voltage-activated; PIPES, piperazine-N,N'-bis(2-ethanesulphonic acid); TEA, tetraethylammonium.
EXPERIMENTAL PROCEDURES

Kindling procedure

Male Wistar rats (200–225 g, Harlan, The Netherlands) were implanted under pentobarbital anaesthesia (65 mg/kg) as described in detail previously. Stainless steel recording electrodes (60 μm diameter) were placed in the stratum pyramidale and the stratum radiatum of the dorsal hippocampus. A stimulation electrode was positioned in the Schaffer collateral/commisural fibre bundle. Half of the rats received, twice a day, a tetanic stimulation (200–300 μA, 50 Hz, 1 s, biphasic bipolar pulses of 0.1 ms) eliciting afterdischarges, which were monitored by electroencephalographic recordings and increased in duration with successive stimuli. Six rats that had experienced a minimum of seven class V seizures were selected for recording.

Potassium currents in the presence of Ni2+

Potassium currents can be evoked by a depolarizing potential step to 30 mV, following a conditioning voltage step of 300 ms at −120 mV (Fig. 1A; voltage protocol given in the inset). Application of 0.5 mM Ni2+ blocks the calcium current and consequently the component of the potassium current that depends on it.

In the presence of Ni2+, depolarizing potential steps of 400 ms from holding potential evoked a slowly activating sustained potassium current (Fig. 1B). The voltage dependence of current activation was determined by measuring its peak current amplitude (A_p) at different levels of depolarization (Fig. 2A, open squares; 12 cells from CS, measured with high-[Ca2+]i, in the pipette). The threshold for activation was around −35 mV. Equimolar substitution of 5 mM extracellular Na+ by 4-aminopyridine (4-AP) reduced A_p of the current evoked at 30 mV (1.4 ± 0.3 nA for 4-AP vs 1.9 ± 0.2 nA for control, n = 11, paired t-test, P < 0.05), while substitution with 10 mM tetraethylammonium (TEA) reversibly reduced A_p (1.4 ± 0.2 nA for TEA vs 2.0 ± 0.3 nA for control, n = 9, P < 0.05). This current resembles a delayed rectifier and will be indicated as I_{KD}.

When the depolarization was preceded by a short hyperpolarizing pulse (40 ms at −120 mV), an additional fast transient potassium current was evoked (Fig. 1C, voltage protocol C1). It was separated from I_{KD} by subtracting the current evoked by a protocol where hyper- and depolarization were separated by a 50 ms pulse at −50 mV, which allowed almost complete inactivation (voltage protocol C2). The threshold for activation of the isolated transient potassium current was around −40 mV (Fig. 2A, open triangles). It inactivated exponentially with a time constant (τ) of ~30 ms at 30 mV. The voltage-dependent removal of inactivation was determined for this current by varying the potential of the conditioning step between −50 and −150 mV (Fig. 2B, inset). Normalized amplitude as a function of conditioning potential (Fig. 2B, open triangles) was fitted by a Boltzmann equation: I(V)/I_{max} = 1 + exp{[(V - V_l)/(V_h - V_l)]}, where V_l is the potential of half-maximal inactivation and V_h proportional to the slope at V_h. V_h was −84 ± 4 mV and V_l was −12 ± 3 mV (n = 12). This transient current was highly sensitive to 5 mM 4-AP (1.0 ± 0.3 nA for 4-AP vs 3.5 ± 0.5 nA for control, n = 11, P < 0.001) and was insensitive to 10 mM TEA (3.2 ± 0.5 nA for TEA vs 3.0 ± 0.4 nA for control, n = 9, n.s.). This current resembles an A-current and will be indicated as I_{KA}.

When the depolarizations were preceded by a longer hyperpolarization (300 ms at −120 mV) and separated by a 50 ms pulse to −50 mV, to inactivate I_{KD}, we evoked a slow potassium current (Fig. 1D, voltage protocol D1). Subtraction of I_{KD} (voltage...
Potassium currents after kindling protocol D2) from this current isolated a potassium current that activates around \(-50\text{ mV}\) and slowly inactivates (\(t_i \approx 140\text{ ms}\) at 30 mV). Inactivation was described by a Boltzmann function with a \(V_{th}\) of \(-99 \pm 4\text{ mV}\) (\(n = 12\)) and \(V_c\) of \(-12 \pm 3\text{ mV}\) (Fig. 2B, open circles). The amplitude of this current was dependent on \([\text{Ca}^{2+}]_i\) set by the pipette as \(C_{S_h}\) differed from \(C_{S_0}\) (\(P < 0.01\); see Table 1). The current was highly sensitive to 10 mM TEA (1.7 \(\pm\) 0.2 nA for TEA vs 6.0 \(\pm\) 0.7 nA for control, \(n = 11\), \(P < 0.001\)) and insensitive to 5 mM 4-AP (4.6 \(\pm\) 0.6 nA for 4-AP vs 5.4 \(\pm\) 0.7 nA for control, \(n = 9\), n.s.). This current is a slow calcium-dependent potassium current \(^{1,2}\) and will be indicated as \(I_{K(Ca,s)}\).

The three potassium currents in the presence of \(\text{Ni}^{2+}\), \(I_{K,D}\), \(I_{K,A}\) and \(I_{K(Ca,s)}\), in cells obtained from short-term kindled rats, were compared with those from matched controls (Table 1) with either low (\(C_{S_h}\) vs \(C_{S_0}\)) or high-\([\text{Ca}^{2+}]_i\) (\(C_{S_h}\) vs \(C_{S_0}\)). Membrane capacitance \(C_m\) was given as a measure of cell surface. \(I_{K,D}\) and \(I_{K,A}\) were not different after kindling epileptogenesis. The \(A_p\) of \(I_{K(Ca,s)}\) was decreased by 38\%, but only when measured under high-\([\text{Ca}^{2+}]_i\) conditions. Voltage dependence of activation and inactivation of \(I_{K(Ca,s)}\) (Fig. 2) was not affected.

![Diagram](image_url)

**Fig. 1.** (A) Potassium currents in a CA1 pyramidal neuron from a control animal, under high-\([\text{Ca}^{2+}]_i\) conditions, evoked by a potential step of 400 ms to 30 mV, following a conditioning potential step of 300 ms to \(-120\text{ mV}\) (voltage protocol is given as an inset). Current evoked either in the absence (\(\text{Ca}^{2+}\)) or in the presence (\(\text{Ni}^{2+}\)) of 0.5 mM \(\text{Ni}^{2+}\) in the bath. B–D give potassium currents in the presence of \(\text{Ni}^{2+}\). (B) Sustained potassium currents (\(I_{K,D}\)) elicited by depolarizations to varying potential levels (voltage protocol is given as an inset).
Calcium influx-dependent potassium currents

Application of Ni²⁺ partially blocked the potassium current (Fig. 1A); subtraction gave the potassium current component that was dependent on calcium influx through voltage-dependent calcium channels.

The calcium influx-dependent component of $I_{K,D}$ was negligible and not further quantified.

The additional component of $I_{K,(Ca)}$ obtained by subtraction is given in Fig. 3A. Its kinetics and voltage dependence of inactivation are indistinguishable from those of $I_{K,(Ca)}$ evoked in the presence of Ni²⁺, suggesting that the additional calcium influx has enhanced the amplitude of a current already present (compare Figs 1D and 3A).

The additional calcium influx-dependent current component evoked with the protocol for $I_{K,A}$ is given in Fig. 3B. This very fast transient calcium-dependent potassium current will be called $I_{K(Ca,f)}$. Further analysis of its properties was carried out in 10 cells from KS, that had an amplitude larger than 1 nA. In comparison with $I_{K,A}$, the threshold for activation of $I_{K(Ca,f)}$ was $15 \text{mV}$ lower and activation was three times faster. Inactivation was almost five times faster, the voltage dependence was shifted slightly ($V_h$: $-92 \pm 1 \text{mV}$ for $I_{K(Ca,f)}$ vs $-85 \pm 2 \text{mV}$ for $I_{K,A}$).
Potassium currents after kindling

Table I. Peak amplitude and inactivation time constant of outward current evoked by a 400 ms potential step to 30 mV, measured with low-[Ca\textsuperscript{2+}]\textsubscript{i}, set by the pipette (I) or with high-[Ca\textsuperscript{2+}]\textsubscript{i} (h), in n cells with membrane capacitance C\textsubscript{m}.

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<th>CS\textsubscript{i}</th>
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Potassium currents in the presence of Ni\textsuperscript{2+}

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<td>I\textsubscript{(Ca,s)}</td>
<td>2.9 ± 0.3</td>
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Additional currents in the absence of Ni\textsuperscript{2+}

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<tr>
<td>I\textsubscript{(Ca,f)}</td>
<td>1.2 ± 0.2</td>
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Upper half of the table gives the current recorded in the presence of Ni\textsuperscript{2+}, lower half the current blocked by Ni\textsuperscript{2+}. Numbers are mean and S.E.M. for n cells obtained from control (CS) and kindled (KS) rats, one day after kindling. Students t-test probability is indicated as *P < 0.05; **P < 0.01; ***P < 0.001 for comparison between control and kindled, and as + for comparison between high- and low-[Ca\textsuperscript{2+}]\textsubscript{i} set by the pipette. Ap, peak amplitude; \( \tau \), inactivation time constant.

Calcium influx-dependent potassium currents after kindling

One day after kindling epileptogenesis, the calcium influx-dependent current component I\textsubscript{(Ca,f)} was increased in neurons from kindled rats, in particular with high-[Ca\textsuperscript{2+}]\textsubscript{i} in the pipette (lower part of Table I). Comparison of kinetics and voltage dependence of I\textsubscript{(Ca,f)} between control and kindled was hampered by the small amplitude in controls.

The calcium influx-related component of I\textsubscript{(Ca,f)} was also larger in the kindled group, but only when high-[Ca\textsuperscript{2+}]\textsubscript{i} solution was used in the pipette. No changes could be detected in voltage dependence of inactivation (\( V_h \): −100 ± 4 mV for KS\textsubscript{h} (n = 14) vs −100 ± 4 mV for CS\textsubscript{h} (n = 12), n.s.).

Long-term changes

For the interpretation of the kindling-related changes, it is important to know whether they persist and could therefore be related to the kindled state. We recorded potassium currents in animals that were not stimulated for six weeks after their last evoked...
class V seizure. Since the changes were only observed with high-[Ca\textsuperscript{2+}] in the pipette, we restricted the measurements to the condition of high calcium and unobstructed calcium influx. The amplitude of the total potassium current (I\textsubscript{K}; voltage protocol given in Fig. 1A) and the properties of the three current components I\textsubscript{KD}, I\textsubscript{KA} and I\textsubscript{K(Ca)} were summarized in Table 2. One day (KS\textsubscript{1}) and six weeks after kindling epileptogenesis (KL\textsubscript{6}), the properties of I\textsubscript{K}, I\textsubscript{KD} and I\textsubscript{K(Ca)} were the same as for controls. One day after kindling, the amplitude and kinetics of the current evoked with the I\textsubscript{KA} protocol (the sum of I\textsubscript{KA} and I\textsubscript{K(Ca,f)}) were changed in accordance with an increased proportion of I\textsubscript{K(Ca,f)} described above. None of the differences could be found in the long-term group, suggesting that they were transient and probably directly related to the evoked seizures, although no further information about the time course is available.

DISCUSSION

Voltage-dependent and calcium-dependent potassium currents were compared between cells acutely isolated from the hippocampal CA1 area in control rats and from fully kindled rats, one day and six weeks after the last evoked seizure. The main question to answer was whether these currents are changed after kindling epileptogenesis and whether the previously described enhancement of calcium current\textsuperscript{24} results in changes in calcium-dependent potassium currents.

Potassium current separation

The potassium currents were separated into four components on the basis of their specific voltage dependence of inactivation and their dependence on calcium influx.

The sustained component that could be evoked
The total potassium current (I_k) was separated into three components; the sustained (I_KD), the transient (I_KA) and the slow-inactivating component (I_KCaL). Numbers and symbols as in Table 1. Ap, peak amplitude; t_i, inactivation time constant; t_p, time to peak.

Changes in potassium currents after kindling epileptogenesis

The total potassium current, I_k, evoked in the absence of Ni^{2+} and the calcium-independent potassium currents, I_KA and I_KD, were not different after kindling epileptogenesis, which confirms the conclusions derived from the unchanged profiles of activity-dependent increases in extracellular potassium concentration and the unchanged action potential repolarization. It also implies that the kindling-induced HVA calcium current enhancement described in previous work was specific and not part of a general change of ion conductances. As a consequence of the calcium current enhancement, we expected an enhancement of calcium influx-related potassium currents after kindling. The fast transient calcium influx-related potassium current I_K(Ca, f) was increased one day after kindling, particularly when high-[Ca^{2+}] was used in the pipette. Since this change was not detected six weeks after kindling, it is most likely a consequence of the occurrence of afterdischarges and cannot underlie the enhanced excitability in the epileptic state. The difference in time course of the increase in I_K(Ca, f) and the long-lasting increase of the HVA calcium current made a direct relation unlikely and suggests the involvement of other factors related to calcium homeostasis. Alternatively, the transient increase in I_K(Ca, f) may be related to a transient increase in LVA calcium current amplitude observed after kindling (Faas G. C. et al., unpublished observations).

The proportion of the slow calcium-dependent potassium current I_K(Ca, o) that was related to calcium influx was increased after kindling epileptogenesis. However, the voltage-dependent and kinetic properties and the amplitude of I_K(Ca, o) measured under maximal Ca^{2+} conditions (Table 2), as well as under minimal Ca^{2+} conditions (low-[Ca^{2+}], Ni^{2+} present), were not affected by kindling epileptogenesis. This makes a reduction of maximal number of available channels unlikely, but rather suggests a change in the modulation of the potassium channels, either due to a change in their sensitivity to calcium, and/or to the calcium level they detect. Detailed experiments

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The transient component activated in the presence of Ni^{2+}, which required a brief hyperpolarization to remove inactivation, was identified as a delayed rectifier (I_KD), based on the activation threshold, the very slow kinetics, the moderate sensitivity to TEA and 4-AP, and the insensitivity to [Ca^{2+}]. The delayed rectifier is the major sustained conductance at depolarized levels and is important for spike repolarization. Its sensitivity to Ni^{2+} and the calcium-independent potassium current, which like I_KA required brief hyperpolarization to remove inactivation, was identified as an A-current, probably conducted by big potassium (BK) channels, based on its voltage dependence, its sensitivity to TEA and [Ca^{2+}], set by the pipette solution and to calcium influx-related potassium currents, I_KD, were not different after kindling epileptogenesis, which confirms the conclusions derived from the unchanged profiles of activity-dependent increases in extracellular potassium concentration and the unchanged action potential repolarization. It also implies that the kindling-induced HVA calcium current enhancement described in previous work was specific and not part of a general change of ion conductances. As a consequence of the calcium current enhancement, we expected an enhancement of calcium influx-related potassium currents after kindling. The fast transient calcium influx-related potassium current I_K(Ca, f) was increased one day after kindling, particularly when high-[Ca^{2+}] was used in the pipette. Since this change was not detected six weeks after kindling, it is most likely a consequence of the occurrence of afterdischarges and cannot underlie the enhanced excitability in the epileptic state. The difference in time course of the increase in I_K(Ca, f) and the long-lasting increase of the HVA calcium current made a direct relation unlikely and suggests the involvement of other factors related to calcium homeostasis. Alternatively, the transient increase in I_K(Ca, f) may be related to a transient increase in LVA calcium current amplitude observed after kindling (Faas G. C. et al., unpublished observations).

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investigating calcium homeostasis are necessary to clarify this point.

CONCLUSIONS

Long-lasting enhancement of cellular excitability, in concert with modulation of synaptic strength, could underlie the enhanced excitability of the local neuronal network, characteristic of the epileptic state induced by kindling.

The intrinsic neuronal excitability is determined by the balance between depolarizing and hyperpolarizing ion currents. We have now demonstrated that the long-lasting enhancement of calcium current amplitude after kindling epileptogenesis is rather specific and not compensated by changes in the potassium current. This may contribute to the enhanced intrinsic excitability and the increase in burst firing propensity of CA1 pyramidal neurons observed after kindling epileptogenesis. Part of the kindling-induced changes in calcium-dependent potassium currents can be attributed to the enhanced calcium influx, but we also obtained indications that either calcium homeostasis or the calcium sensitivity of the potassium channels are affected by kindling. A more detailed analysis of the time course of the changes in calcium-dependent potassium currents after kindling is necessary to elucidate their precise relation to the changes in calcium currents.

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