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Hyperpolarization-Activated Current $I_h$ Disconnects Somatic and Dendritic Spike Initiation Zones in Layer V Pyramidal Neurons

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Berger, Thomas, Walter Senn, and Hans-R. Lüscher. Hyperpolarization-activated current $I_h$ disconnects somatic and dendritic spike initiation zones in layer V pyramidal neurons. J Neurophysiol 90: 2428–2437, 2003. First published June 11, 2003; 10.1152/jn.00377.2003. Layer V pyramidal cells of the somatosensory cortex operate with two spike initiation zones. Subthreshold depolarizations are strongly attenuated along the apical dendrite linking the somatic and distal dendritic spike initiation zones. Sodium action potentials, on the other hand, are actively back-propagating from the axon hillock into the apical tuft. There they can interact with local excitatory input leading to the generation of calcium action potentials. We investigated if and how back-propagating sodium action potentials alone, without concomitant excitatory dendritic input, can initiate calcium action potentials in the distal dendrite. In acute slices of the somatosensory cortex, layer V pyramidal cells were studied under current-clamp with simultaneous recordings from the soma and the apical dendrite. A train of four somatic action potentials had to reach high frequencies to produce back-propagating action potentials in the axon hillock (back-propagation-activated calcium spike firing, BAC firing) (Larkum et al. 1999b). The resulting change in the output pattern of the cell from single spikes to bursts reflects the detection of simultaneous somatic and dendritic inputs.

The density of the hyperpolarization-activated current $I_h$ (Kaupp and Seifert 2001; Pape 1996) is higher in the distal apical dendrite of layer V pyramidal cells in comparison to the proximal region of the dendrite and the soma (Berger et al. 2001; Löhrncz et al. 2002; Williams and Stuart 2000a). $I_h$ leads to the attenuation of synaptic potentials and impairs their summation (Berger and Lüscher 2003; Berger et al. 2001; Williams and Stuart 2000a, 2002). In spite of the uneven distribution of this conductance, the apical dendrite of these cells behaves linearly in the subthreshold range (Berger et al. 2001) and the excitatory postsynaptic potential (EPSP) shape is primarily affected by the shunting effect of $I_h$. In addition, $I_h$ may modulate the back-propagation of sodium action potentials and thereby their ability to initiate BAC firing.

Layer V pyramidal cells receive synaptic input from different sources through different layers. This property puts layer V pyramidal cells into the unique position to associate concomitant bottom-up input to the soma and the basal dendrites on one side and top-down inputs to the distal apical dendrite on the other side. Simultaneous activation of the two inputs leads to BAC firing resulting in a burst of action potentials (Larkum et al. 1999b). To enable this associative mechanism, a high density of voltage-gated sodium and calcium channels is needed in the dendrite. This actively supports the back-propagation of action potentials in the dendrite and the generation of calcium spikes. To differentiate this mechanism from normal cell firing, activation of the somatic spike initiation zone alone should not initiate dendritic calcium action potentials. Under these conditions, a long “electrotonic distance” between the two zones is essential. The presence of leak conductances mediates by potassium channels or $I_h$ helps to disconnect both initiation zones in the subthreshold range (Berger et al. 2001). In the present work, we examined if $I_h$ prevents the generation of subthreshold depolarizations.
of supra-threshold calcium events in the distal dendrite due to somatic spikes.

METHODS

Brain slice preparation and cell identification

Three-hundred-µm-thick parasagittal slices of the somatosensory cortex were prepared from 28- to 37-day-old Wistar rats according to national and institutional guidelines. Preparations were done in ice-cold extracellular solution using a vibratome (Microslicer DTK-1000, Dosaka, Kyoto, Japan). Slices were incubated at 37°C for 30 mins and then left at room temperature until recording. Layer V pyramidal neurons from the somatosensory area with a thick apical dendrite were visualized by infrared differential interference contrast videomicroscopy using a Newvicon camera (C2400, Hamamatsu, Hamamatsu City, Japan) and an infrared filter (RG9, Schott, Mainz, Germany) mounted on an upright microscope (Axioskop FS, Zeiss, Oberkochen, Germany).

Electrophysiology and intracellular stimuli

Current-clamp whole cell recordings were made either from the soma alone or simultaneously from the soma and apical dendrite of layer V pyramidal neurons. An Axoprobe-1A amplifier (Axon Instruments, Foster City, CA) was used. Resistance compensation and capacitance neutralization were applied. In-vivo-like input currents were generated as an Ornstein–Uhlenbeck process (Cox and Miller 1965). These noisy currents are Gaussian distributed with mean μ, standard deviation σ, and a correlation length τ, and follow the equation

\[ I(t) = I(t) + (\mu - I(t))\frac{dt}{\tau} + \sigma G \sqrt{2dt/\tau} \]

\( G \) is a Gaussian random variable with mean 0 and SD 1. Such a current mimics a large number of asynchronously firing excitatory and inhibitory presynaptic cells. These contribute to the mean μ and variance σ² according to μ = \∫₀^∞ q(t) dt and σ² = \∫₀^∞ q(t)² dt - μ² (Tuckwell 1988). Here, \( q(t) \) represent the firing rates of the presynaptic excitatory and inhibitory population, respectively, and \( I_{\text{in}} \) are the peak amplitudes of a single excitatory and inhibitory postsynaptic current, respectively. These unitary currents are characterized by a sharp rise and an exponential decay with a time constant τ. The current amplitudes \( I_{\text{in}} \) are the product of the peak conductance times the driving force, \( I_{\text{in}} = g_{\text{Na}}(E_{\text{Na}} - V) \).

A total mean and SD of μ = σ = 400 pA, for instance, can be obtained with \( r_1 = 15,000 \) Hz, \( r_2 = 8,000 \) Hz, \( g_{\text{Na}} = 1 \) nS, \( g_{\text{K}} = 6 \) nS, \( E_{\text{Na}} = 0 \) mV, \( E_{\text{K}} = -70 \) mV, \( \tau = 3 \) ms, and a fixed membrane potential V = -55 mV. The total firing rates \( f_{\text{in}} \) are the product of the number of synapses times the firing rate of the individual excitatory or inhibitory afferent fibers (e.g., 5000 excitatory afferents each firing with a mean rate of 3 Hz, and 1000 inhibitory afferents each firing with a mean rate of 8 Hz) (compare Abeles 1991; Schüz and Palm 1989).

Electrodes were made from borosilicate glass tubing (Hilgenberg, Malsfeld, Germany). The resistance was 4–6 MΩ for somatic and 10–16 MΩ for dendritic recording pipettes. All experiments were done at ~34°C. Data were low-pass filtered at 5 kHz using the internal filter of the amplifier. The sampling frequency was at least twice the filter frequency (10–20 kHz). Data were digitized and stored on-line using either Clampex8 (Axon Instruments) or a custom-made, Matlab-based acquisition and analysis program (www.cns.unibe.ch/MecDuck). Data were analyzed off-line with Clampfit8 and Matlab. Pooled data are expressed as means ± SD.

Chemicals and solutions

Slices were continuously superfused with a physiological extracellular solution containing (in mM) 125 NaCl, 25 NaHCO₃, 2.5 KCl, 1.25 NaH₂PO₄, 2 CaCl₂, 1 MgCl₂, and 25 glucose, bubbled with 95% O₂/5% CO₂. Pipette solution contained (in mM) 110 K-gluconate, 30 KCl, 10 EGTA, 10 HEPES, 0.3 Na₃-ATP, and 10 Na₃-Phosphocreatine, pH adjusted to 7.3 with KOH. The membrane potential values given were not corrected for the liquid junction potential. 4-(N-ethyl-N-phenylamino)-1,2-dimethyl-6-(methylamino) pyridinium chloride (ZD7288) was a generous gift from Astra-Zeneca (Macclesfield, UK). A stock of 50 mM ZD7288 was prepared in bidistilled water. Dilution in the extracellular solution provided the final concentration given in the Results section. All other drugs and chemicals were from Sigma or Merck.

RESULTS

To study the separation properties of \( I_{\text{h}} \) with regard to the two spike initiation zones, we performed three sets of experiments. First, simultaneous somatic and dendritic recordings were used to determine the critical frequency (CF) of back-propagating action potentials for eliciting a dendritic calcium action potential. In addition, the dependence of the CF from the dendritic membrane potential was investigated. Second, the CF was determined in the presence of a blocker of the hypopolarization-activated current \( I_{\text{h}} \). Third, the possibility of the cells to generate calcium action potentials was studied with in-vivo-like, noisy current injections.

Dendritic calcium spike initiation requires a high somatic action potential frequency

Is it possible to activate the distal dendritic calcium spike initiation zone in response to proximal synaptic input and the resulting somatic sodium action potentials? We used a well-defined stimulation paradigm previously developed by Larkum et al. (1999a). Four consecutive action potentials were induced at different frequencies in the soma of layer V pyramidal cells with short supra-threshold somatic current injections (3–5 nA for 2 ms; \( V_{\text{m}} = -69.3 \pm 5.0 \) mV, \( R_{\text{m}} = 24.4 \pm 6.5 \) MΩ, \( n = 56 \) cells; Fig. 1A). The spikes back-propagated into the dendrite. Above a CF of the back-propagating action potentials, a calcium-mediated action potential was elicited in the dendrite (\( n = 22 \) combined somato-dendritic recordings; distance of the dendritic recording from the soma: 302 ± 92 µm). The presence of this dendritic calcium potential was also visible in the somatic recording as an additional afterdepolarization after the last spike (Figs. 1, A and B, 2A, and 3A). The calcium events were blocked by the combined bath application of 100 µM NiCl₂ and 200 µM CdCl₂ (\( n = 5 \) cells, Fig. 1B). This confirms the dependence of these events from the activation of voltage-gated calcium channels. Calcium action potentials were only present at high frequencies (CF = 104.5 ± 23.4 Hz; range: 55.5–166.7 Hz; \( n = 56 \) cells; Fig. 1D). The CF could also be defined using the integral below the voltage transient of the dendritic recording. This integral was plotted against the frequency of the somatic spikes (Fig. 1C), and it increased with frequency due to an improved temporal summation of the four dendritic action potentials. At the CF, a nonlinear increase reflected the activation of calcium conductances. With frequencies even higher than the CF, the integral decreased slightly. This could be explained by the relative refractory period of the sodium and calcium action potential at short inter-stimulus intervals (Figs. 1, A and C).

The CF was strongly modulated by the dendritic membrane potential. When four consecutive action potentials below the CF were combined with a depolarizing constant current injection
into the dendrite, calcium action potentials were seen ($n = 3$ cells of 3; Fig. 2A). These changes in the ability to generate dendritic calcium action potentials reflected a decrease in the CF. Additional hyperpolarizing current injection into the dendrite did not change the shape of the somatic or dendritic recording significantly. Dendritic calcium events evoked beyond the CF could be prevented by the injection of a hyperpolarizing constant current (Fig. 2B), while depolarizing current increased their amplitude slightly. Dendritic hyperpolarization led to an increase in the CF.

Thus combined somatic and excitatory dendritic activity decreased dramatically the amount of somatic activity necessary for dendritic calcium events.

$I_h$ increases critical frequency

Application of the specific $I_h$ blocker ZD7288 (20 μM) (Harris and Constanti 1995) reduces the CF to 68.2 ± 7.4% of control (78.4 ± 21.2 Hz; $P < 0.001$, paired $t$-test; $n = 11$ cells out of 11 tested; Fig. 3). To study the importance of neuro-modulation of $I_h$ via changes in the intracellular cAMP, we investigated the effect of different cAMP modulators. Bath application of serotonin (concentration range: 5–100 μM), isoproterenol (at concentrations of 1 and 10 μM), or dopamine (50 μM) did not influence the CF ($n = 12$ cells in total; not shown).

Blockade of $I_h$ resulted in marked changes of the action potential shape in the dendrite and a larger afterdepolarization in the soma. In four of five somatodendritic recordings, application of 20 μM ZD7288 reduced the amplitude of the first dendritic action potential (Fig. 4C). However, the action potential amplitude was not significantly changed over all cells (69.9 ± 36.5% of the control value; control: 23.0 ± 6.2 mV; in ZD7288: 15.9 ± 8.0 mV; $n = 5$ cells; Fig. 4). The decay of

FIG. 1. Backpropagating action potentials can induce dendritic calcium potentials only beyond a high critical frequency. Simultaneous recording from the soma and the dendrite of a layer V pyramidal cell (see sketch in the inset; scale bar in the inset: 400 μm). In all figures, the top traces represent the somatic, the bottom traces the dendritic recordings. A: 4 consecutive action potentials are induced in the soma with short supra-threshold somatic current injections (pattern on top). The spikes are back-propagating into the dendrite and can evoke a dendritic calcium action potential depending on their frequency. The presence of this dendritic calcium potential is also visible in the somatic recording as an additional afterdepolarization following the last spike (see arrow. B: in another cell, combined bath application of 100 μM NiCl2 and 200 μM CdCl2 prevented the generation of the dendritic calcium action potential and of the somatic afterdepolarization (dotted traces). Same scale bars in A and B. Rats P31 and P35, dendritic recordings 350 and 320 μm from the soma for A and B, respectively. C: the integral below the voltage transient of the dendritic recording reflecting the charge transferred is plotted against the frequency of the somatic spikes for the cell in A. A critical frequency (CF, arrow) of 125 Hz is obtained for the induction of a calcium spike. D: the CF from 52 cells is shown in a histogram.
the first dendritic action potential was fitted with a monoexponential function, yielding a decay time constant of 3.5 ± 1.2 ms under control conditions. Blocking \( I_h \) prolonged the dendritic action potential decay to values between 148 and 570% of control. The decay time of the calcium action potential could also be fitted with a monoexponential function (decay time constant under control: 5.9 ± 0.8 ms; under ZD7288: 10.0 ± 2.8 ms; 172.5 ± 52.0% of control; Fig. 4). This shortening of the dendritic calcium action potential with \( I_h \) was due to two factors: a change in the membrane time constant and the presence of an undershoot (Fig. 4, A and B; compare the \( I_h \)-induced undershoot during the decay phase of EPSPs; see Berger et al. 2001). Although the majority of the dendritic action potentials was smaller without \( I_h \), they could better summate due to their longer decay (Fig. 4, A and B). In addition, the longer depolarization may have facilitated the activation of voltage-gated calcium channels underlying the calcium action potential. In turn, the somatic spike without \( I_h \) was characterized by a reduced fast afterhyperpolarization and an enlarged afterdepolarization, while rise and decay were only minimally affected (Fig. 4C). The afterdepolarization became larger from the first to the fourth spike and this increase may be due to the longer and larger forward-propagated dendritic action potentials.

**FIG. 2.** Dendritic depolarization decreases, dendritic hyperpolarization increases the critical frequency. A: 4 consecutive action potentials with a spike frequency of 125 Hz cannot evoke calcium action potentials in the dendrite of this cell (continuous traces). If in addition to the generation of somatic spikes a depolarizing current (±250 pA) was injected into the dendrite, calcium action potentials were seen (dotted traces). B: in the same cell, 4 spikes with a frequency of 167 Hz resulted in a calcium action potential (continuous traces). Injection of a hyperpolarizing current (−250 pA) prevented these dendritic potentials (dotted traces). Same scale bars in A and B. Rat P33, dendritic recording 500 μm from the soma.

**FIG. 3.** High CF is due to the presence of \( I_h \). A: using the same experimental paradigm as in Fig. 1, a critical frequency of 125 Hz for the induction of dendritic calcium potentials is found in this cell. Somatic and dendritic recordings are aligned to the beginning of the 4th spike and are shown superimposed. Four action potentials are induced at (dotted traces) and below (continuous traces) the CF. B: application of 20 μM 4-((N-ethyl-N-phenylamino)-1,2-dimethyl-6-(methylamino) pyridinium chloride (ZD7288), a specific blocker of the hyperpolarization-activated current \( I_h \), results in a reduction of the CF to 7 Hz. Beyond the CF, additional somatic action potentials and concomitant dendritic calcium events can be seen (see arrows). Rat P33, dendritic recording 420 μm from the soma. C: for eleven cells, this shift in the CF due to block of \( I_h \) is shown (circles, control values of CF; rectangles, CF in 20 μM ZD7288).
have chosen a mean $\mu = 200$ or $400$ pA, a SD $\sigma = 400$ pA and correlation time constants $\tau = 1$–100 ms (see METHODS). This resulted in an overall spike frequency of $14.2 \pm 2.4$ Hz (in 2 cells with 10 realizations of 20 s) and a coefficient of variation of the inter-spike intervals (CV) between 0.5 and 1.72, depending on the correlation time constant $\tau$. Under control conditions, isolated action potentials (no further spike 15 ms before and after the actual one) or doublets were observed in the soma and the dendrite (Fig. 5A). Interestingly, calcium action potentials were only rarely seen ($n = 7$ calcium events within the total 200 s of current injection). To investigate the effect of $I_h$ onto the generation of calcium action potentials at similar rates of isolated action potentials, we injected an additional constant somatic current to compensate for the hyperpolarization caused by the blockade of $I_h$ ($\sim 200$–300 pA) (see Berger et al. 2001). Blocking $I_h$ with 20 $\mu$M ZD7288 markedly increased the number of bursts of somatic action potentials and the concomitant calcium events in the dendrite ($n = 157$ within 200 s of stimulation in 10 realizations; Fig. 5B). The average frequency of isolated action potentials was 10.4 Hz, compared with 10.2 Hz under control conditions. The overall action potential frequency including action potentials within bursts was 27.8 $\pm$ 10.4 Hz (10 realizations in 2 cells), and the CV increased to values between 0.81 and 2.05 (depending on the correlation

$I_h$ prevents the generation of calcium action potentials with in-vivo-like input

The four-spike-protocol used permitted us to study the relationship between calcium action potential generation in the dendrite and spike frequency in the soma under well-defined conditions. We wanted to further investigate what kind of proximal synaptic activity might activate dendritic calcium spikes under in-vivo-like input conditions. We therefore injected noisy, Gaussian-distributed currents with stationary statistics into the soma, which created the kind of membrane potential deflections seen in vivo. To mimic a realistic population of excitatory and inhibitory presynaptic neurons, we

FIG. 4. Blockade of $I_h$ results in a prolongation of the back-propagating dendritic action potential and an increased afterdepolarization of the somatic spike. Using the same experimental paradigm as in Fig. 1, 4 spikes are induced below ($f = 90$ Hz; A) and above ($f = 137$ Hz; B) the CF. The same protocol is used under control conditions (continuous traces) and under 20 $\mu$M ZD7288 (dotted traces). Somatic and dendritic recordings are aligned to the beginning of the 1st spike and are shown superimposed. Under ZD7288, the dendritic action potential becomes smaller and its decay is prolonged. Due to this prolongation, summation is improved and calcium action potentials can be induced. In addition, the afterdepolarization of the somatic spike is markedly increased. C: the 1st action potentials from A are displayed with an extended time scale showing the kinetic changes in greater detail. Rat P30, dendritic recording 280 $\mu$m from the soma. Membrane potential under control conditions and under ZD7288 (soma/dendrite): $-68/\sim 64$ mV and $-68/\sim 70$ mV, respectively (depolarizing current was injected to compensate the hyperpolarization due to $I_h$ blockade).

FIG. 5. $I_h$ prevents calcium action potentials under in-vivo-like conditions. Gaussian distributed currents (traces on top) are injected for 20 s into the soma of a pyramidal cell (mean current: 200 pA; sigma: 400 pA; correlation time constant: 3 ms; see METHODS) under control conditions (A) and with $I_h$ blocked (B). This resulted in noisy membrane potential deflections and irregularly distributed action potentials. A: under control conditions, single somatic spikes or pairs of spikes (doubles; middle traces) result in the corresponding dendritic action potentials (bottom traces). The peaks of the somatic and dendritic action potentials are marked by dots. Calcium action potentials are not seen. B: under $I_h$ blockade, bursts of somatic action potentials and the concomitant calcium action potentials in the dendrite are frequently seen. Rat P37, dendritic recording 420 $\mu$m from the soma. Overall frequency 16.1 Hz under control and 20.9 Hz in 20 $\mu$M ZD7288, respectively; coefficient of variation of the inter-spike intervals 0.88 under control and 0.96 in ZD7288, respectively.
The peak values of the dendritic action potentials were plotted against the inter-spike intervals before the corresponding somatic action potentials (Fig. 6). Under control conditions, the peak depolarizations were all <10 mV, reflecting the absence of dendritic calcium action potentials. Summation of spikes is only seen at brief inter-spike intervals (Fig. 6A). When $I_h$ was blocked, these short inter-spike intervals were sufficient to induce dendritic calcium action potentials. In addition, calcium action potentials were found with much longer somatic inter-spike intervals (Fig. 6B, dotted arrow). These belonged to action potentials generated during a dendritic calcium spike when the preceding inter-spike interval was largely irrelevant.

$I_h$ enhances the critical frequency by impairing the summation properties of back-propagating action potentials

We investigated the effect of $I_h$ on the generation of somatic bursts and dendritic calcium action potentials under in-vivo-like conditions. Only seven calcium action potentials were found under control conditions that were all triggered by a spike triplet in the soma (example shown in Fig. 7A). When blocking $I_h$, a current with the same statistical properties evoked 157 calcium action potentials. To study the mechanisms of this increased dendritic excitability, we extracted the somatic and dendritic voltage signals around the calcium action potentials (peaks of the dendritic membrane potential beyond ~10 mV). The dendritic membrane potentials and the corresponding somatic current injections were aligned at the peak depolarization after the first crossing of the ~10-mV threshold and averaged (calcium spike-triggered average; Fig. 7B). Within a time window of 20 ms before the peak, we found an average frequency of 170 Hz (3.4 spikes within the 20 ms preceding the dendritic voltage crossing of ~10 mV) under control conditions. The injected somatic current which triggered the calcium spikes reached in the average ~1200 pA immediately before the peak depolarization (Fig. 7B). When $I_h$ was blocked, the dendritic calcium events were longer (Fig. 7C). The calcium spike-triggered average under these conditions revealed a frequency of 140 Hz (2.8 spikes within the 20 ms preceding the dendritic voltage crossing of ~10 mV; 82% of control; $P = 0.15$, unpaired $t$-test; Fig. 7D). The corresponding injected current was smaller (~800 pA) and had its maximum 10 ms before the peak depolarization (Fig. 7D). Hence, under control conditions, only bursts with very high spiking frequency evoked dendritic calcium spikes.

To study the summation of the back-propagating action potential under in-vivo-like conditions, we constructed the sodium spike-triggered average of isolated spikes. As in the four-spike-paradigm, the average back-propagating action potential was narrower and larger in the presence of $I_h$ (Fig. 8A) in comparison to the situation when $I_h$ was blocked (Fig. 8B). The longer dendritic depolarization observed under ZD7288 caused an afterdepolarization in the soma, which in turn increased the probability of triggering subsequent spikes.
contrast to the currents necessary to evoke calcium action potentials, there was no difference in the currents necessary to evoke isolated action potentials with and without \( I_h \). To better reveal the effect of \( I_h \), we superimposed the somatic and dendritic action potentials (Fig. 8, C and D). The average amplitude and decay time constant of the back-propagating action potential was 22 mV and 2.3 ms, respectively, in the presence of \( I_h \), and 10 mV and 7.8 ms when \( I_h \) was blocked.

**DISCUSSION**

\( I_h \) increases the electrotonic distance between somatic and dendritic spike initiation zone

Coincident back-propagating somatic action potentials and distal dendritic EPSPs can result in calcium spike firing in the dendrite and bursts of action potentials in the soma (back-propagation-activated calcium spike firing, BAC firing) (Larkum et al. 1999b; Stuart and Häusser 2001). To ensure the associative capability of BAC firing, isolated somatic input alone should not trigger dendritic calcium spikes (but see Larkum and Zhu 2002 for the generation of calcium spikes using a train of four spikes initiated by locking, BAC firing). We studied the generation of dendritic calcium spikes using a train of four spikes initiated by separate current pulses with increasing frequency (Larkum et al. 1999a). When the spikes reach a CF (CF = 104.5 Hz; range: 55.5–166.7 Hz), dendritic calcium action potentials were seen that resulted in enlarged somatic afterdepolarizations. This CF value is identical to that found by Larkum et al. (1999a). In comparison, in vivo recordings in different cortical areas show in general much lower frequencies during tonic firing. Cortical regular spiking cells generated spikes at an overall frequency of 9.4 Hz in the awake state, whereas the spiking frequency increased to 11.8 and 14.0 Hz during slow wave sleep and REM sleep, respectively (nonanesthetized cat) (Steriade et al. 2001).
resistance in the distal dendrite and at the soma (Zhu 2000). \(I_h\) attenuates synaptic potentials traveling from the soma to the dendrite to a larger extent than those traveling in the opposite direction (Berger et al. 2001). The impact of \(I_h\) on the temporal properties of synaptic signals is even stronger: EPSPs are shortened markedly and summation of dendritic inputs is effectively impaired (Berger and Lüscher 2003; Berger et al. 2001; Williams and Stuart 2002).

What is the impact of \(I_h\) on dendritic calcium action potential generation due to somatic spike activity? Passive membrane properties of the dendrite increasingly determine the propagation of the action potential the further it progresses into the dendrite. The axial current in front of the action potential encounters a higher membrane resistance and consequently a longer membrane time constant if \(I_h\) is blocked. Therefore the dendritic action potential gets slower in rise and decay. Moreover, this slower kinetics may lead to an impaired activation of the remaining dendritic sodium channels and, as a consequence, to a reduction in dendritic action potential amplitude.

In a study on the importance of \(I_h\) channels for the integrative properties in the dendrites of CA1 pyramidal cells, Magee (1998) found also a shortening of the decaying phase of the dendritic action potential due to \(I_h\). In the present study, we found inhomogeneous effects of \(I_h\) blockade on the dendritic action potential amplitude while the decay became always longer. The dendritic spikes appeared more like an EPSP under ZD7288 (compare Berger and Lüscher 2003). Even with decreased dendritic spike amplitudes, the summation was better without \(I_h\) and this resulted in a decrease of the CF. In addition to the improvement of the summative properties of the dendrite, longer lasting back-propagating action potentials favor the opening of voltage-gated calcium channels (Markram et al. 1995). Low- and high-voltage-activated calcium channels activate more slowly than sodium channels, and their inactivation time constants are in the range of tens of ms (T-, N-, R-type) or they do not inactivate at all (L-, P-type). Their deactivation, in contrast, is very fast (Magee 1999). A smaller, depolarization due to a long dendritic spike will therefore be more efficient in the activation of calcium channels in comparison to high-amplitude, short events. Due to the mechanisms discussed in the preceding text, the \(I_h\) channels in layer V pyramidal cells with their fast kinetics have opposite effects on burst generation in comparison to \(I_h\) channels with slow kinetics like in thalamic relay neurons (time constants in the range of hundreds of ms; based on HCN-2 to -4 subunits) (Franz et al. 2000). These slow \(I_h\) channels interact with low-threshold calcium channels and thereby generate rhythmic oscillations of the membrane potential (McCormick and Pape 1990). \(I_h\) channels with relatively fast kinetics like in layer V pyramidal cells are in the position to prevent dendritic action potentials and consecutive burst firing.

\(I_h\) can be activated by intracellular cAMP, but there are strong differences in the cAMP sensitivity of the different HCN subunits assembling the \(I_h\) channels (Kaupp and Seifert 2001). We activated different transmitter systems, to increase the active \(I_h\) population and to study its role in the interaction between somatic spikes and dendritic calcium potentials. However, none of the neuromodulatory transmitters (serotonin, isoproterenol, or dopamine) tested over a broad range of concentrations changed the CF. This is possibly due to the presence of \(I_h\) channels constituted by HCN subunits with low...
cAMP sensitivity (e.g., HCN-1) in the layer V neocortical pyramidal cells. CA1 pyramidal cells lack also an effect of an increased intracellular cAMP level on \( I_h \) (Chen et al. 2001). Although layer V and CA1 pyramidal cells possess all four HCN subunits (single-cell PCR) (Franz et al. 2000), the HCN-1 subunit seems to reduce the cAMP sensitivity of the native channels in this cell type. Alternatively, the measurement of the CF may not be sensitive enough to reveal effects of the neuromodulators on \( I_h \) channels or the effect of the intracellular cAMP level on other conductances may have covered that one on \( I_h \).

\( I_h \) disconnects the two spike initiation zones under in-vivo-like conditions

The CF assessed with the four-spike-paradigm in the presence of \( I_h \) is very high, typically \( \approx 100 \) Hz. One may argue that four action potentials at such a high transient frequency are never found in vivo. However, in-vivo-like noisy currents as they may arise from a barrage of asynchronous excitatory and inhibitory synaptic inputs (Shadlen and Newsome 1998) can lead to spike doublets and triplets. If dendritic calcium spikes are meant to represent the binding mechanism between basal and apical input (Larkum et al. 1999b), it would be advantageous that somatic current voltage deflections alone should not be able to evoke dendritic calcium spikes by themselves. In fact, this is what we observed. Only in seven exceptional cases, when somatic spike triplets exceeded a frequency of \( \approx 170 \) Hz, was a calcium spike triggered in the dendrite. The corollary is that, when high-frequency burst are observed in vivo, they are most likely to indicate the simultaneous input to the proximal and distal regions of the cell. The situation changed dramatically when \( I_h \) was blocked. Plenty of dendritic calcium spikes \((n = 157)\) emerged at a comparable frequency of isolated spikes \((\approx 10 \) Hz). When \( I_h \) was blocked, less input current is needed to evoke calcium action potentials. We conclude that \( I_h \) efficiently separates the somatic and dendritic initiation zones preventing the proximally located inputs from generating dendritic spikes alone.

Despite the depolarization caused by the noisy current injection, the effect of \( I_h \) is not abolished. This is remarkable because a steady depolarization from \(-65 \) to \(-55 \) mV would decrease the active population of \( I_h \) channels by roughly one half (see Berger et al. 2001). The mechanism by which \( I_h \) disconnects the two spike initiation zones is identical to that revealed by the four-spike-paradigm: the presence of \( I_h \) reduces the dendritic membrane time constant and shortens the back-propagating action potentials in the dendrite. The shortening of the dendritic action potential has two effects: it diminishes the afterdepolarization of the somatic action potential, thereby reducing the probability for a spike doublet or triplet, and it prevents the summation of the back-propagating action potentials necessary to trigger dendritic calcium spikes.

The slower back-propagating action potential is a direct consequence of the reduced dendritic leak with blocked \( I_h \) (Fig. 8D). The concomitant reduction in amplitude, however, cannot be explained by purely passive properties. Because \( I_h \) contributes as an additional leak to the total dendritic conductance, \( g_D = g_{\text{leak}} + g_h \), the dendritic amplitude should increase when this conductance is blocked. This is because in a purely passive model a somatic voltage oscillation with frequency \( \omega \) appears to be attenuated in the dendrite by a factor \( \alpha = 1/\sqrt{1 + g_{\text{leak}} R_T^2} \), where \( R_T \) is the total transfer resistance. The formula confirms that with a passive dendrite a decreased conductance \( g_D \) increases the dendritic voltage response evoked by a somatic voltage deflection. The reduced amplitude of the back-propagating action potential observed under blockade of \( I_h \) (Figs. 4 and 8D) must therefore be caused by active, voltage-dependent dendritic conductances. A slower rise time of the back-propagating action potential activates less sodium channels because these may inactivate during the slower rising phase. As confirmed by simulations, a slower rise time leads to a markedly reduced amplitude, provided the inactivation time constant of the sodium channels is in the range of the activation time constant (see e.g., Rhodes and Llinás 2001). Active dendritic processes are also revealed by the bi-exponential decay of the back-propagating action potential in the presence of \( I_h \), as opposed to the smaller amplitude and mono-exponential decay without \( I_h \) (Fig. 4).

The summation properties of back-propagating action potentials are dominated by the decay phase not the amplitude of the individual dendritic potentials. In fact, the summated dendritic spikes within a high-frequency train may show a smaller peak depolarization in the presence of \( I_h \), despite the fact that the individual amplitudes are larger (Fig. 4). The increased dendritic leak caused by \( I_h \) speeds up the dendritic time constant, and this produces a faster and higher back-propagating action potential. Despite the fact that \( I_h \) leads to a boosting of the dendritic amplitude, however, it shortens the width and impairs the summation property of the back-propagated action potential. The impaired summation prevents the generation of dendritic calcium spikes by somatic input alone. This mechanism actively disconnects the two spike initiation zones and is therefore an important ingredient for layer V pyramidal neurons to restrict the association properties to joint somatic and distal dendritic input.

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DISCLOSURES

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