Decreased hyperpolarization-activated currents in layer 5 pyramidal neurons enhances excitability in focal cortical dysplasia

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Albertson AJ, Yang J, Hablitz JJ. Decreased hyperpolarization-activated currents in layer 5 pyramidal neurons enhances excitability in focal cortical dysplasia. J Neurophysiol 106: 2189–2200, 2011. First published July 27, 2011; doi:10.1152/jn.00164.2011.—Focal cortical dysplasia is associated with the development of seizures in children and is present in up to 40% of intractable childhood epilepsies. Transcortical freeze lesions in newborn rats reproduce many of the anatomical and physiological characteristics of human cortical dysplasia. Rats with freeze lesions have increased seizure susceptibility and a region of hyperexcitable cortex adjacent to the lesion. Since alterations in hyperpolarization-activated nonspecific cation (HCN) channels are often associated with epilepsy, we used whole cell patch-clamp recording and voltage-sensitive dye imaging to examine alterations in HCN channels and inwardly rectifying hyperpolarization-activated currents (I_h) in cortical dysplasia. (L5) pyramidal neurons in lesioned animals had hyperpolarized resting membrane potentials, increased input resistances and reduced voltage “sag” associated with I_h activation. These differences became nonsignificant after application of the I_h blocker ZD7288. Temporal excitatory postsynaptic potential (EPSP) summation and intrinsic excitability were increased in neurons near the freeze lesion. Using voltage-sensitive dye imaging of neocortical slices, we found that inhibiting I_h with ZD7288 increased the half-width of dye signals. The anticonvulsant lamotrigine produced a significant decrease in spread of activity. The ability of lamotrigine to decrease network activity was reduced in the hyperexcitable cortex near the freeze lesion. These results suggest that I_h serves to constrain network activity in addition to its role in regulating cellular excitability. Reduced I_h may contribute to increased network excitability in cortical dysplasia.

HCN channel; epilepsy; I_h; voltage-sensitive dye

FOCAL CORTICAL DYSPLASIA is associated with the development of seizures in children (Krasek et al. 2009) and is present in up to 40% of intractable childhood epilepsies (Leventer et al. 2008). Current antiepileptic drugs are often ineffective in these patients (Mathern et al. 1999), leading to surgical treatment (Sisodiya 2000). Brain slices prepared from human dysplastic cortex display abnormal synaptic connections and increased excitability (Cepeda et al. 2006). Transcortical freeze lesions in the newborn rat (Dvorak and Feit 1977; Dvorak et al. 1978) reproduce many of the anatomical and electrophysiological characteristics of human focal cortical dysplasias (DeFazio and Hablitz 1998; Jacobs et al. 1996, 1999a, 1999b, 1999c; Luhmann and Raabe 1996). Such lesions also increase susceptibility to complex hyperthermic seizures (Scantlebury et al. 2004). Reduced inhibition (Zhu and Roper 2000) and alterations in glutamate receptors (DeFazio and Hablitz 2000) and transporters (Campbell and Hablitz 2008) have been shown to contribute to hyperexcitability in cortical dysplasia, possibly interacting with local changes in connectivity (Jacobs and Prince 2005) to further increase excitability. Although abnormalities in several voltage-dependent currents have been implicated in epilepsy (Avanzini et al. 2007; Becker et al. 2008; Catterall et al. 2008), changes in intrinsic excitability in cortical dysplasia have not been extensively investigated.

Hyperpolarization-activated, nonselective cation (HCN) channels are encoded by four mammalian genes, termed HCN1–4. Distinct patterns of activation and inactivation and varying sensitivities to cyclic nucleotides are displayed by each subunit (Santoro et al. 2000; Wainger et al. 2001). Depending on the cell type and brain region, the inwardly rectifying hyperpolarization-activated current I_h contributes to generation of rhythmic activity (McCormick and Pape 1990), determination of the resting membrane potential (Robinson and Siegelbaum 2003), and synaptic integration (Magee 2000; Berger et al. 2001). Alterations in I_h and HCN expression occur in a variety of seizure models including kainic acid- and pilocarpine-induced epilepsy (Jung et al. 2007; Shin et al. 2008), early-life hyperthermia (Chen et al. 2001), temporal lobe kindling (Powell et al. 2008), and absence seizures (Kole et al. 2007; Schridde et al. 2006; Strauss et al. 2004). HCN1 subunit-specific knockout mice have a reduced seizure threshold (Huang et al. 2009), whereas HCN2 knockout mice exhibit an absence epilepsy phenotype (Ludwig et al. 2003). Paradoxically, hyperexcitability has been associated with both up- and downregulation of HCN channels (reviewed by Dyhrfjeld-Johnsen et al. 2009). Modifications in I_h have not been examined in cortical dysplasia.

Despite the relatively well-characterized role of I_h in cellular excitability, its contribution to network activity is not well understood. Maturation of rhythmic slow-wave sleep activity patterns is dependent on the density and the properties of I_h during development (Kanyshkova et al. 2009). Working memory networks are strengthened by inhibition of HCN channel signaling in prefrontal cortex (Wang et al. 2007). Theta activity in hippocampus (Hu et al. 2002; Marcelin et al. 2009; Xu et al. 2004) and subthreshold oscillations in entorhinal cortex (Dickson et al. 2000) are disrupted by I_h blockers. The timing of interictal bursts in the neonatal rat hippocampus is positively modulated by I_h (Agmon and Wells 2003). The contribution of I_h to network hyperexcitability in cortical dysplasia has not been established. In the present study, we have used whole cell patch-clamp recordings and voltage-sensitive dye imaging to determine the effect of HCN channel alterations on intrinsic excitability of individual cells and activity in local circuits.
Results suggest that $I_h$ contributes significantly to the normal pattern of spread of activity across the cortical mantle. Decreases in $I_h$ in cortical dysplasia augment network excitability, possibly contributing to the hyperexcitability seen in malformed cortex.

**METHODS**

**Animals.** All experiments were performed in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals with protocols approved by the University of Alabama at Birmingham Institutional Animal Care and Use Committee. Every effort was made to minimize pain and discomfort. Focal freeze lesions were induced in postnatal day (PN)1 Sprague-Dawley rats. In brief, newborn rat pups were anesthetized by hypothermia, and a small incision was made to expose the skull. A 2-mm copper rod cooled to approximately $-50^\circ$C was placed on the surface of the skull for 3 s. Sham-operated animals received similar treatment without cooling of the probe. After the scalp was sutured, the animals were warmed and returned to their home cage. Rats were allowed to recover for 21–27 days before recordings were made.

**Preparation of in vitro brain slices.** Rats were anesthetized and decapitated. The brain was quickly removed and placed in ice-cold cutting solution consisting of (in mM) 135 Na-methyl-d-glucamine, 1.5 KCl, 1.5 KH$_2$PO$_4$, 23 choline HCO$_3$, 0.4 ascorbic acid, 0.5 CaCl$_2$, 3.5 MgCl$_2$, and 25 t-glucose (Tanaka et al. 2008). The solution was bubbled with 95% O$_2$-5% CO$_2$ to maintain a pH around 7.4. Coronal brain slices (300 µm thick) were cut with a vibratome (Microm, Walldorf, Germany). Slices were obtained from an area of somatosensory neocortex containing the microgyrus in freeze-lesioned animals and a corresponding location in sham-operated control animals. The slices were stored for 40–60 min at 37°C in oxygenated recording solution containing (in mM) 124 NaCl, 2.5 KCl, 10 t-glucose, 26 NaHCO$_3$, 2.0 Ca$^{2+}$, and 2.0 Mg$^{2+}$ and then kept at room temperature. For recording, individual slices were transferred to a recording chamber and continuously perfused (4 ml/min) with oxygenated recording solution.

**Whole cell recording.** A Zeiss Axioskop FS (Carl Zeiss, Thornwood, NY) microscope, equipped with Nomarski optics, a 40× water immersion lens, and infrared illumination, was used to view neurons immersed in recording saline at a rate of 4 ml/min for at least 30 min before recording in order to wash out excess dye. A bipolar stimulating electrode was positioned intracortically in middle cortical layers. Activity was evoked with single shocks 40–100 µA in amplitude and 190 µs in duration. A hexagonal photodiode array containing 464 diodes (Neuroplex, Red Shirt Imaging, Fairfield, CT) was used to detect activity-dependent changes in fluorescence. Excitation of the dye was achieved with a stabilized power supply (Hewlett-Packard, Palo Alto, CA), a 100-W halogen lamp, and a 535 ± 40-nm filter. The emitted light passed through a 590-nm long-pass filter. Optical signals were amplified and stored on a computer for later analysis. The resting light intensity measured for each diode was used to normalize fluorescent measurements. Correction for dye bleaching was done by using measurements taken in the absence of stimulation. All optical signals are represented as changes in fluorescence with stimulation divided by resting fluorescence (∆F/∆F$_{0}$, where F is the fluorescence measured in the absence of stimulation and ∆F is the change in fluorescence following stimulation). Responses to three stimulations were averaged. RH 414 responds to membrane depolarization with a decrease in fluorescence. This is plotted as an upward deflection in all figures. Using fixed scaling for individual figures, pseudocolor images were generated to visualize spatiotemporal patterns of activity in the slice. A digital image of the slice in the recording chamber was taken with a CCD camera attached to a dissecting microscope in order to

![Fig. 1. L5 pyramidal neurons from freeze-lesioned rats have depolarized membrane potentials ($V_m$) and increased input resistances ($R_{in}$). A: the resting $V_m$ of pyramidal neurons near the freeze lesion is significantly hyperpolarized compared with sham-operated control animals. This difference is not significant after hyperpolarization-activated nonspecific cation (HCN) channel inhibition with ZD7288. B: the $R_{in}$ of pyramidal neurons near the freeze lesion is significantly higher than that of sham-operated control animals. This difference is not significant after HCN channel inhibition. * $P < 0.05$](http://jn.physiology.org/doi/10.1152/jn.01229.2010)
document the position of the photodiode array with respect to cortical layers.

Data analysis. For analysis of changes in amplitude and duration of dye signals, a region of interest containing 18 diodes showing significant dye signals before drug application was selected. The peak amplitudes and half-widths of these responses were compared before and during drug administration. To examine changes in spread of activity, the number of diodes showing peak signal amplitudes three times the baseline noise levels was determined. The baseline noise level was determined from 10 diodes that exhibited no obvious activity. A two-way ANOVA was used for statistical comparison, with differences being considered significant if \( P < 0.05 \). Data are expressed as means ± SE.

Drugs. Drugs were stored in frozen stock solution and dissolved in the recording solution prior to each experiment. After recording control responses, drugs were bath applied for 20 min. Lamotrigine and ZD7288 were obtained from Tocris Bioscience (Ellisville, MO).

RESULTS

Membrane properties of L5 pyramidal neurons. To observe the impact of \( I_h \) changes on L5 pyramidal neurons, we obtained somatic whole cell patch-clamp recordings from 22- to 28-day-old sham-operated and lesioned animals. Recordings in lesioned animals were obtained 1–2 mm lateral to the lesion. Consistent with a reduction in the expression level of \( I_h \), the somatic resting membrane potential (\( V_m \)) in L5 pyramidal neurons was more hyperpolarized in slices from lesioned (−76.5 ± 1.0 mV, \( n = 24 \)) than sham-operated (−73.8 ± 0.9 mV, \( n = 26 \); \( P < 0.05 \)) animals (Fig. 1A, left). Furthermore, L5 pyramidal neurons in slices from lesioned animals had a significantly larger somatic input resistance (\( R_{in} \)) (lesioned: 77.4 ± 4.2 MΩ, \( n = 24 \); sham-operated: 64.9 ± 3.7 MΩ, \( n = 26 \); \( P < 0.05 \)) (Fig. 1B, left). These differences in membrane properties were no longer significant after bath application of the \( I_h \) channel blocker ZD7288 (10 μM) (\( V_m \): lesioned −79.1 ± 1.4 mV; sham operated −78.5 ± 0.81 mV; \( R_{in} \): lesioned 92.3 ± 6.5 MΩ; sham operated 85.6 ± 5.3 MΩ), suggesting that the initial differences arose from alterations in \( I_h \) expression (Fig. 1, A and B, right).

When neurons exhibit a prominent \( I_h \), hyperpolarizing current pulses evoke a voltage response that reaches a peak and then “sags” back toward rest (Berger et al. 2001; Maccaferri et al. 1993; Sutor and Hablitz 1993). Figure 2A shows responses to a series of hyperpolarizing current pulses in an L5 neuron from a sham-operated animal. Sag responses were prominent. When the same currents were applied to a neuron from a lesioned animal, sag responses were reduced (Fig. 2B), indicating a decreased \( I_h \). For example, when a current pulse of −400 pA was employed, the sag response was 2.26 ± 0.3 mV (\( n = 9 \)) in control animals and 1.91 ± 0.2 mV (\( n = 9 \)) in lesioned animals. These differences were statistically signifi-
cant ($P < 0.05$, 1-way ANOVA). At the end of the current pulse, the smaller deactivating $I_h$ in cells from lesioned animals led to a smaller rebound depolarization. With a $-400$ pA current pulse, rebound amplitudes were $1.99 \pm 0.2$ and $1.26 \pm 0.2$ pA in control and lesioned animals, respectively. The differences between control and lesioned animals were significant ($P < 0.05$, 1-way ANOVA). A summary plot of the changes in responses to hyperpolarizing current pulses is shown in Fig. 2C. It can be seen that that sag responses (Fig. 2C, left) and rebound depolarizations (right) were significantly reduced in neurons from lesioned animals.

**Intrinsic excitability changes in L5 pyramidal neurons.** The changes described above, a more hyperpolarized $V_m$ and an increased $R_{in}$ make it difficult to predict the net effect on intrinsic excitability of L5 neurons (Dyrhøj-Johansen et al. 2009). We therefore examined the relationship between somatic current injection and AP firing in neurons from sham-operated and lesioned animals. At least 5 min after a whole cell recording was obtained, cells were stimulated, at their resting potential, with $500$-pA depolarizing current pulses. Figure 3A, top left, shows a typical response in a neuron from a sham-operated animal. The depolarizing current pulse evoked a train of action potentials. In L5 pyramidal neurons from lesioned animals (Fig. 3B, top right), the number of action potentials was significantly higher than in sham-operated animals (lesioned: $9.8 \pm 0.4$ spikes/pulse, $n = 9$; sham operated: $5.6 \pm 0.4$ spikes/pulse, $n = 9$; $P < 0.05$) despite the fact that $V_m$ was more hyperpolarized. When $10 \mu M$ ZD7288 was bath applied, the number of action potentials in the sham-operated neuron was markedly increased, whereas the cell from the lesioned animal showed a smaller increase. A summary plot of the results from a group of cells is shown in Fig. 3C. It can be seen that neurons from lesioned animals are more excitable under baseline conditions. This difference was no longer significant in the presence of ZD7288 (lesioned $12.4 \pm 0.9$ spikes/pulse; sham operated $11.3 \pm 0.8$ spikes/pulse, $n = 9$; $P > 0.05$). These results suggest that decreased $I_h$ in neurons from lesioned animals results in increased intrinsic excitability of L5 pyramidal cells.

**Voltage-clamp analysis of $I_h$.** Somatic voltage-clamp recordings were performed to examine $I_h$ currents. Cells were held at $-50$ mV in the presence of TTX ($1 \mu M$). Voltage steps $500$ ms in duration were given from $-50$ to $-130$ mV in $10$-mV increments to activate $I_h$ currents. ZD7288 ($10 \mu M$) was then bath applied to block HCN channels. Currents evoked after a $10$-min perfusion with ZD7288 were subtracted from control to obtain the ZD7288-sensitive current. Specimen records of ZD7288-sensitive currents from a sham-operated animal are shown in Fig. 4A. The ZD7288-sensitive currents recorded in a neuron from a lesioned animal were significantly smaller in amplitude (Fig. 4B). Currents began to activate around $-200$ mV. When the membrane potential was held at $-120$ and $-130$ mV, $I_h$ currents showed a significant decrease in lesioned compared with sham-operated animals. [holding potential ($V_h$) = $-120$ mV: sham operated $298.1 \pm 23$ pA ($n = 9$), lesioned $230.6 \pm 22$ pA ($n = 9$), $P < 0.05$; $V_h$ = $-130$ mV: sham operated $342.6 \pm 25$ pA, lesioned $262.1 \pm 27.2$ pA, $P < 0.05$]. However, because of space-clamp errors, which result in the incomplete control of dendritic membrane potential, it is likely that these somatic voltage-clamp data underestimated the HCN channel conductance, in particular, at more hyperpolarized potentials. The higher $R_{in}$ in lesioned animals is expected to reduce this potential confound. Currents evoked at $-130$ mV were fitted to single exponential functions to determine activation time constants. There were no significant differences between sham-operated and lesioned groups [sham operated: $24.7 \pm 4$ ms ($n = 9$), lesioned $29.6 \pm 4$ ms ($n = 9$); $P > 0.05$]. This value is in the range for $I_h$ in thalamic neurons (Santoro et al. 2000), hippocampal interneurons (Santoro et al. 2000), and neocortical pyramidal cells (Williams and Stuart 2000) and is consistent with mediation by HCN1–HCN2 subunits.

**Alterations in excitatory postsynaptic potential temporal summation.** During a train of evoked excitatory postsynaptic potentials (EPSPs) in L5 pyramidal neurons, summation is reduced or prevented by the presence of $I_h$ (Berger et al. 2001). To determine whether the observed $I_h$ decreases in lesioned animals altered synaptic integration, distal EPSPs were evoked by a bipolar stimulating electrode positioned 150–200 $\mu M$ above the recording pipette. A train of five stimuli at 20 Hz was used to evoke EPSPs in L5 neurons. As shown in Fig. 5, sublinear temporal summation was observed in neurons from both sham-operated and lesioned animals under control conditions. When the ratio of the amplitude of the fifth to the first EPSP in the train (EPSP5/EPSP1) was calculated, a significantly increased ratio was observed in the lesioned group [sham operated $1.7 \pm 0.2$ ($n = 26$), lesioned $2.3 \pm 0.2$ ($n = 26$); $P < 0.05$]. This value is in the range for studies examining $I_h$ in thalamic neurons (Santoro et al. 2000), hippocampal interneurons (Santoro et al. 2000), and neocortical pyramidal cells (Williams and Stuart 2000) and is consistent with mediation by HCN1–HCN2 subunits.

![Fig. 3. L5 pyramidal neurons from freeze-lesioned rats have increased intrinsic excitability.](http://jn.physiology.org/)

*A* recordings showing a somatically evoked train of action potentials in a neuron from a sham-operated animal (top). In the same cell during bath application of ZD7288, $V_m$ is hyperpolarized and the number of action potentials is increased (bottom). *B*; records obtained from a pyramidal neuron near a lesion. The same current injection resulted in a greater number of spikes under control conditions (top). After ZD7288, $V_m$ and number of evoked action potentials are virtually unchanged. *C*; summary graphs showing difference in number of action potentials (APs) between sham-operated and lesioned animals before (left) and during (right) ZD7288. The difference in AP number is not significant after $I_h$ inhibition. *$P < 0.05$.*
The effect of $I_h$ blockade on synaptic activation was further examined with the use of ZD7288 (10 \mu M). In the presence of the $I_h$ channel blocker, temporal summation during the EPSP train was significantly increased in both sham-operated and lesioned groups. However, in the presence of ZD7288, the groups were no longer statistically different from each other (sham operated 3.28 ± 0.4, lesioned 3.35 ± 0.4 mV; $P > 0.05$). These results suggest that dendritic $I_h$ is reduced but not abolished in the lesioned animals.

Spatiotemporal spread of activity in dysplastic cortex. Multi-electrode field potential recordings of paroxysmal discharges in freeze-lesioned cortex have demonstrated propagation over long distances in the horizontal direction (Jacobs et al. 1996; Luhmann and Raabe 1996). Voltage-sensitive dye studies of evoked activity in normal neocortex have shown that the time courses of dye signals are similar to those of locally recorded field potentials. Dye signal responses peak rapidly (Yuste et al. 1997) and spread horizontally over relatively short distances (Langenstroth et al. 1996). Using voltage-sensitive dye imaging, we have shown that spread of activity in lesioned animals was greater in upper cortical layers in the paramicrogyral area relative to sham-operated control animals (Bandyopadhyay and Hablitz 2006). More persistent activation of local cortical circuits was also seen in dysplastic cortex. Experiments described below examine the role of $I_h$ in regulating spread of activity in dysplastic neocortex.

The voltage-sensitive dye RH 414 and optical imaging were used to quantify how alterations in $I_h$ modify spatiotemporal patterns of activity. The hexagonal photodiode array used for this purpose covered an area of $1.8 \times 1.8$ mm of the slice at the magnification (×10) used. Figure 6A shows the typical positioning of the photodiode array over the neocortex. The arrow indicates the location of the stimulating electrode. Figure 6B shows the typical position of the array over slices from lesioned animals. The small arrow shows the location of the microgyrus. Four stimulus intensities were tested in each slice (40, 60, 80, and 100 \mu A). A typical pseudocolored voltage-sensitive dye response is shown superimposed on an image of the cortex in Fig. 6C. Examples of individual diode responses from a slice from a sham-operated animal are shown in Fig. 6D. Fluorescence changes had a rapid rising phase and a slower decay (Fig. 6D).

Stimulation in slices from sham-operated control animals evoked responses near the site of stimulation with subsequent
vertical and horizontal spread. Figure 7A is a montage of 20 pseudocolor maps showing the spatial distribution of dye signals (ΔF/F) at given points in time. The first panel displays activity 2–5 ms after stimulation, and additional panels are shown at 3-ms intervals. Warm colors represent larger-amplitude dye signals, i.e., high levels of activity. The pial surface is up in each panel. Activity first spread to more superficial layers and then laterally. When the same stimulation intensity was used in a slice from a lesioned animal, activity rapidly spread across large portions of the superficial layers and was more persistent (Fig. 7B), as described previously (Bandyopadhyay and Hablitz 2006). To quantify these results, the average peak amplitude from selected diodes (see METHODS) and the number of diodes activated (indicative of activity spread) were determined. Peak amplitudes and the number of diodes activated were significantly increased at all stimulus intensities in slices from lesioned animals (Fig. 7C; P < 0.05, 2-way ANOVA).

$I_h$ and spread of activity. $I_h$ has significant effects on dendritic excitability and attenuation of EPSPs in L5 pyramidal cells (Berger et al. 2001; Day et al. 2005; Williams and Stuart 2000). Blockade of $I_h$ results in enhanced temporal summation (Berger et al. 2001) and increased dendritic calcium action potential generation (Tsuy et al. 2007). Given these changes, it was reasoned that $I_h$ blockade should result in enhanced spatiotemporal spread of activity.

The spatiotemporal distribution of evoked activity from a sham-operated animal under control conditions is shown in Fig. 8A. The first panel shows activity ~2–5 ms after stimulation. Subsequent panels show responses at 3-ms intervals.

Responses following application of the HCN channel blocker ZD7288 (10 μM) are shown in Fig. 8B. Activity was seen to persist longer in the presence of ZD7288. Pseudocolor scaling was the same for all conditions. Superimposed dye signals from three different diodes under control conditions and in the presence of ZD7288 are shown in Fig. 8C. Response half-widths were significantly increased when the $I_h$ blocker was present at all stimulation intensities (Fig. 8D). We did not observe a significant difference in the effect of ZD7288 on response half-width between lesioned and control animals (P > 0.05, 2-way ANOVA). We also observed a slight decrease in response amplitude following 20 min of ZD7288 that did not differ between lesioned and control animals (data not shown). ZD7288 did not significantly change the number of diodes activated (indicating spread of activity) in either group.

Anticonvulsant drugs such as lamotrigine (Peng et al. 2010; Poolos et al. 2002) and gabapentin (Surges et al. 2003) have been shown to enhance $I_h$. The effect of enhancing $I_h$ on network behavior has received little attention. We therefore tested the effect of bath application of lamotrigine (100 μM) on spatiotemporal spread of activity in neocortical slices. A montage of 20 pseudocolored maps under control conditions is shown in Fig. 9A. Activity 2–5 ms after stimulation is shown in the first panel. Panels are subsequently shown at 2.5-ms intervals. Figure 9B shows responses to the same stimulation 20 min after bath application of lamotrigine (100 μM). Lamotrigine altered the spatiotemporal pattern of evoked neocortical activity. When individual responses before and after lamotrigine were superimposed, a decrease in amplitude was observed (Fig. 9, C and D). Lamotrigine also decreased the number of diodes activated (indicating spread of activity) (Fig. 9E). Additionally, we observed a small, but significant, de-
crease in diode half-width after lamotrigine (data not shown). This is in contrast to the increase observed after ZD7288.

Lamotrigine is known to have effects on ion channels other than \( I_{\text{h}} \) (Thompson et al. 2011). We therefore tested the effect of lamotrigine when applied in the presence of ZD7288. Figure 9, D and E, show that lamotrigine had a significantly reduced effect on the amplitude of voltage-sensitive dye signals and number of diodes activated, respectively, in the presence of ZD7288 (\( P < 0.05 \), 2-way ANOVA). This suggests that a significant portion of lamotrigine’s effect on network activity is mediated via an action on \( I_{\text{h}} \).

The effects of lamotrigine on response amplitude in slices from sham-operated and lesioned animals are summarized in Fig. 10. In both groups, bath application of lamotrigine produced a significant reduction in amplitude at all intensities (\( P < 0.05 \), 2-way ANOVA) (Fig. 10A). The effect of lamotrigine on response amplitude was significantly decreased in lesioned compared with control animals (\( P < 0.05 \), 2-way ANOVA). The effect of lamotrigine on the number of diodes activated is shown in Fig. 10B. A significant decrease was observed in the number of diodes reaching threshold levels of activation was also observed in both groups. Again, this effect was significantly reduced in the lesion group (\( P < 0.05 \), 2-way ANOVA). A decrease was observed in the ability of lamotrigine to reduce half-width in lesioned animals compared with control animals.

We also examined the ability of lamotrigine to alter the \( I_{\text{h}} \)-dependent voltage sag and rebound (as seen in Fig. 2) in control and lesioned animals. Lamotrigine significantly (\( P < 0.05 \), 2-way ANOVA) increased both the voltage sag (−250 pA injection, 1.48 ± 0.82 mV increase, \( P < 0.05 \)) and rebound depolarization (−250 pA injection, 1.31 ± 0.86 mV increase, \( n = 7; P < 0.05 \)) in neurons from control animals. Lamotrigine did not have a significant effect on \( I_{\text{h}} \)-dependent voltage sag or rebound in neurons in dysplastic cortex (sag: −250 pA current injection, −0.29 ± 0.6 mV change, \( P < 0.05 \); rebound: −0.27 ± 0.8 mV change, \( n = 7, P < 0.05 \)). The lack of a significant effect of lamotrigine on sag and rebound in lesioned animals further suggests that animals with freeze lesions have reduced \( I_{\text{h}} \). This reduction may contribute to the reduced effectiveness of lamotrigine in constraining network activity in lesioned animals.

**DISCUSSION**

In the present study, we used whole cell patch-clamp recording and voltage-sensitive dye imaging to examine alterations in HCN channels and \( I_{\text{h}} \) in the rat freeze-lesion model of cortical dysplasia. L5 pyramidal neurons in lesioned animals demonstrated hyperpolarized resting membrane potentials, increased \( R_{in} \), and a reduction in the voltage “sag” associated with \( I_{\text{h}} \) activation. Temporal EPSP summation and intrinsic excitability were increased in neurons near the freeze lesion. These differences became nonsignificant after application of the \( I_{\text{h}} \) blocker ZD7288. Furthermore, we demonstrated a role for \( I_{\text{h}} \) in
constraining network activity, finding that this effect was reduced in dysplastic cortex.

$I_h$ changes in epilepsy. Alterations in $I_h$ have been described in several animal models of epilepsy. A progressive, persistent downregulation of dendritic HCN channels is seen in the rat pilocarpine model of epilepsy (Jung et al. 2007). Rats with pilocarpine-induced epilepsy exhibit increases in input resistance and dendritic excitability. A reduction in $I_h$ and increased dendritic EPSP summation also have been observed after status epilepticus induced by kainic acid (Shin et al. 2008). Similarly, the spontaneously epileptic WAG/Rij rat exhibits reduced $I_h$ associated with increased $R_m$ and enhanced synaptic summation (Kole et al. 2007; Strauss et al. 2004). Perinatal seizures induced by hypoxia are also accompanied by a downregulation of $I_h$ (Zhang et al. 2006). The present study indicates that reductions in $I_h$ associated with increases in cellular excitability and enhanced EPSP summation are found in a nonchemically induced malformation epilepsy model. This suggests that persistent $I_h$ downregulation associated with increased excitability may be a pervasive finding in many types of epilepsy.

Genetic reduction in HCN channels is strongly associated with epilepsy. HCN2 knockout animals exhibit spontaneous absence-type seizures (Ludwig et al. 2003), whereas HCN1 knockouts have enhanced seizure susceptibility (Huang et al. 2009). Additionally, Apathetic mice, which possess spontaneously truncated HCN2 channels, display an absence epilepsy phenotype (Chung et al. 2009). Whereas our findings suggest a decrease in $I_h$ as one potential mechanism for hyperexcitability in cortical dysplasia, increases in $I_h$ have been reported to produce increased excitability in a febrile seizure model (Chen et al. 2001). Although differential effects on $I_h$ may occur depending on the initial insult, it appears that proper network function can be perturbed by up- or downregulation of HCN channels.

$I_h$ has a well-characterized role in regulating dendritic excitability. $I_h$ activation increases resting membrane conductance, depolarizes the resting membrane potential, and decreases dendritic excitability (Magee 1998; Poolos et al. 2002; Robinson and Siegelbaum 2003). In the present study, L5 pyramidal neurons

Figure 8. HCN channel inhibition increases the duration of evoked network activity. A: typical network response evoked before HCN channel inhibition in a control animal. $B$: the same response after HCN channel inhibition with 10 μM ZD7288. $C$: responses from individual diodes before (blue) and after (red) HCN channel inhibition are shown superimposed. HCN channel inhibition increased the half-width of these responses. $D$: bar graphs showing that $I_h$ inhibition increases the duration of evoked activity in both control and lesioned animals.
from lesioned animals have significantly reduced \( I_h \), increased \( R_{in} \), and hyperpolarized \( V_m \). Despite the membrane hyperpolarization, depolarizing current pulses of the same amplitude elicited more spikes from neurons near the lesion compared with sham-operated controls. This counterintuitive inhibitory effect of \( I_h \) on action potential firing in the sham-operated group has previously been attributed to HCN channels active at the resting membrane potential decreasing \( R_{in} \) (Poolos et al. 2002; Robinson and Siegelbaum 2003). In addition to changes in intrinsic excitability, \( I_h \) blockade also enhances temporal summation of distal excitatory inputs (Magee 1999; Williams and Stuart 2000). Our observed increase in EPSP summation coupled with enhanced intrinsic excitability may be an underlying mechanism contributing to the hyperexcitability seen in dysplastic cortex. HCN channels are highly expressed in the apical dendrites of L5 pyramidal neurons (Lorincz et al. 2002), where they regulate excitability (Berger et al. 2001). Somatic recordings, like those employed here, do not faithfully reproduce dendritic \( I_h \) (Day et al. 2005). Changes observed at the somatic level are nonetheless informative since they can potentially influence neuronal output. Spike initiation in L5 pyramidal neurons occurs in the distal portion of the axon initial segment (Palmer and Stuart 2006). Somatic membrane potential changes resulting from alterations in dendritic \( I_h \) could influence action potential generation. Our results indicate that, despite the presumptive dendritic localization of HCN channels in L5 pyramids, \( I_h \) modulates \( V_m \), intrinsic excitability, and synaptic responses at the somatic level.

Presynaptic HCN channels have been reported in hippocampus (Aponte et al. 2006; Bender et al. 2007; Notomi and Shigemoto 2004), brain stem (Cuttle et al. 2001), and entorhinal cortex (Huang et al. 2011). Such presynaptic channels have been reported to affect both GABA (Aponte et al. 2006; Southan et al. 2000) and glutamate (Huang et al. 2011) release. If present in neocortex, presynaptic HCN channels would increase the repertoire of mechanisms whereby HCN channels could influence network excitability.

The factors responsible for \( I_h \) alterations in cortical dysplasia are unclear. A single seizure episode can decrease \( I_h \) (Shah et al. 2004), and long-term downregulation of total \( I_h \) has previously been shown to occur independent of repeated seizure

Fig. 9. Effects of the anticonvulsant lamotrigine on evoked network activity. A: typical network response evoked in a control animal before lamotrigine. B: response to the same stimulation 20 min after application of lamotrigine. C: responses from individual diodes before (blue) and after (red) lamotrigine. D: lamotrigine (LTG) reduced the amplitude of diode responses in control animals. This effect was significantly attenuated by coapplication of ZD7288 (ZD). E: lamotrigine reduced the number of diodes activated (indicating spread of activity) in control animals. This effect was also significantly attenuated by coapplication of ZD7288.
activity in the pilocarpine model of epilepsy (Jung et al. 2007). Although spontaneous seizures are not typically seen in the freeze-lesion model, increases in synaptic activity have been observed (Jacobs and Prince 2005) and high-frequency stimulation is known to downregulate $I_h$ in CA1 pyramidal neurons (Campanac et al. 2008). Increased extracellular glutamate levels have been shown to be present in dysplastic cortex (Campbell and Hablitz 2008). In cultured hippocampal neurons, activation of AMPA and NMDA receptors is capable of acutely augmenting HCN1 surface expression while diminishing channel trafficking (Noam et al. 2010). It is currently unclear whether the observed decreases in $I_h$ are activity dependent or result from the initial cortical injury.

Regulation of activity in local circuits by $I_h$. Although numerous studies have characterized the role of $I_h$ in regulating the excitability of individual neurons (George et al. 2009; Magee 1998; Rosenkranz and Johnston 2006; Williams and Stuart 2000), the functional outcome on network activity has received less attention. The ability of $I_h$ to constrain synaptic excitability suggests that $I_h$ also could serve to restrict activity across networks of neurons. Using voltage-sensitive dye imaging to quantify cortical circuit organization and dynamics, we have found significant changes in network activity in sham-operated animals following either $I_h$ blockade or enhancement, effects that were altered in dysplastic cortex. As previously reported, intracortical stimulation elicited synchronized, horizontally restricted areas of activity extending from L1 to L5 (Bandyopadhyay and Hablitz 2006; Kubota et al. 1999; Yuste et al. 1997). In the presence of ZD7288, activity persisted significantly longer. A similar increase in half-width has previously been described for distally evoked EPSPs in single cells (Williams and Stuart 2000). It is tempting to hypothesize that the network effect of ZD7288 is simply due to a net increase in the time constant of EPSPs. Enhancement of $I_h$ with the anticonvulsant lamotrigine decreased response half-width, dampened network excitability, and reduced the spatio-temporal spread of activity.

The ability of the anticonvulsant lamotrigine to constrain network activity was significantly reduced in lesioned animals. This suggests that the ability of $I_h$ to constrain network activity in dysplastic cortex was reduced. We did not observe a similar decrease in the ability of ZD7288 to enhance the duration of activity. The hyperexcitability in dysplastic cortex, the low concentration of ZD7288 used, remaining $I_h$, and variability in epileptiform events may mask subtle alterations in the ability of ZD7288 to enhance the duration of network activity. Although HCN staining is prominent in L5 pyramidal neurons, $I_h$ have been reported in L2/3 pyramidal cells (Strauss et al. 2004; Sutor and Hablitz 1993) and GABAergic neurons (Wu and Hablitz 2005). How $I_h$ properties in these cells are altered in cortical dysplasia has not been established.

The decrease in HCN channel staining (Hablitz and Yang 2010), total $I_h$, and accompanying voltage sag observed in the freeze-lesioned animals is associated with increases in synaptic integration and intrinsic excitability. These changes are mimicked in sham-operated control animals when $I_h$ is blocked. This includes increased summation, increased spiking following current injection, as well as decreased membrane conductance. We also observed greatly increased network activation following electrical stimulation. Decreased $I_h$ may contribute to the excitability changes observed in cortical dysplasia and malformation epilepsy. Blockade of $I_h$ increased the duration of network activity, whereas enhancement of $I_h$ limited the spread of network activity. The ability of the anticonvulsant lamotrigine to limit network activity was significantly reduced in freeze-lesioned rats. These novel observations lead us to hypothesize that $I_h$ serves to constrain network activity in addition to its role in constraining cellular excitability. Reduced $I_h$ in rats with cortical malformations may contribute to the increased network excitability.

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Fig. 10. Sensitivity of network activity to lamotrigine. A: the ability of lamotrigine (LTG) to decrease voltage-sensitive dye signal amplitude was significantly reduced in lesioned animals (open bars). B: the ability of lamotrigine to reduce the spread of the voltage-sensitive dye signal was significantly reduced in lesioned animals (open bars).
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DISCLOSURES
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