Migraine is the most common neurological condition, affecting 10% to 20% of the population. Stroke is a major cause of death and disability worldwide. An intriguing association between migraine and stroke is well established. Epidemiological studies identified migraine with aura as an independent factor increasing stroke risk by >2-fold. The relative risk is particularly high in otherwise healthy young adults without cardiovascular risk factors. The prevalence of migraine is on par with that of other known stroke risk factors. Spreading depression (SD), an intense depolarization that underlies migraine aura, also occurs in peri-infarct tissue as an overlapping mechanism between migraine and stroke.

Indirect evidence implicates enhanced cerebral excitability in common migraine, as well as in familial hemiplegic migraine (FHM). FHM1 mutations enhance CaV2.1 channel open probability, presynaptic calcium influx and cortical glutamate release, and render the brain hyperexcitable. As a result, FHM1 mutations markedly enhance SD susceptibility. Underscoring the importance of SD in migraine and stroke, transgenic mice expressing FHM1 mutations exhibit faster onset of anoxic depolarization (AD) and rapid infarct growth linked to higher frequency of PIDs during experimentally induced focal cerebral ischemia.

Background and Purpose—Migraine with aura is an established stroke risk factor, and excitatory mechanisms such as spreading depression (SD) are implicated in the pathogenesis of both migraine and stroke. Spontaneous SD waves originate within the peri-infarct tissue and exacerbate the metabolic mismatch during focal cerebral ischemia. Genetically enhanced SD susceptibility facilitates anoxic depolarizations and peri-infarct SDs and accelerates infarct growth, suggesting that susceptibility to SD is a critical determinant of vulnerability to ischemic injury. Because chronic treatment with migraine prophylactic drugs suppresses SD susceptibility, we tested whether migraine prophylaxis can also suppress ischemic depolarizations and improve stroke outcome.

Methods—We measured the cortical susceptibility to SD and ischemic depolarizations, and determined tissue and neurological outcomes after middle cerebral artery occlusion in wild-type and familial hemiplegic migraine type 1 knock-in mice treated with vehicle, topiramate or lamotrigine daily for 7 weeks or as a single dose shortly before testing.

Results—Chronic treatment with topiramate or lamotrigine reduced the susceptibility to KCl-induced or electric stimulation-induced SDs as well as ischemic depolarizations in both wild-type and familial hemiplegic migraine type 1 mutant mice. Consequently, both tissue and neurological outcomes were improved. Notably, treatment with a single dose of either drug was ineffective.

Conclusions—These data underscore the importance of hyperexcitability as a mechanism for increased stroke risk in migraineurs, and suggest that migraine prophylaxis may not only prevent migraine attacks but also protect migraineurs against ischemic injury. (Stroke. 2015;46:00-00. DOI: 10.1161/STROKEAHA.114.006982)

Key Words: cortical spreading depression ■ lamotrigine ■ middle cerebral artery occlusion ■ migraine ■ prophylaxis ■ stroke ■ topiramate

Migraine Prophylaxis, Ischemic Depolarizations, and Stroke Outcomes in Mice

Katharina Eikermann-Haerter, MD*; Jeong Hyun Lee, PhD*; Nilufer Yalcin, MD; Esther S. Yu, BS; Ali Daneshmand, MD; Ying Wei, MD; Yi Zheng, PhD; Anil Can, MD; Buse Sengul, MD; Michel D. Ferrari, MD, PhD; Arn M.J.M. van den Maagdenberg, PhD; Cenk Ayata, MD

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From the Neurovascular Research Laboratory, Department of Radiology, Massachusetts General Hospital, Harvard Medical School, Charlestown (K.E.-H., J.H.L., N.Y., E.S.Y., A.D., Y.W., Y.Z., A.C., B.S., C.A.); Department of Neurology (M.D.F., A.M.J.M.v.d.M), and Department of Human Genetics, Leiden University Medical Centre, The Netherlands (A.M.J.M.v.d.M); and Stroke Service and Neuroscience Intensive Care Unit, Department of Neurology, Massachusetts General Hospital, Harvard Medical School, Boston (C.A.).

Current address for J.H.L.: Division of Drug Discovery Research, Korea Research Institute of Chemical Technology, Korea.

*Drs Eikermann-Haerter and Lee are joint first authors and are listed in alphabetical order.

Correspondence to Cenk Ayata, MD, Stroke and Neurovascular Regulation Laboratory, Massachusetts General Hospital, 149 13th St, Room 6403, Charlestown, MA 02129. E-mail cayata@partners.org

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Chronic treatment with widely prescribed migraine prophylactic drugs of various pharmacological classes dose-dependently suppresses SD susceptibility in rats as a possible mechanism of action. The majority of these drugs, however, are ineffective after a single dose, reminiscent of the delayed onset of action requiring chronic treatment in migraine prophylaxis. We, therefore, examined the efficacy of migraine prophylactic drugs on stroke outcome and its mechanisms in relation to ischemic depolarizations. We chose topiramate as a prophylactic drug because it is efficacious in migraine prophylaxis, and inhibits experimental SD on chronic treatment in rats. We tested lamotrigine because it also inhibits SD on chronic treatment in rats, although its efficacy in migraine is not proven. Both drugs have been studied previously in experimental focal ischemia models without consistent efficacy, albeit as a single dose or as short-term postischemic dosing. Therefore, neither drug has been tested as a prophylactic intervention in stroke.

We, therefore, tested these drugs in commonly used experimental models of focal cerebral ischemia, and did this not only in wild-type (WT) but also in FHM1 mutant mice to test drug efficacy on a background of cerebral hyperexcitability modeling migraine. Here, we show that chronic daily treatment for 7 weeks with the migraine prophylactic drugs topiramate or lamotrigine delays AD, inhibits PID occurrence and improves tissue and neurological outcomes after filament occlusion of the middle cerebral artery in both WT and FHM1 mutant mice. In contrast, single doses of each drug are ineffective, suggesting that the efficacy of migraine prophylactic drugs in stroke corresponds to their efficacy on SD, and that SD susceptibility is a critical but modifiable determinant of vulnerability to ischemic injury.

Methods

Experimental Animals
All experimental procedures were carried out in accordance with the Guide for Care and Use of Laboratory Animals (National Health Institutes Publication No. 85-23, 1996) and were approved by the institutional review board (Massachusetts General Hospital Subcommittee on Research Animal Care [MGH SRAC]). In addition to C57BL/6J WT mice, transgenic knock-in Cacna1a mice models homozygous for the R192Q FHM1 mutation were used, generated by a gene targeting approach, and backcrossed on C57BL/6J background for >10 generations. We studied mice between 2 and 6 months of age (23–30 g) because stroke risk is highest in young adult migraineurs. We studied male mice in stroke experiments to avoid the confounding effects of female hormones on outcome, and female mice in SD experiments because of their higher SD susceptibility compared with males, and because migraine is more prevalent in women.

Treatment Paradigm
In the chronic treatment group, we treated mice for 7 weeks with once a day orogastric gavage doses of migraine prophylactic drugs topiramate (80 mg kg⁻¹ d⁻¹) or lamotrigine (30 mg kg⁻¹ d⁻¹), and compared these with vehicle (Ora plus/Ora sweet); the last daily dose was administered 2 hours before the experiment. In a separate cohort, we tested the efficacy of a single dose of these drugs administered 2 hours before the experiment. We selected the doses based on previously reported efficacy in other experimental models in mice. All experiments were performed with the investigators blinded, and confirmatory genotyping was done in mutant cohorts.

Study Design
Study end points were defined a priori. Experiments were performed in 3 stages. First, efficacy of topiramate and lamotrigine was tested on SD susceptibility end points in WT and FHM1 mutant mice. Second, efficacy of both drugs on PID frequency and ischemic outcome was tested in 2 separate cohorts of WT mice. Finally, efficacy of both drugs on ischemic outcome was tested in FHM1 mutant mice. Animals were randomly assigned to the treatment groups for each cohort. A different experimenter blinded to the treatment performed each experimental stage. Experiments were performed according to the intention-to-treat principle; therefore, data points were excluded only if technical failures prevented reliable data collection. Because focal cerebral ischemia experiments in WT and FHM1 mutant mouse cohorts were separated in time, and performed by different operators using different equipment and experimental setups, we could not perform comparisons of ischemic tissue and neurological outcome end points between WT and FHM1 mutant strains in this study.

Systemic Physiological Monitoring
Arterial pH, pO₂, pCO₂, and blood pressure were measured via a femoral artery catheter under isoflurane anesthesia (2.5% induction, 1.5% maintenance, in 70% N₂O and 30% O₂; Table) and maintained by endotracheal intubation and mechanical ventilation during electrophysiological recordings (ie, SD susceptibility, PID frequency). In 24-hour survival experiments, these interventions were not performed to minimize morbidity and improve survival rates. Rectal temperature was controlled at 37°C.

SD Susceptibility
As described previously, 3 burr holes were drilled under saline cooling at the following coordinates (mm from bregma): 3.5 posterior, 2 lateral (2 mm diameter for electric stimulation and KCl application onto occipital cortex); 1.5 posterior, 2 lateral (1 mm diameter, recording site 1); 0.5 anterior, 2 lateral (1 mm diameter, recording site 2). The dura was kept intact to minimize trauma. Two glass capillary microelectrodes were placed to record extracellular steady (DC) potential and electrocorticogram. Electric SD threshold was determined by escalating intensity cathodal square pulses (10–8000 μC) via a bipolar electrode placed on the occipital cortex, and then a 1-mm cotton ball soaked in 300 mmol/L KCl was topically applied for 1 hour to record the frequency of evoked SDs. The protocol was then repeated on the opposite hemisphere. Data were averaged between the 2 hemispheres to yield a single data point per animal. SD frequency and threshold were taken as primary end points. The amplitude, propagation speed (distance/latency between the 2 recording electrodes), and duration at half-amplitude of the first SD in each hemisphere were also measured as secondary end points. There was no technical failure leading to exclusion in this cohort.

Transient Filament Occlusion of the Middle Cerebral Artery
A nylon monofilament was inserted into the internal via the external carotid artery followed by reperfusion after 60 minutes, under isoflurane anesthesia (2.5% induction, 1.5% maintenance, in 70% N₂O and 30% O₂) and laser Doppler monitoring (Perimed, Järfälla, Sweden), as described previously.

PID Occurrence
To record PIDs after transient filament occlusion of the middle cerebral artery (fMCAO), mice were transferred to a stereotaxic frame and performed by different operators using different equipment and experimental setups, we could not perform comparisons of ischemic tissue and neurological outcome end points between WT and FHM1 mutant strains in this study.
Assessment of Tissue and Neurological Outcome After fMCAO

After reperfusion, mice were transferred to a temperature-controlled incubator with access to food and water ad libitum. Neurological outcomes were scored as a primary end point 24 hours after reperfusion, using a 5-point scale: 0, normal; 1, forepaw monoparesis; 2, circling to left; 3, falling to left; 4, no spontaneous walking and depressed consciousness; and 5, death. Premature death after ischemia was incorporated in the neurological outcome scale because of the intention-to-treat design; however, infarct volume data from these mice were not measured because of postmortem confounders. Infarct volume was calculated as a primary end point by subtracting the volume of contralateral hemisphere from the volume of ipsilateral hemisphere. Technical failures occurred in WT cohorts only, and led to the exclusion of 1 chronic and 3 single dose lamotrigine-treated mice for PID assessments. Extensive surgery, intubation, mechanical ventilation, and arterial cannulation for PID monitoring precluded 24-hour survival. Therefore, infarct volumes were determined in a separate cohort.

Measurement of AD Latency

The latency between fMCAO and AD onset was measured as a secondary end point using the characteristic secondary hypoperfusion caused by AD on laser Doppler tracings, as described in detail previously.13 We measured this parameter in all WT mice undergoing fMCAO either for PID frequency determination or in infant and neurological outcome assessment. Absence of a detectable secondary hypoperfusion because of technical reasons was taken as an a priori exclusion criterion for this data set. Although this occurred more commonly, it resulted in the exclusion of only 16 of 112 animals in which this secondary end point was studied, distributed relatively evenly among experimental groups.

Statistical Analysis

Data were analyzed using SPSS (v11.0) and GraphPad Prism 6, and presented as whisker-box plot (whiskers, full range; box, 25% to 75% range; line, median; cross, mean) in the figures and mean±SD in the table. Statistical tests used to analyze each data set, group sizes (n) and details of statistical outcomes are provided in the figure legends. P values are 2-tailed, and P<0.05 was considered statistically significant.

Results

Suppression of KCl-Induced or Electrically Triggered Cortical SD

We have previously shown in rats that migraine prophylactic drugs suppress SD susceptibility.14 To first test whether migraine prophylactic drugs are also efficacious in mice, we treated WT and FHM1 knock-in mice with chronic daily doses of topiramate or lamotrigine for 7 weeks. Chronic treatment with topiramate or lamotrigine elevated the electrical threshold for SD induction and reduced the frequency of KCl-induced SDs (Figure 1A). Both drugs also reduced the SD propagation speed by ≈30%, albeit only in the FHM1 mutant. In addition, lamotrigine decreased SD duration, and tended to be more efficacious on all SD end points compared with topiramate. A single dose of either drug administered 2 hours before SD, tested in WT mice only, did not affect any of the SD attributes although a trend for lamotrigine to elevate the electrical threshold and reduce KCl-induced SD frequency was noted (Figure 1B).

Suppression of Cortical PIDs During Middle Cerebral Artery Occlusion

We next tested whether migraine prophylactic drugs also suppress PIDs, akin to SD. Intracortical microelectrode
Figure 1. Chronic topiramate and lamotrigine treatment suppresses spreading depression (SD) susceptibility. A, Representative electrophysiological tracings show SD triggered on stepwise escalating cortical cathodal stimulation at intensities indicated above each tracing to determine the SD threshold (left), and repetitive SDs triggered by continuous topical KCl application for 1 hour onto the cortex to determine SD frequency (right), in wild-type (WT) or familial hemiplegic migraine type 1 (R192Q) mutant mice after 7 weeks of daily treatment with vehicle (VEH, blue), topiramate (TPM, red), or lamotrigine (LTG, green). Whisker-box plots summarize the effects of chronic treatment on SD threshold, frequency, speed, and duration; n=6, 7, and 6 WT mice in vehicle, topiramate and lamotrigine groups, respectively; n=7 R192Q mice in vehicle, topiramate, and lamotrigine groups each. Two-way ANOVA followed by Sidak and Tukey multiple comparisons. SD threshold: genotype effect \( F(1,34)=18.8, P=0.0001 \); treatment effect \( F(2,34)=8.4, P=0.0011 \); interaction \( F(2,34)=1.9, P=0.1674 \). SD frequency: genotype effect \( F(1,34)=83.8, P<0.0001 \); treatment effect \( F(2,34)=15.4, P<0.0001 \); interaction \( F(2,34)=1.8, P=0.1857 \). SD speed: genotype effect \( F(1,34)=42.8, P<0.0001 \); treatment effect \( F(2,34)=10.7, P=0.0002 \); interaction \( F(2,34)=4.8, P=0.0142 \). SD duration: genotype effect \( F(1,34)=0.3, P=0.5647 \); treatment effect \( F(2,34)=7.8, P=0.0016 \); interaction \( F(2,34)=3.8, P=0.0332 \). Post hoc comparisons: *\( P<0.05 \) vs vehicle; †\( P<0.05 \) vs WT. B, Whisker-box plots summarize the effect of a single dose of each drug on SD frequency, threshold, speed, and duration in WT mice. n=10, 6, and 9 mice in vehicle, topiramate, and lamotrigine groups, respectively. One-way ANOVA followed by Holm–Sidak multiple comparisons test. Treatment effects were not statistically significant.

recordings during fMCAO showed that chronic treatment with topiramate or lamotrigine reduced PID occurrence by 50% and 80%, respectively (Figure 2A). A single dose of topiramate 2 hours before ischemia onset was ineffective, whereas lamotrigine showed a strong trend (Figure 2B). In a separate cohort of mice, we found that chronic treatment with valproate (200 mg/kg, IP for 6 weeks) also reduced the number of PIDs (3.1±0.6 PIDs/h) compared with vehicle (5.7±0.5 PIDs/h);
P<0.001, n=5 each), consistent with its inhibitory effect on KCl or electrically induced SDs previously shown in rats, and suggesting a class effect for migraine prophylactic drugs on PIDs.

**Improved Stroke Outcomes After Chronic Treatment**

We next tested whether suppression of PIDs translated into improved stroke outcomes in WT mice. Chronic treatment with either drug reduced the infarct size after transient fMCAO by ≈30%, and improved neurological outcomes (Figure 3A). Smaller infarcts predominantly reflected less severe cortical involvement (71±10, 50±11, and 48±9 mm³ in vehicle, topiramate, and lamotrigine groups, respectively; P<0.05). Ischemic brain swelling, calculated by subtracting the contralateral from ipsilateral hemispheric volume, was also reduced by chronic topiramate or lamotrigine treatment compared with vehicle (8±2, 8±2, and 16±2 mm³, respectively; P<0.05), possibly linked to less frequent PIDs. Neurological outcomes assessed using a combined death and disability score as a clinically relevant end point were improved after chronic treatment with topiramate or lamotrigine compared with vehicle (Figure 3A). In contrast to chronic treatment, single doses of either drug did not affect any of the outcome end points compared with vehicle after transient fMCAO (Figure 3B).

**Delayed AD Onset**

AD represents loss of membrane ionic gradients on ischemic failure of Na⁺/K⁺-ATPase function. We have previously shown that migraine mutations hasten AD after focal ischemia and this correlated well with SD susceptibility and tissue outcome. Therefore, we assessed whether decreased SD susceptibility after administrating migraine prophylactic drugs was associated with delayed AD onset in WT mice, detected by its cerebral vasoconstrictive effect as previously described.

**Figure 2.** Chronic topiramate and lamotrigine treatment suppresses peri-infarct depolarizations (PIDs). **A**, Upper panel shows representative electrophysiological tracings of repetitive PIDs that spontaneously arise around focal ischemic tissue during filament middle cerebral artery occlusion (fMCAO) after 7 weeks of daily treatment with vehicle (VEH, blue), topiramate (TPM, red), or lamotrigine (LTG, green) in WT mice. Lower left panel summarizes all experiments. Horizontal lines indicate the time of onset and end of electrophysiological recordings with respect to fMCAO onset in each mouse, and circles indicate PIDs. Line graph shows average cumulative PID occurrence per mouse as a function of time. When calculating the cumulative PID occurrence over time, differences in group sizes and recording durations were taken into account. Whisker-box plots show average overall PID frequency; n=6, 9, and 8 mice in vehicle, topiramate, and lamotrigine groups, respectively. One-way ANOVA followed by Holm–Sidak multiple comparisons test. Treatment effect F(2,23)=18.1, P<0.0001. Post hoc comparisons: *P<0.05 vs VEH; †P<0.05 vs TPM. **B**, Left panel summarizes all experiments where horizontal lines indicate the time of onset and end of electrophysiological recordings with respect to fMCAO onset in each mouse, and circles indicate PIDs. Line graph shows average cumulative PID occurrence per mouse as a function of time. When calculating the cumulative PID occurrence over time, differences in group sizes and recording durations were taken into account and corrected for. Whisker-box plots show average overall PID frequency; n=7, 5, and 4 mice in vehicle, topiramate, and lamotrigine groups, respectively. One-way ANOVA followed by Holm–Sidak multiple comparisons test. Treatment effects were not statistically significant.
delayed the onset of AD by ≈25% (Figure 4A). The magnitude of cerebral blood flow reduction in the ischemic core did not differ among groups (residual cerebral blood flow 12±5%, 13±5%, and 12±3% of baseline for vehicle, topiramate, and lamotrigine, respectively), eliminating the possibility that slower AD onset was because of milder ischemia. A single dose of either drug did not affect the latency to AD (Figure 4B).

Improved Stroke Outcomes After Chronic Treatment in FHM1 Mice

After showing that migraine prophylaxis with topiramate and lamotrigine improves stroke outcomes in WT mice, we also tested whether efficacy is sustained in migraine-susceptible FHM1 brains. Chronic treatment with either topiramate or lamotrigine reduced infarct size after transient fMCAO in FHM1 mutants by 30% to 35% (Figure 5); however, improved neurological function and the delay in the onset of AD reached statistical significance only in the lamotrigine group.

Discussion

Migraine is an established risk factor for ischemic stroke. We have recently shown that genetically enhanced SD susceptibility worsens the effect of cerebral ischemia on the brain by facilitating ischemic depolarization events, as a mechanism to explain the increased risk of stroke in migraineurs. Conversely, we here show that pharmacological suppression of SD susceptibility by migraine prophylactic drugs inhibits AD and PIDs and improves stroke evolution in both WT and FHM1 mutant mice. The magnitude of SD suppression by each drug corresponded well with the magnitude of AD and PID suppression, and stroke outcome. Consistent with this, genetically reduced susceptibility to SD as observed in rolling Nagoya and leaner mice, which have spontaneously arisen mutations in the Cacna1a gene leading to loss of CaV2.1 function, was associated with smaller infarcts, compared with WT on experimental stroke. These data strongly support intrinsic SD susceptibility of brain tissue (ie, the tissue factor) as an important determinant of stroke outcome.

Although in vitro studies of topiramate and lamotrigine have suggested a neuroprotective effect, in vivo studies were generally negative in various models of focal cerebral ischemia. All studies, however, have tested single doses or short-term treatment administered before or after ischemia onset. Our data suggest that chronic treatment is required for efficacy, as has been the case for SD suppression in rats and for the prophylactic effect on migraine in patients. Both topiramate and lamotrigine have been shown to acutely inhibit various voltage-gated ion channels as well as glutamatergic neurotransmission. Whether chronic treatment simply enhances these effects by achieving higher tissue levels, or induces structural or gene expression changes, remains to be determined.

Although PIDs are generally thought to enlarge infarcts by worsening the supply demand mismatch, an alternative and possibly complementary mechanism is a further increase in cerebral excitability by SD shown in neocortical slices; and for the prophylactic effect on migraine in patients. Both topiramate and lamotrigine have been shown to acutely inhibit various voltage-gated ion channels as well as glutamatergic neurotransmission. However, whether chronic treatment simply enhances these effects by achieving higher tissue levels, or induces structural or gene expression changes, remains to be determined.

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It is well established that PIDs worsen stroke outcomes, and that drugs acutely inhibiting PIDs after a single dose (eg, NMDA receptor antagonists) are protective in focal cerebral ischemia both in experimental animals and in stroke patients. However, clinical translation of this neuroprotective target has been difficult because of the cognitive and sedative side effects of such potent drugs. In this respect, migraine prophylaxis may provide a better-tolerated antiepileptic treatment alternative targeting SD and PIDs in stroke prophylaxis. Consistent with this notion, chronic treatment with lamotrigine was reported to diminish stroke-like episodes in a migraineur with mitochondrial encephalopathy, lactic acidosis, and stroke-like episodes, suggesting that the approach may be even more efficacious in hyperexcitable subsets of patients.

Summary and Conclusions

In summary, our data suggest that pharmacological suppression of SD susceptibility may protect against ischemic injury in patients at high risk for stroke, migraineurs, and nonmigraineurs alike. Whether migraine prophylaxis clinically improves stroke outcomes or reduces the stroke risk remains to be tested in large population-based studies. Although chronic treatment purely as a form of stroke prophylaxis may not be justified at this time because of potential side effects, migraine patients who are already on a migraine prophylactic regimen may indeed see a reduction in their stroke risk as an additional benefit.

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Disclosures

None.

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