Erythropoietin (EPO) is a potent neuroprotectant against ischemic brain injury both in animal experiments and in the clinic. Thus, using EPO as a neuroprotective approach in stroke, especially in treatment of patients who are not suitable for tissue-type plasminogen activator treatment, represents a potentially exciting new clinical application. However, large doses and multiple administrations of EPO are required for the treatment of stroke. Such a regimen of EPO administration may result in multiple high-risk factors for patients with stroke due to the erythropoietic effects of EPO such as increases in hematocrit, quantity of platelets, and vascular muscle contraction, raising the likelihood of microcoagulation and secondary infarction. EPO may also potentially interact with or be contraindicated with thrombolytic drugs and cause unexpected side effects, as evidenced by a recently failed EPO/tissue-type plasminogen activator combinatorial clinical trial. Accordingly, alternate strategies to reduce erythropoietic activity and other potential side effects of EPO will greatly improve its clinical applicability for the treatment of stroke.

A recent study indicated that a mutant EPO (MEPO) lacking erythropoietic activity was neuroprotective against N-methyl-D-aspartate (NMDA) toxicity in cultured neurons. However, the in vitro model bypasses all the vascular events critical in stroke pathology. Thus, whether MEPO has neuroprotective effects against brain ischemia still remains unknown. In this study, we constructed and subsequently tested a series of MEPOs, each containing a single amino acid mutation within the erythropoietic motif, and characterized a MEPO that completely lacked erythropoietic activity but retained neuroprotective effects and underlying mechanism in an animal model of cerebral ischemia.

**Results**—The serine to isoleucine mutation at position 104 (S104I-EPO) completely abolished the erythropoietic and platelet-stimulating activity of EPO. Administration of S104I-EPO significantly inhibited N-methyl-D-aspartate-induced neuronal death in primary cultures and protected against cerebral infarction and neurological deficits with an efficacy similar to that of wild-type EPO. Both S104I-EPO and wild-type EPO activated similar prosurvival signaling pathways such as phosphatidylinositol 3-kinase/AKT, mitogen-activated protein kinase/extracellular signal-regulated kinase 1/2, and STAT5. Inhibition of phosphatidylinositol 3-kinase/AKT or mitogen-activated protein kinase/extracellular signal-regulated kinase 1/2 signaling pathways significantly attenuated the neuroprotective effects of S104I-EPO, indicating that activation of these pathways underlies the neuroprotective mechanism of mutant EPO against cerebral ischemia.

**Conclusions**—S104I-EPO confers neuroprotective effects comparable to those of wild-type EPO against ischemic brain injury with the added benefit of lacking erythropoietic and platelet-stimulating side effects. Our novel findings suggest that the nonerythropoietic mutant EPO is a legitimate candidate for ischemic stroke intervention.

**Key Words:** AKT ◼ cerebral ischemia ◼ ERK1/2 ◼ erythropoietin ◼ erythropoietin mutant ◼ neuroprotection ◼ neurotoxicity

**Background and Purpose**—Erythropoietin (EPO) confers potent neuroprotection against ischemic injury. However, treatment for stroke requires high doses and multiple administrations of EPO, which may cause deleterious side effects due to its erythropoietic activity. This study identifies a novel nonerythropoietic mutant EPO and investigates its potential neuroprotective effects and underlying mechanism in an animal model of cerebral ischemia.

**Methods**—We constructed a series of mutant EPOs, each containing a single amino acid mutation within the erythropoietic motif, and tested their erythropoietic activity. Using cortical neuronal cultures exposed to N-methyl-D-aspartate neurotoxicity and a murine model of transient middle cerebral artery occlusion, neuroprotection and neurofunctional outcomes were assessed as well as activation of intracellular signaling pathways.

**Results**—The serine to isoleucine mutation at position 104 (S104I-EPO) completely abolished the erythropoietic and platelet-stimulating activity of EPO. Administration of S104I-EPO significantly inhibited N-methyl-D-aspartate-induced neuronal death in primary cultures and protected against cerebral infarction and neurological deficits with an efficacy similar to that of wild-type EPO. Both S104I-EPO and wild-type EPO activated similar prosurvival signaling pathways such as phosphatidylinositol 3-kinase/AKT, mitogen-activated protein kinase/extracellular signal-regulated kinase 1/2, and STAT5. Inhibition of phosphatidylinositol 3-kinase/AKT or mitogen-activated protein kinase/extracellular signal-regulated kinase 1/2 signaling pathways significantly attenuated the neuroprotective effects of S104I-EPO, indicating that activation of these pathways underlies the neuroprotective mechanism of mutant EPO against cerebral ischemia.

**Conclusions**—S104I-EPO confers neuroprotective effects comparable to those of wild-type EPO against ischemic brain injury with the added benefit of lacking erythropoietic and platelet-stimulating side effects. Our novel findings suggest that the nonerythropoietic mutant EPO is a legitimate candidate for ischemic stroke intervention. 

(Stroke. 2012;43:3071-3077.)

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*DOI: 10.1161/STROKEAHA.112.663120*

**Received May 2, 2012; final revision received July 26, 2012; accepted August 16, 2012.**

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neuroprotective effects against in vitro neural excitotoxicity. We then further investigated this MEPO in the context of in vivo cerebral ischemia and explored the potential signaling mechanisms underlying the observed neuroprotection.

Materials and Methods

Generation of MEPO Protein

H56-tagged (3’ end) EPO cDNAs, each containing a single amino acid mutation, were generated by polymerase chain reaction-based site mutagenesis and transfected into 293 cells. Recombinant protein was purified from the culture medium of 293 stable cell lines overexpressing MEPO using superflow Ni-NTA agarose columns (Qiagen).

Bioactivity Assays of MEPO

In vitro bioactivity was determined using a proliferation assay in the EPO-dependent murine myeloid cell line 32D-EPOR. 32D-EPOR cells (2×10⁴ cells/well) were factor-starved for 4 hours in RPMI 1640 medium (Invitrogen) and then incubated in the presence of MEPOs or wild-type EPO (1 U/mL). Live cells were counted using trypan blue exclusion 72 hours later. For in vivo erythropoietic activity bioassay, C57BL/6 mice (Jackson Laboratory, Bar Harbor, Maine) were intraperitoneally injected with S104-EPO or wild-type EPO twice weekly for 4 weeks at a dose of 5000 U/kg body weight. Hemoglobin and platelet levels were determined before the first EPO administration and then analyzed every 2 weeks.

NMDA Neurotoxicity

Primary cortical neurons at 11 days in vitro from pregnant Sprague-Dawley rats were pretreated with MEPOs or wild-type EPO (1 U/mL) for 8 hours and then challenged with NMDA (200 μmol/L) for 15 minutes. The neurons were then returned to normal culture medium supplied with the same concentration of MEPOs or wild-type EPO. Cell death was analyzed by nuclear staining (Hoechst 33258) and lactate dehydrogenase release 24 hours after NMDA treatment.

Murine Model of Focal Ischemia, Drug Administration, and Determination of Infarct Volume

All procedures were approved by the Institutional Animal Care and Use Committee of the University of Pittsburgh. Temporary focal ischemia was induced by left middle cerebral artery occlusion (MCAO) for 60 minutes as previously described. Animals were randomized and S104-EPO, wild-type EPO, or vehicle (saline) was administered intraperitoneally at the concentration indicated at the onset of reperfusion and again at 24 and 48 hours of reperfusion. Pharmacological inhibitors of phosphatidylinositol 3-kinase (PI3K; 2 μL of 10 mmol/L LY294002) and extracellular signal-regulated kinase (ERK; 2 μL of 5 mmol/L PD98059) were injected (intracerebroventricularly) individually or in combination into the brain 30 minutes before MCAO. Infarct volume was determined 72 hours after MCAO by a researcher blinded to the experimental groups using the MCID image analysis system (Imaging Research, Inc) after 2% 2,3,5-triphenyltetrazolium chloride staining.

Neurobehavioral Tests

Three different neurobehavioral tests were performed in animals by an observer blinded to the experiments. Neurological deficits were scored on a 0 to 5 scale: no neurological deficit (0); failure to extend the right forepaw fully (1); circling to the right (2); falling to the right (3); unable to walk spontaneously (4); or dead (5). The Rotorod test was begun 2 days before surgery and then administered on a daily basis at 1 to 7 days after surgery with 5 trials per test. For the corner test, the ischemic mice turns preferentially toward the nonimpaired (right) side. The turns in one versus the other direction are recorded from 10 trials for each test. The data are expressed as the percentage of mean duration of time on the Rotorod per day compared with the presurgery control value.

Statistical Analysis

Results are presented as means±SEM. The statistical significance of the difference between means was analyzed by the Student t test for single comparisons or by analysis of variance followed by post hoc Bonferroni/Dunn tests for multiple comparisons. Differences among groups were regarded as significant if P≤0.05.

Results

Generation of Neuroprotective MEPOs That Lack Erythropoietic Activity

To obtain MEPOs that lack erythropoietic activity, we constructed and subsequently tested 12 EPO receptor-binding motif regions that are essential for EPO’s erythropoietic activity: the amino terminal (amino acids 1–17), internal (amino acids 99–109), and carboxyl-terminal motif (amino acids 147–151). The bioactivity of these MEPOs was analyzed using an in vitro proliferation assay in the EPO-dependent myeloid cell line 32D-EPOR. As shown in Figure 1A, the survival and proliferation of 32D-EPOR cells depends entirely on the existence of EPO in the medium. Mutations within the carboxyl-terminal motif (N147A, N147K, and G151A) either increased or only partially reduced EPO bioactivity, whereas mutations within the amino-terminal motif (R14E, R14A, R14Q, and Y15I) significantly reduced but did not completely abolish EPO bioactivity.
However, mutations within the internal motif (S100E, R103A, R103E, S104I, and L108K) resulted in complete loss of EPO bioactivity (Figure 1A), consistent with previous reports, indicating that the internal motif is essential for EPO bioactivity. 7,8

Next, we tested whether the MEPOs retain neuroprotective effects against excitotoxic neural injury. MEPOs significantly reduced NMDA-induced neuronal cell death with an efficacy similar to that of wild-type EPO (Figure 1B). However, there was a nonsignificant trend toward better protection against NMDA toxicity after mutations within the internal motif compared with mutations within the amino terminal. Taken together, these data suggest that, although all amino terminal or internal motif MEPOs assayed retained equivalent neuroprotection against NMDA neurotoxicity compared with wild-type EPO, mutations within the amino-terminal motif resulted in only a partial loss of EPO bioactivity. In contrast, mutations within the internal motif not only retained neuroprotective effects, but also caused a complete loss of EPO bioactivity. We therefore chose mutants with mutations within the internal motif for further assessment.

Characterization of S104I-EPO

Amino acid residues 100, 103, 104, and 108 are exposed on the surface of the EPO molecule; thus, change of charge may potentially result in EPO binding to new targets due to charge–charge interactions. Among the 5 mutants targeting the internal motif, only S104I-EPO is a neutral amino acid substitution, whereas the other mutations either increased or decreased the charge. Interestingly, the 293 cells secreted higher levels of S104I-EPO into the medium compared with other MEPOs. The mechanism for this remains unclear, but it is likely due to impaired EPO secretion mechanism caused by charge change. Based on these observations, we chose S104I-EPO for further investigation.

S104I-EPO completely lost the ability to induce myeloid proliferation, even at a high concentration (100 U/mL, equivalent to 25 nmol/L; Figure 2A). To further confirm whether S104I-EPO loses its erythropoietic activity, hemoglobin levels in mice were measured after injection of a high dose of either S104I-EPO or wild-type EPO (both at 5000 U/kg) twice weekly. As shown in Figure 2B, S104I-EPO did not induce the production of hemoglobin even when continuously present at high concentrations over 4 weeks, whereas wild-type EPO significantly increased hemoglobin level at Weeks 2 and 4 (by 15% and 39%, respectively). EPO has been reported to stimulate the production of platelets, which may increase the likelihood of microcoagulation and secondary stroke; we therefore also measured platelet levels in mice. S104I-EPO administration did not induce the production of platelets at least up to 4 weeks posttreatment, whereas wild-type EPO significantly increased the platelet counts (Figure 2C).

To determine whether S104I-EPO retains neuroprotective effects, we first tested it in an in vitro model of NMDA neurotoxicity in primary neuronal cultures. As illustrated, pre-treatment with S104I-EPO significantly decreased the number of neurons containing condensed nuclei in cultures (Figures 2D–g, 2D–h, and 2D–i) and prevented necrotic cell death after NMDA treatment as determined by lactate dehydrogenase release (Figure 2D–j). Importantly, no significant difference in neuroprotective efficacy was observed between S104I-EPO and wild-type EPO, suggesting that S104I-EPO and wild-type EPO are equally effective in protecting neurons against NMDA neurotoxicity with a mixed cell death phenotype.

S104I-EPO Is Neuroprotective Against Focal Cerebral Ischemia

The neuroprotective effects of S104I-EPO were further determined in the murine model of focal ischemia. S104I-EPO treatment significantly decreased infarct volume in a dose- and time-dependent manner (Figure 3A–B) with an efficacy similar to that of the wild-type EPO. S104I-EPO provided optimal protection at a concentration of 5000 U/kg administered intraperitoneally, a dose that has been widely used in the field to test the neuroprotective effect of wild-type EPO in rodent models of cerebral ischemia. 5,9 At this dose, S104I-EPO reduced infarct volume by 53% (Figures 3A and 3C). S104I-EPO still exerted significant neuroprotection at 2000 U/kg, but the effect disappeared when administered at doses <1000 U/kg.

To determine the temporal time frame for neuroprotection, we examined whether postischemic administration of S104I-EPO would be capable of decreasing ischemic infarct volume. Injection of S104I-EPO immediately after the ischemic period provided optimal protection. However, S104I-EPO exerted significant neuroprotective effects even when administered up to 4 hours after ischemia, although the effects were diminished and lost when administered 6 hours after ischemia. Physiological parameters (blood pressure, gases, and glucose) and recombinant cerebral blood flow were measured with no significant differences between groups (data not shown).

Administration of S104I-EPO Improves Neurological Outcomes After Ischemia

We next tested whether the neuroprotective effect of S104I-EPO could be translated into functional improvement. S104I-EPO significantly improved neurological deficit scores as assessed at 72 hours after ischemia (Figure 4A). To further determine the impact of S104I-EPO on neurological recovery, 2 behavioral tests, the Rotorod and corner tests, were performed during a 7-day recovery period. As illustrated in Figure 4B, S104I-EPO-treated mice performed significantly better on the Rotorod at all time points tested after ischemia compared with vehicle-treated mice. Similarly, S104I-EPO-treated mice decreased preferential turning behavior toward the nonimpaired (right) side as assessed by the corner test, indicating improved bilateral motor behavior compared with vehicle-treated mice. No significant differences were found for functional outcomes between S104I-EPO-treated and wild-type EPO-treated mice, suggesting that S104I-EPO improves neurological outcomes with an efficacy similar to that of wild-type EPO.
S104I-EPO and Wild-Type EPO Exert Neuroprotective Effects Through Similar Signaling Pathways

We next sought to determine if MEPO and wild-type EPO activate similar cell survival pathways. Previous studies suggested that EPO derivatives do not bind to EPO receptors, but rather to a tissue-protective receptor complex, the common β receptor/EPO receptor heteroreceptors.10 However, the downstream survival signaling pathways relevant to ischemic neuroprotection may be similar to those activated by...
wild-type EPO. Therefore, we tested whether MEPO mediates neuroprotection through PI3K/AKT, mitogen-activated protein kinase/ERK1/2, and STAT5 signaling, because these pathways are critical to the neuroprotective effects of EPO.2,11 Primary neurons were treated with S104I-EPO, and the activation of signaling molecules was analyzed by Western blot (Figure 5A). Similar to wild-type EPO, S104I-EPO increased the phosphorylation of AKT and ERK1/2 as early as 30 minutes after exposure. Increased phospho-AKT and phospho-ERK1/2 levels were observed over the time course assessed, including 24 hours after exposure. S104I-EPO also increased the level of phosphorylated STAT5, beginning 16 hours after S104I-EPO exposure. To determine the role of these signaling pathways in the context of MEPO-mediated neuroprotection, primary neurons were challenged with NMDA in the presence or absence of either the PI3K inhibitor LY294022 (Figure 5B) or the ERK1/2 inhibitor PD98059 (Figure 5C). Both inhibitors significantly decreased the protective effects of EPO and S104I-EPO against NMDA neurotoxicity. Finally, we tested the relevance of these signaling pathways in MEPO-mediated neuroprotection against cerebral ischemia in mice. Intracerebroventricular injection of either LY294002 or PD98059 led to a diminished neuroprotective effect of S104I-EPO, and combined injection of LY294002 and PD98059 completely abolished S104I-EPO-induced neuroprotection. Injection of LY294002 or PD98059 alone did not show a significant difference compared with the vehicle control group. These data suggest that the PI3K/AKT and ERK1/2 signaling pathways may synergistically mediate the neuroprotective effect of MEPO. Furthermore, the data underscore that both S104I-EPO and wild-type EPO may activate similar signaling pathways to induce neuroprotection.

**Discussion**

EPO exerts a potent neuroprotective effect against ischemic brain injury in both animal experiments and clinical trials.3,12 However, several critical limitations have hampered the potential for extensive use of EPO as a clinically therapeutic tool after stroke. Of primary concern, the delivery of EPO to the brain through systemic administration is technically...
Consistent with this, carbamylated EPO activates the same signaling pathways in neurons such as PI3K/AKT, mitogen-activated protein kinase/ERK1/2, and STAT5 (Figure 5A). Inhibition of these signaling pathways using either the PI3K inhibitor LY294002 or the ERK1/2 inhibitor PD98059 not only attenuated the neuroprotective effect of S104I-EPO against NMDA-induced neurotoxicity (Figure 5B–C), but also inhibited the neuroprotective effect of S104I-EPO against ischemic brain injury in the MCAO model (Figure 5D). Interestingly, combined application of LY294002 and PD98059 completely abolished the neuroprotective effect of S104I-EPO in ischemia, suggesting that PI3K/AKT and mitogen-activated protein kinase/ERK1/2 pathways may synergistically mediate the neuroprotective effect of S104I-EPO. The observation that STAT5 activation is delayed until 16 hours after addition of S104I-EPO suggests that STAT5 signaling might occur downstream of either PI3K/AKT or mitogen-activated protein kinase/ERK1/2 signaling. The further characterization of neuroprotective signaling triggered by MEPO warrants additional investigation, including the identification of the receptor required for neuroprotection, a deeper understanding of downstream signaling molecules, and the exploration of parallel signaling pathways.

In summary, S104I-EPO completely lacks erythropoietic activity but retains neuroprotective effects against in vitro NMDA neurotoxicity and ischemic brain injury in a murine model of MCAO with an efficacy similar to that of wild-type parameters or ischemic outcomes under our treatment paradigm. Importantly, the current study also demonstrates that S104I-EPO not only inhibits NMDA-induced neuronal death in primary cultures (Figure 2D), but also reduces infarct volume and improves posts ischemic neurological outcomes in a murine MCAO model (Figure 4). Our results indicate that such a nonerythropoietic EPO mutant may be a promising candidate for treatment of brain injury and may avoid clinical complications associated with increased hematocrit or platelet aggregation. Obviously, before moving to clinical trials, further investigations are required such as whether MEPO has long-term blood-stimulating and other undiscovered side effects and whether MEPO administration has long-term effects on histological and behavioral improvements after ischemia. In addition, the effect of MEPO needs to be tested in multiple ischemic model/species systems according to Stroke Treatment Academic Industry Roundtable (STAIR) guidelines. Considering that side effects of EPO in stroke therapy may not appear in animal stroke models, testing MEPO in nonhuman primates may also be necessary before clinical trials.
EPO. Furthermore, although S104I-EPO activates survival signaling pathways similar to those of wild-type EPO, the nonerythropoietic feature of S104I-EPO avoids important clinical confounds for the patient with stroke. Thus, the novel S104I-EPO should be explored as a therapeutic agent for the treatment of stroke and other neurological diseases.

Acknowledgments
We thank Rehana K. Leak and Carol Culver for editorial assistance and Professor Murat O. Arcasoy from Duke University for providing the 32D-EPOR cell line.

Sources of Funding
This project was supported by Department of Veteran's Affairs Merit Review grant I01RX000199 (to Dr Cao), National Institutes of Health/National Institute of Neurological Disorders and Stroke grant NS053473 (to Dr Cao), and American Heart Association Scientist Development Grant 06300064N (to Dr Cao).

Disclosures
None.

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Mutant Erythropoietin Without Erythropoietic Activity Is Neuroprotective Against Ischemic Brain Injury
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Stroke. 2012;43:3071-3077; originally published online September 13, 2012; doi: 10.1161/STROKEAHA.112.663120

Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0039-2499. Online ISSN: 1524-4628

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://stroke.ahajournals.org/content/43/11/3071

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