Intraventricular Infusion of TrkB-Fc Fusion Protein Promotes Ischemia-Induced Neurogenesis in Adult Rat Dentate Gyrus

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Background and Purpose—We have previously shown that delivery of brain-derived neurotrophic factor (BDNF) through direct intrahippocampal gene transduction with a viral vector suppresses the formation of new dentate granule cells triggered by global forebrain ischemia. Here, we investigated whether inhibition of endogenous BDNF alters ischemia-induced neurogenesis in the dentate gyrus.

Methods—Rats were subjected to 30 minutes of global forebrain ischemia and then received intraventricular infusion of either the BDNF scavenger, TrkB-Fc fusion protein, or control Hu-Fc for 2 weeks. In parallel, all animals were injected intraperitoneally with the mitosis marker 5-bromo-2'-deoxyuridine-5'-monophosphate (BrdU). Animals were killed at 2 or 6 weeks after the ischemic insult, and neurogenesis was then assessed immunocytochemically with epifluorescence or confocal microscopy.

Results—Infusion of TrkB-Fc fusion protein gave rise to elevated numbers of ischemia-generated new neurons, double-labeled with BrdU and the early neuronal marker Hu or the mature neuronal marker NeuN, in the dentate subgranular zone and granule cell layer at 2 and 6 weeks after the insult.

Conclusions—Our findings provide evidence that endogenous BDNF counteracts neuronal differentiation, but not cell proliferation or survival, in ischemia-induced dentate gyrus neurogenesis. (Stroke. 2003;34:2710-2715.)

Key Words: brain-derived neurotrophic factor cerebral ischemia, global hippocampus neurons stroke rats
Materials and Methods

Animals and Experimental Design
Thirty adult, male Wistar rats (Taconic M&B A/S) weighing 280 to 290 g at the time of the ischemic insult were housed under 12-hour light/12-hour dark conditions with ad libitum access to food and water. After fasting overnight with free access to water, all animals were implanted intraventricularly with a cannula connected to an osmotic minipump delivering either TrkB-Fc (n = 10) or control Hu-Fc (n = 20). Immediately thereafter, the rats were subjected to 30 minutes of global forebrain ischemia (n = 10 for TrkB-Fc, n = 11 for Hu-Fc) or sham treatment (n = 9 for Hu-Fc). Starting the next day, all animals received injections of 5-bromo-2′-deoxyuridine-5′-monophosphate (BrdU; twice daily, 50 mg/kg) for 2 weeks. At this time point, 6 rats that had been subjected to the ischemic insult (n = 3 with TrkB-Fc, n = 3 with Hu-Fc) and 3 sham-treated rats were transcendally perfused for immunocytochemistry. The minipumps were removed in the remaining animals, but the rats were not killed until 4 weeks later. In the immunocytochemical analysis, the investigator was blinded to whether TrkB-Fc– or Hu-Fc–containing minipumps were implanted in the individual animals.

Minipump Implantation
Rats were anesthetized with 1% halothane in N2O/O2 (70%/30%), and a cannula connected to an osmotic minipump (Alzet; model 2002; 200 μL; flow rate, 0.5 μL/h) was then implanted into the right lateral ventricle (0.5 mm caudal to bregma, 1.2 mm lateral from midline, and 3.5 mm ventral from skull with tooth bar – 3.2 mm according to the atlas of Paxinos and Watson22). Minipumps were filled with either TrkB-Fc (1 mg/pump; gift from Regeneron Pharmaceuticals) or Hu-Fc (0.34 mg/pump; ICN Biomedicals Inc) in 0.1 mol/L phosphate-buffered saline (PBS). All brains were cut into 30-μm coronal sections, which were then stored in a cryoprotective solution containing H2 O2 and 10% methanol. Subsequently, the sections were immersed in 3% hydrogen peroxide for 30 minutes and then washed in PBS. After washing, the sections were incubated in 1:250 Alexa 488-conjugated streptavidin (Molecular Probes) or Hu-IgG (1:10000; goat polyclonal; Sigma). Briefly, the sections were first rinsed and endogenous peroxidase was quenched in 3% H2O2 and 10% methanol. Subsequently, the sections were incubated with the primary antibody in 2% normal rabbit serum in 0.25% Triton X-100 in potassium and PBS (KPBS) at 4°C overnight. After rinsing, sections were incubated with the biotinylated rabbit anti-goat secondary antibody (1:200; Vector Laboratories) in 2% normal rabbit serum in 0.25% Triton X-100 in KPBS for 1 hour. Then sections were rinsed and incubated in avidin-biotin-peroxidase complex (Elite ABC Kit, Vector Laboratories), and peroxidase was developed by the diaminobenzidine reaction.

For double-labeled fluorescence immunocytochemistry, the following antibodies were used: NeuN (1:100; mouse monoclonal; Chemicon), BrdU (1:100; rat monoclonal; Harlan Sera-Laboratory Ltd), and Hu (1:500; mouse monoclonal; Chemicon). Briefly, free-floating sections were denatured in 1 mol/L hydrochloric acid at 65°C for 30 minutes. After rinsing, the sections were incubated for 36 hours with either BrdU and NeuN or BrdU and Hu antibodies in 5% normal donkey serum and 5% normal horse serum in 0.25% Triton X-100 in KPBS at 4°C. The sections were then rinsed and incubated for 2 hours with 1:200 secondary Cy3-conjugated donkey anti-rat antibody (Jackson ImmunoResearch) and 1:200 secondary biotinylated horse anti-mouse antibody (Vector) in a mixture of 2% normal donkey serum and 2% normal horse serum in 0.25% Triton X-100 in KPBS. After several rinses, sections were incubated for 2 hours with 1:250 Alexa 488–conjugated streptavidin (Molecular Probes) in 0.25% Triton X-100 in KPBS, rinsed, mounted on gelatin-coated slides, and coveredslipped with PVA-DABCO mounting medium. When staining for Hu, the streptavidin step was preceded by tyramide amplification procedure (TSA biotin system, NEN).

Microscopic Analysis
Penetration of TrkB-Fc and Hu-Fc into the brain parenchyma was assessed in sections stained with antibody against human IgG using 4′,6-diamidino-2-phenylindole (DAPI) as a nuclear counterstain. Only nuclei showing nuclear fluorescence were counted. Labeled cells in the brain were identified with NeuN (1:100; mouse monoclonal; Chemicon) and BrdU (1:100; rat monoclonal; Harlan Sera-Laboratory Ltd) antibodies. The penetration of TrkB-Fc and Hu-Fc was monitored using 40× objective in an epifluorescence microscope. Labeled cells within the dentate granule cell layer (GCL) and SGZ ipsilateral to the cannula implantation were counted in 4 coronal sections separated by 300 μm and located −2.8 to −4.2 mm from bregma. The validity of the double labeling as observed in the epifluorescence microscope was evaluated with a confocal laser scanning microscope (Leica) in 1 randomly chosen section from every other animal. Cells were considered double labeled when BrdU and NeuN or Hu immunoreactivity was colocalized in a minimum of 3 consecutive images in a z series with a 1-μm interval.

Statistical Analysis
All values are given as mean ± SEM. Comparisons between numbers of single- or double-labeled cells and percentages of NeuN- and Hu-positive cells were performed with Student’s unpaired t test. Significance was set at P < 0.05.

Results
The penetration of TrkB-Fc and Hu-Fc into the brain parenchyma from the infusion site in the right lateral ventricle 2 weeks after ischemia closely resembled the previously observed pattern.24 Both TrkB-Fc and Hu-Fc were detected in the rostral part of the hippocampus, in most rats bilaterally, but with a higher staining intensity and wider distribution on the right side. We observed no differences in hippocampal staining pattern between TrkB-Fc– and Hu-Fc–infused animals. The septal region was intensely stained, and both TrkB-Fc and Hu-Fc were detected bilaterally in the dorsomedial striatum. There was also penetration of TrkB-Fc and Hu-Fc into the cerebral cortex, mostly in the cingulate and frontal cortices close to the cannula tract. In rats that had
survived for 4 weeks after removal of the pump, staining was detectable only close to the cannula tract, presumably where the concentration had been the highest. In other areas, immunostaining was absent, indicating that TrkB-Fc and Hu-Fc had been washed away.

In agreement with previous studies, the ischemic insult gave rise to a significant increase in the number of BrdU-NeuN double-labeled cells (Figure 1) in the SGZ and GCL of rats infused with Hu-Fc. Elevated numbers of BrdU-NeuN double-positive cells were observed at both 2 and 6 weeks after ischemia (3.6- and 4.1-fold increase, respectively). However, at 6 weeks after the insult, the number of double-labeled cells was higher, probably reflecting the time required for the new neurons to fully express mature neuronal markers such as NeuN (data not shown).

We observed no significant differences in the total number of BrdU-positive cells in the dentate SGZ and GCL between ischemic animals infused with TrkB-Fc or Hu-Fc (Figure 2A). Thus, TrkB-Fc does not influence the number of new cells in these areas at either 2 or 6 weeks after global forebrain ischemia. In addition, the number of BrdU-NeuN double-labeled cells was similar in the 2 groups 2 weeks after ischemia (Figure 2B). However, at 6 weeks after the insult, the animals that had been infused with TrkB-Fc had a significantly higher number of BrdU-NeuN–positive neurons compared with the Hu-Fc–treated rats (Figure 2B). Similarly, whereas there was no difference between the groups at 2 weeks, the proportion of BrdU-positive cells also expressing NeuN immunoreactivity was significantly higher in TrkB-Fc–treated rats (~50%) compared with Hu-Fc–treated rats (~30%) at 6 weeks (Figure 2C).
to a condition resembling peripheral inflammation, raises BDNF levels in sensory neurons and increases nociceptive spinal reflex excitability. This increased central excitability is reduced by TrkB-Fc. Moreover, intraventricular delivery of TrkB-Fc suppresses epileptogenesis, similar to what has been observed in heterozygous BDNF knockout mice and in transgenic mice overexpressing truncated TrkB receptors and with decreased endogenous BDNF levels. In contrast to these data, Croll et al reported that TrkB-Fc can potentiate BDNF-induced TrkB phosphorylation. However, this effect was observed only when TrkB-Fc and BDNF were coinfused intracerebrally in equimolar concentrations. Thus, it is highly unlikely that the TrkB-Fc infusion performed in the present study would act by enhancing endogenous BDNF activity.

The present findings provide further support for the hypothesis that BDNF can counteract the neuronal differentiation of new cells generated in the DG after global forebrain ischemia. Local elevation of BDNF levels and inhibition of endogenous BDNF, as used here, reduces and increases, respectively, the ischemia-induced neurogenesis. In contrast, cell proliferation and survival are unaffected by these manipulations of BDNF activity. We have suggested that BDNF may act by blocking the maturation of the newly generated cells beyond an intermediate developmental stage. In agreement with this interpretation, BDNF-overexpressing cerebellum-derived progenitor cells showed reduced expression of neuronal markers and appeared as round, flattened cells without processes. Conversely, the same cells, when genetically manipulated to produce less BDNF by expressing antisense BDNF, exhibited increased expression of neuronal markers and smaller cell bodies, often bearing complex, multiple processes.

In contrast to the suppressant action of BDNF on the differentiation step in ischemia-induced DG neurogenesis, increased BDNF production evoked by systemic injection of the voltage-dependent sodium channel blocker riluzole has been reported to promote proliferation of DG progenitor cells in the intact rats. This effect could be blocked by intraventricular administration of BDNF antibodies. Also, heterozygous BDNF knockout mice with decreased hippocampal BDNF levels have been found to exhibit decreased proliferation of DG progenitors. Dietary restriction leading to elevated BDNF levels improved the survival of the newly generated DG cells in wild-type and, to a lesser extent, in knockout mice. The discrepancies between these data and
our own observations suggest that BDNF has different modulatory actions on basal and ischemia-induced SGZ neurogenesis. Analogously, N-methyl-D-aspartate receptor activation has been reported to reduce basal neurogenesis but to enhance the formation of new DG neurons after both global forebrain ischemia and stroke. 7,48

In the other neurogenic area, the SVZ, BDNF seems to promote both basal and insult-induced neurogenesis. Thus, administration of BDNF to the lateral ventricle in intact rats 15 increases the generation of new neurons in the SVZ. Recently, we have observed 52 that viral vector-mediated delivery of BDNF to the striatum leads to an increased number of new striatal neurons formed in the SVZ after stroke. The contradictory effects of BDNF on ischemia-induced neurogenesis in the 2 neurogenic areas are in agreement with the idea that the adult SVZ contains multipotential NSCs, whereas neuron-specific progenitors reside in the SGZ. 50

We previously hypothesized that the viral vector-mediated long-term delivery of high levels of BDNF to the DG 19 may have acted by downregulating the TrkB receptor. 51 Ensuing desensitization of the progenitor cells or their progeny to the elevated endogenous BDNF levels triggered by the cerebral ischemia could therefore explain the subsequent attenuation of neurogenesis. 19 Arguing against this possibility is the finding in the present study that TrkB-Fc infusion started at the time of the ischemic insult had an effect opposite that after long-term BDNF delivery.

In conclusion, the results of the present study indicate that intraventricular administration of TrkB-Fc, which most likely leads to decreased activity of endogenous BDNF, increases the formation of new dentate granule cells after 30 minutes of global forebrain ischemia by promoting neuronal differentiation. We have previously demonstrated that intraventricular infusion of TrkB-Fc in rats during 1 week before and 1 week after the same aggravates ischemic damage and gives rise to significantly lower number of surviving CA4 pyramidal and neuropeptide Y-immunoreactive dentate hilar neurons. 24 Taken together, these studies reveal a remarkable diversity of BDNF function in hippocampal cellular plasticity after global forebrain ischemia.

Acknowledgments

This work was supported by the Swedish Research Council; the Söderberg, Kock, Crafoord, Elsa and Thorsten Segerfalk, and Swedish Stroke Foundations; and the Swedish Association of Neurologically Disabled.

References

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