Niacin Treatment of Stroke Increases Synaptic Plasticity and Axon Growth in Rats

Xu Cui, PhD; Michael Chopp, PhD; Alex Zacharek, MS; Cynthia Roberts, BS; Benjamin Buller, BS; Madalina Ion, BS; Jieli Chen, MD

Background and Purpose—Niacin is the most effective medication in current clinical use for increasing high-density lipoprotein cholesterol. We tested the hypothesis that niacin treatment of stroke promotes synaptic plasticity and axon growth in the ischemic brain.

Methods—Male Wistar rats were subjected to 2 hours of middle cerebral artery occlusion and treated with or without Niaspan (a prolonged-release formulation of niacin, 40 mg/kg) daily for 14 days starting 24 hours after middle cerebral artery occlusion. The expression of synaptophysin, Nogo receptor, Bielschowsky silver, brain-derived neurotrophic factor, and its receptor tropomyosin-related kinase B were measured by immunohistostaining and Western blot, respectively, in the ischemic brain. Complementing in vivo studies, primary cultured neurons were used to test the effect of niacin and high-density lipoprotein on neurite outgrowth and brain-derived neurotrophic factor/tropomyosin-related kinase B expression.

Results—Niaspan treatment of stroke significantly increased synaptophysin, Bielschowsky silver, brain-derived neurotrophic factor/tropomyosin-related kinase B expression, and decreased Nogo receptor expression in the ischemic brain compared with middle cerebral artery occlusion control animals (P<0.05, n=8/group). Niacin and high-density lipoprotein treatment significantly increased neurite outgrowth and brain-derived neurotrophic factor/tropomyosin-related kinase B expression in primary cultured neurons. Tropomyosin-related kinase B inhibitor attenuated niacin-induced neurite outgrowth (P<0.05, n=6/group).

Conclusions—Niacin treatment of stroke promotes synaptic plasticity and axon growth, which is mediated, at least partially, by the brain-derived neurotrophic factor/tropomyosin-related kinase B pathways. (Stroke. 2010;41:2044-2049.)

Key Words: axon growth ■ HDL-cholesterol ■ niacin ■ plasticity ■ stroke ■ synaptic

Synaptic plasticity and axon growth are related to behavioral change and functional recovery after brain and spinal cord injury.1 Functional alterations in motor cortex organization are accompanied by changes in dendritic and synaptic structure.2 Cortical stimulation-induced functional improvements after stroke are mediated by synaptic structural plasticity.3 Increases in dendritic arborization and spine density are potential morphological strategies that enable the brain to reorganize its neuronal circuits.4 High-density lipoprotein cholesterol (HDL-C) is critical in maintaining the homeostasis of cell membrane cholesterol and thus plays an essential role in the regulation of synaptic function and cell plasticity.5 The expression of brain-derived neurotrophic factor (BDNF) and its receptor tropomyosin-related kinase B (TrkB) supports neuron survival and axon growth after neuronal injury.6-7 Voluntary exercise leads to an endogenous upregulation of BDNF and associated proteins involved in synaptic function and enhances functional recovery after traumatic brain injury.8 Synaptic plasticity is also influenced by mutations in BDNF.9 Niacin (nicotinic acid) is the most effective medication in current clinical use for increasing HDL-C.10 Our previous study showed that Niaspan (a prolonged-release formulation of niacin) treatment of stroke significantly increases serum HDL-C level and improves functional outcome in rats.11 However, whether niacin increases synaptic plasticity and axon growth and whether BDNF/TrkB play a role in niacin-induced synaptic plasticity and axon growth has not been investigated. In this study, we tested a novel hypothesis, that niacin treatment of stroke promotes synaptic plasticity and axon growth in the ischemic brain in rats. In addition, the contributions of BDNF/TrkB to niacin-induced synaptic plasticity and axon growth were investigated.

Materials and Methods

Animal Middle Cerebral Artery Occlusion and Experimental Groups
Adult male Wistar rats weighing 270 to 300 g (Jackson Laboratory, Bar Harbor, Maine) were subjected to 2 hours of right middle
cerebral artery occlusion (MCAO). Rats were gavaged starting 24 hours after surgery with: (1) saline for vehicle control; or (2) 40 mg/kg Niapsan (KOS Pharmaceuticals) daily for 14 days. Sham-operated rats underwent the same surgical procedure without suture insertion. These rats were euthanized 14 days after MCAO for immunostaining (n=8/group). Additional sets of rats (n=4/group) were euthanized 5 days after MCAO, and the brain tissues were prepared for Western blot assay.

**Histological and Immunohistochemical Assessment**

Rats were euthanized 14 days after stroke. The brains were fixed by transcardial perfusion with saline followed by perfusion and immersion in 4% paraformaldehyde before being embedded in paraffin. A standard paraffin block was obtained from the center of the lesion (bregma –1 mm to +1 mm). A series of 6-μm thick sections were cut from the block. Every 10th coronal section for a total 5 sections was used for immunohistochemical staining. Antibody against Synaptophysin (1:1000; Chemicon), Nogo receptor (NgR; 1:50; Santa Cruz), BDNF (1:300; Santa Cruz), and TrkB (1:500; Santa Cruz) immunostaining was performed. Bielschowsky silver staining was also used as previously described. Control experiments consisted of staining brain coronal tissue sections as outlined previously, but nonimmune serum was substituted for the primary antibody. The immunostaining analysis was performed by an investigator blinded to the experimental groups.

**Immunostaining Quantification**

Like our previous description, synaptophysin, NgR, BDNF, TrkB, and Bielschowsky silver immunohisto stained sections were digitized using a 40× objective (Olympus BX40) using a 3-CCD color video camera (Sony DXC-970MD) interfaced with the Micro Computer Imaging Device (software imaging analysis system (Imaging Research)). Synaptophysin-, BDNF-, and TrkB-positive area was counted in the ischemic boundary zone (IBZ, which adjacent to the ischemic core) in each section. Five sections and 8 views in each section were counted per rat. For semiquantitative measurements of Bielschowsky silver and NgR, the positive stained areas in the bundle of striatum in the IBZ were measured. Data were analyzed in a blinded manner and presented as percentage of positive area for synaptophysin, Bielschowsky silver, NgR, BDNF, and TrkB immunoreactivity, respectively.

**Primary Cultured Neuron and Treatments**

To test whether niacin regulates dendrite outgrowth, primary cultured neuron (PCN) culture was used. Embryonic Day 17 cortical cells were isolated under the 10× microscope from embryonic brain of Wistar rats and cultured in 4-chamber slides with Neurobasal-A medium (GIBCO) containing 2% B27 medium supplement (GIBCO) and antibiotics for 7 days (6 chambers/group) in vitro. To mimic the ischemic condition in vivo, oxygen-glucose deprivation (OGD) was induced in vitro as previously described. OGD was induced within an anaerobic chamber. Briefly, the PCN cultures and the neurite outgrowth in vitro. All data are presented as mean ± SE.

**Quantification of PCN Numbers and Measurement of PCN Neurite Outgrowth**

To count PCN numbers and trace the axonal arbors of fluorescently labeled neurons, the fluorescent photomicrographs were captured at 40× magnification with a digital camera; the TUJ1-positive dendrites were measured using Micro Computer Imaging Device analysis system. The average number of TUJ1-positive PCNs per 40× field and the average length of total 20 neuronal dendrite outgrowth were presented.

**Western Blot**

Rats were euthanized 5 days after MCAO and brain tissues were extracted from the IBZ tissue. Equal amounts of cell lysate were subjected to Western blot analysis, as previously described. PCN cells were harvested after 24 hours of treatment for Western blot. Total protein was isolated from treated cells with TRIzol (Invitrogen) following a standard protocol. Heat the protein samples in 1% sodium dodecyl sulfate for approximately 20 minutes at 60°C to recover the protein activity. Specific proteins were visualized using a SuperSignal West Pico chemiluminescence kit (Pierce). The following primary antibodies were used: anti-BDNF (1:1000; Santa Cruz), anti-TrkB (1:1000; Santa Cruz), and anti-β-actin (1:2000; Sigma).

**Real-Time Polymerase Chain Reaction**

PCN cultures were harvested after 24 hours of treatment and total RNA was isolated with TRIzol (Invitrogen). Quantitative PCR was performed using the SYBR Green RT-PCR method on an ABI 7000 PCR instrument (Applied Biosystems), as previously described. The following primers for RT-PCR were designed using Primer Express software (ABI). BDNF forward: TAC TTC GGT TGC ATG GGC; reverse: GTC AGA CCT TCT GAA CCT GCC. TrkB forward: TCA TCA AGT CAG AGG TGA CAG G; reverse: ACT GGG TAC ACT CCT TCT CTC G. glyceraldehyde-3-phosphate dehydrogenase forward: AGA ACA TCA TCC CTG CAT CC; reverse: CAC ATT GGG GGT AGG AAC AC. Each sample was tested in triplicate, and samples were obtained from 6 independent experiments that were used for analysis of relative gene expression data using the 2^-ΔΔct method.

**Statistical Analysis**

Two-way analysis of variance was performed on data of the percentage of positive area for synaptophysin, NgR, Bielschowsky silver, BDNF, and TrkB in the ischemic brain. If an overall treatment group effect was detected at P<0.05, Tukey test after post hoc test was used for multiple comparison. Independent-sample t test was used for testing the expression of BDNF and TrkB by Western blot assay in the brain tissues between 2 groups. One-way analysis of variance and least significant difference analysis after post hoc test was performed to assess data of BDNF and TrkB expression by Western blot and RT-PCR assay in the ischemic brain and PCN cultures and the neurite outgrowth in vitro. All data are presented as mean ± SE.

**Results**

**Niaspan Treatment of Stroke Increases Synaptic Plasticity and Axon Growth in the Ischemic Brain**

To test whether Niaspan treatment of stroke induces synaptic plasticity and axon growth, synaptophysin, Bielschowsky silver, and NgR immunostaining were performed. Synaptophysin is a marker for presynaptic plasticity and synaptogenesis. Bielschowsky silver is a marker for axons. Niaspan, a neurite outgrowth inhibitor, regulates axonal growth as well as axon regeneration after injury. Figure 1A–L shows that the expression of Bielschowsky silver (Figure 1A–D) and synaptophysin (Figure 1I–L) significantly increased in the...
IBZ, whereas the expression of NgR (Figure 1E–H) significantly decreased in the Niaspan treatment rats compared with MCAO control rats ($P < 0.05, n = 8/group$).

**Niaspan Treatment of Stroke Increases BDNF and TrkB Expression in the Ischemic Brain**

To elucidate the mechanism of Niaspan-induced synaptic plasticity and axon growth, BDNF and TrkB expression in the ischemic brain was measured using immunostaining and Western blot assays. Figure 1M–T shows that Niaspan treatment of stroke significantly increased BDNF (Figure 1M–P) and TrkB (Figure 1Q–T) expression in the IBZ compared with MCAO alone control animals ($P < 0.05, n = 8/group$).

To verify the immunohistostaining data, rat brain tissues were extracted from Niaspan-treatment and MCAO control rats 5 days after MCAO, and Western blot assays were performed. Figure 2A–C shows that BDNF and TrkB expression in the IBZ significantly increased in Niaspan-treated rats compared with MCAO control rats ($P < 0.05, n = 4/group$).

**Niacin Increases BDNF and TrkB Expression in PCNs**

To further investigate the mechanism underlying the BDNF/TrkB pathway mediates niacin-induced synaptic plasticity and axon growth, and whether the increased BDNF/TrkB expression is mediated by niacin treatment-induced increase in HDL, the expression of BDNF and TrkB were also investigated using an in vitro PCN culture model. PCNs were subjected to OGD and treated with niacin (1 mmol/L or 5 mmol/L) and HDL (80 μg/mL) for 24 hours. Figure 2D–H shows that niacin (1 mmol/L or 5 mmol/L) and HDL (80 μg/mL) significantly increased BDNF and TrkB expression in PCNs ($P < 0.05, n = 8/group$).
μg/mL) treatment significantly increased BDNF and TrkB protein and mRNA expression measured by Western blot assay (Figure 2D–F) and RT-PCR (Figure 2G–H) in PCN cultures compared with the nontreatment control (P<0.05, n=6/group).

Niacin Increases Neurite Outgrowth in PCNs
To test whether niacin/HDL affects PCN cell number and increases neurite outgrowth, and whether the BDNF/TrkB pathway plays a role in niacin/HDL-induced neurite outgrowth, PCN cultures were treated with HDL, 1 mmol/L niacin, 5 mmol/L niacin, and a TrkB inhibitor (K252a; 200 nmol/L) for 24 hours after OGD. TUJ1 immunofluorescent staining, TUJ1-positive cell number, and dendrite outgrowth measurements were performed. Figure 3A–I shows that HDL (Figure 3B), 1 mM niacin (Figure 3C), and 5 mM niacin (Figure 3D) significantly increased neurite outgrowth; TrkB inhibitor (Figure 3E), however, significantly decreased neurite outgrowth in PCNs compared with the nontreatment control (Figure 3A). The TrkB inhibitor significantly de-
creased HDL- (Figure 3F) and niacin- (Figure 3G–H) induced neurite outgrowth in PCNs compared with the niacin-treated alone group ($p<0.05$, n=6/group). Niacin and HDL do not affect PCN number; TrkB inhibitor decreases PCN numbers in niacin-treated PCN compared with niacin alone-treated PCN ($p<0.05$, n=6/group). These data indicate that niacin treatment significantly increased neurite outgrowth in PCNs, and niacin-induced neurite outgrowth is, at least partially, mediated by HDL-induced upregulation in BDNF/TrkB.

Discussion

Functional recovery after acute central nervous system injury in humans such as stroke is exceptionally limited, leaving the affected individual with lifelong neurological deficits. This lack of functional recovery such as motor recovery can, at least in part, be attributed to the restriction of axon growth and synaptic plasticity.\(^2\)\(^2\)\(^3\)

Cellular cholesterol modulates axon and dendrite outgrowth and neuronal polarization under culture conditions.\(^24\)\(^25\) Astrocytes are a major source of HDL-C synthesis in the central nervous system.\(^26\) Growing evidence strengthens the link between brain HDL-C metabolism and factors involved in synaptic plasticity. For example, the scavenger receptor, Class B, Type I, binds HDL and mediates the selective transfer of cholesteryl esters and $\alpha$-tocopherol from circulating HDL to cells. Aged scavenger receptor, Class B, Type I knockout mice also display selective impairments in recognition memory and spatial memory.\(^5\) The cholesterol transporter ATP-binding cassette transporter A1 (ABCA1) also plays a critical role in brain cholesterol metabolism. Mice that specifically lacked ABCA1 in the central nervous system exhibit reduced plasma HDL-C levels and changes in synaptic ultrastructure, including reduced synapse and synaptic vesicle numbers. Disturbances in cholesterol transport in the central nervous system are associated with structural and functional deficits in neurons.\(^27\) Thus, agents that increase HDL level may increase synaptic plasticity and axon growth after stroke. Niacin is the most potent HDL-C-increasing drug used in the clinic. Our previous study showed that Niaspan treatment of stroke significantly increases serum HDL-C level and promotes functional outcome in rats.\(^11\) In this study, we find that Niaspan treatment of stroke significantly decreases NgR expression, upregulates synaptophysin, and increases axon growth in the ischemic brain in rats. In addition, HDL and niacin treatment significantly increase neurite outgrowth after OGD in PCN cultures. Therefore, Niaspan promotes functional outcome by increasing HDL-C, which acts in concert to promote synaptic plasticity and axon growth after stroke.

Synaptic plasticity and axon growth induced by niacin treatment of stroke may be mediated by HDL-induced upregulation in the BDNF/TrkB axis. In the mature nervous system, BDNF/TrkB is crucial for regulating neuronal migration, morphological and biochemical differentiation, and controlling synaptic function and synaptic plasticity, at the same time as continuing to modulate neuronal survival.\(^28\)\(^29\) After somatosensory cortex injury, NgR is downregulated specifically in cortical areas deprived of sensory input and in adjacent cortex, whereas BDNF is upregulated.\(^30\)\(^31\) NgR mRNA is downregulated in the dentate gyrus after delivery of BDNF into the rat hippocampus formation in rats subjected to kainic acid.\(^32\) In the present study, niacin treatment of stroke significantly increases BDNF/TrkB expression both in the ischemic brain and in PCN cultures. HDL also significantly increases the expression in BDNF/TrkB and neurite outgrowth in PCN cultures. In addition, a TrkB inhibitor significantly decreases HDL- and niacin-induced neurite outgrowth, which indicates that the BDNF/TrkB axis may mediate, at least in part, niacin/HDL-induced synaptic plasticity and axon growth.

Summary

We demonstrated that niacin treatment of stroke promotes synaptic plasticity and axon growth in rats. The BDNF/TrkB pathways appear to contribute to niacin/HDL-induced synaptic plasticity and axon growth after stroke.

Acknowledgments

We thank Qinge Lu and Sutapa Santra for technical assistance.

Sources of Funding

This work was supported by National Institute on Aging R01 AG031811 (J.C.), National Institute of Neurological Disorders and Stroke PO1 NS23393 (M.C.) and 1R41NS064708 (J.C.), and American Heart Association grant 09GRNT2300151 (J.C.).

Disclosures

None.

References


Niacin Treatment of Stroke Increases Synaptic Plasticity and Axon Growth in Rats
Xu Cui, Michael Chopp, Alex Zacharek, Cynthia Roberts, Benjamin Buller, Madalina Ion and Jieli Chen

Stroke. 2010;41:2044-2049; originally published online July 29, 2010;
doi: 10.1161/STROKEAHA.110.589333
Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2010 American Heart Association, Inc. All rights reserved.
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/41/9/2044

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Stroke can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Stroke is online at:
http://stroke.ahajournals.org//subscriptions/