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Accessibility
**Decreed Cerebrovascular Brain-Derived Neurotrophic Factor–Mediated Neuroprotection in the Diabetic Brain**

Deepi Navaratna,1 Shu-zhen Guo,1 Kazuhide Hayakawa,2 Xiaoying Wang,1 Chiara Gerhardinger,2 and Eng H. Lo1

**OBJECTIVE**—Diabetes is an independent risk factor for stroke. However, the underlying mechanism of how diabetes confers that risk is not fully understood. We hypothesize that secretion of neurotrophic factors by the cerebral endothelium, such as brain-derived neurotrophic factor (BDNF), is suppressed in diabetes. Consequently, such accrued neuroprotective deficits make neurons more vulnerable to injury.

**RESEARCH DESIGN AND METHODS**—We examined BDNF protein levels in a streptozotocin-induced rat model of diabetes by Western blotting and immunohistochemistry. Levels of total and secreted BDNF protein were quantified in human brain microvascular endothelial cells after exposure to advanced glycation end product (AGE)-BSA by enzyme-linked immunosorbent assay and immunocytochemistry. In media transfer experiments, the neuroprotective efficacy of conditioned media from normal healthy endothelial cells was compared with AGE-treated endothelial cells in an in vitro hypoxic injury model.

**RESULTS**—Cerebrovascular BDNF protein was reduced in the cortical endothelium in 6-month diabetic rats. Immunohistochemical analysis of 6-week diabetic brain sections showed that the reduction of BDNF occurs early after induction of diabetes. Treatment of brain microvascular endothelial cells with AGE caused a similar reduction in BDNF protein and secretion in an extracellular signal–related kinase-dependent manner. In media transfer experiments, conditioned media from AGE-treated endothelial cells were less neuroprotective against hypoxic injury because of a decrease in secreted BDNF.

**CONCLUSIONS**—Taken together, our findings suggest that a progressive depletion of microvascular neuroprotection in diabetes elevates the risk of neuronal injury for a variety of central nervous system diseases, including stroke and neurodegeneration. *Diabetes 60:1789–1796, 2011*

Diabetes mellitus significantly elevates the risk for a variety of neurologic diseases, including stroke (1–3). Age-adjusted incidence rates suggest that diabetic patients are three times more likely to have a stroke compared with nondiabetic patients, a disparity that is seen across multiple racial/geographic groups (4–7). In addition, diabetes is associated with more severe strokes, in-hospital mortality, and slower recovery compared with nondiabetic individuals (8–11). Diminished cognitive abilities are found in patients with type 1 diabetes, whereas type 2 diabetes is known to also affect learning and memory (12,13). Many population-based studies have found an association between diabetes and an increased risk of developing Alzheimer’s disease and vascular dementia (14,15).

How does diabetes confer this elevated risk for progressive neuronal injury? In this study, we explored the hypothesis that cerebrovascular neurotrophic protection is reduced in diabetes, thereby causing progressive neuronal dysfunction. Neurons do not exist in isolation, and symbiotic trophic coupling mechanisms exist between cerebral microvasculature and neurons (16–21). Recent studies suggest that endothelial cells serve endocrine functions in the brain by secreting neuroprotective factors, such as brain-derived neurotrophic factor (BDNF) (22,23). In this study, we investigate the implications of decreased cerebrovascular BDNF–mediated neurotrophic function in diabetes in an effort to examine the role of vascular dysfunction in diabetes complications of the brain.

**RESEARCH DESIGN AND METHODS**

**Diabetic rat model of diabetes.** All experiments were performed following an institutionally approved protocol in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals. Diabetes was induced with streptozotocin (STZ) (57.5 mg/kg body wt) dissolved in citrate buffer, pH 4.5, through a tail-vein injection. Induction of diabetes was verified after 3 days, and rats with blood glucose concentrations >250 mg/dL were included in these studies. Body weight was measured three times per week, and 3–4 units of neutral protamine Hagedorn insulin (0.5 IU) was administered subcutaneously, as needed, to prevent weight loss and ketosis. The diabetic rats were killed, and brains were collected after perfusion along with age-matched controls. Cerebral cortex was dissected from whole brains for microvessel-enriched fractions and stored at −80°C before fraction preparation. At the time of death, blood was obtained by cardiac puncture for estimation of glycosylated hemoglobin (Glyco-Tek Affinity Kit, Helena Laboratories, Beaumont, TX).

**Brain microvessel preparation by dextran gradient centrifugation.** Isolation of microvessel-enriched fractions from rat tissue was performed as described by Wu et al. (24) and Galea and Estrada (25). Briefly, brain tissues were collected from rats after PBS perfusion. The cortical gray matter was dissected and rolled on filter paper to remove the large blood vessels and then homogenized with PBS and centrifuged. After washing with PBS, the pellet was resuspended in four volumes of 18% dextran and centrifuged at 1,500g for 20 min. The new pellet was saved, and the remaining tissue was reprocessed twice similarly. All three pellets were pooled, washed again with PBS, and lysed in lysis buffer (Cell Signaling Technology, Danvers, MA) with protease inhibitors for immunoblotting. Microvessel-enriched fractions in all experiments were not pooled and were derived from a single animal cortex.

**Immunoochemical procedures.** For immunohistochemistry, whole brain sections (2-mm thick) were prepared from frozen rat brains. Sections were kept frozen at −80°C, after which they were air-dried, fixed in ice-cold acetone, blocked with 5% BSA, and probed with an anti-BDNF rabbit polyclonal antibody (Millipore, Billerica, MA). For immunocytochemistry, cells were seeded onto gelatin-coated glass coverslips and maintained in complete media. Cells were fixed in ice-cold ethanol, rinsed with PBS, blocked with 5% BSA, and probed with an anti-BDNF antibody (Millipore) or anti-CD31 antibody (BD Biosciences, San Diego, CA).

**Cell culture and treatments.** Primary human brain microvessel endothelial cells were purchased from Cell Systems Corporation (Kirkland, WA), mostly.
TABLE 1

Body weight and glycated hemoglobin of study rats (6 months’ diabetes duration)

<table>
<thead>
<tr>
<th></th>
<th>Body weight at start (g)</th>
<th>Body weight at end (g)</th>
<th>Glycated hemoglobin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nondiabetic</td>
<td>260.5 ± 48.5</td>
<td>606.7 ± 58.1</td>
<td>4.2 ± 0.22</td>
</tr>
<tr>
<td>Diabetic</td>
<td>253.2 ± 50.9</td>
<td>385.7 ± 30.9</td>
<td>14.2 ± 1.6*</td>
</tr>
</tbody>
</table>

Percentage of glycated hemoglobin in blood samples of 6-month diabetic rats was significantly higher than in age-matched nondiabetic rats. Values are mean ± SD. Statistical analysis was performed with unpaired t test. *P < 0.05 compared with nondiabetic rats.

RESULTS

BDNF expression is reduced in diabetic rat brain endothelium in vivo. Diabetes was induced in adult male SD rats by STZ injection. After 6 months of diabetes, the diabetic rats showed lower body weight and higher glycated hemoglobin levels than the age-matched nondiabetic control rats (Table 1).

Diabetic and nondiabetic rat cerebral cortices were extracted, and microvessel-enriched fractions were prepared for Western blotting. These fractions were positive

![Diagram A](Image 345x255 to 427x315)

**A** Graph showing BDNF protein levels in the diabetic rat cortex.

![Diagram B](Image 88x125 to 247x189)

**B** Graph showing NSE and GFAP protein levels in the diabetic rat cortex.

![Diagram C](Image 110x285 to 211x315)

**C** Graph showing BDNF and TBP protein levels in the diabetic rat cortex.

![Diagram D](Image 170x295 to 220x345)

**D** Graph showing BDNF immunoblot density in control and diabetic rat cortices.

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for vascular endothelial cadherin, confirming their endothelial identity (Fig. 1A), whereas staining for neuron-specific enolase and glial fibrillary acidic protein was weak, suggesting that they were not overly contaminated with neurons or astrocytic components (Fig. 1B). A 16-kDa band corresponding to bioactive BDNF protein was detected in all fractions. BDNF levels were significantly reduced in microvessel-enriched fractions from diabetic rats compared with nondiabetic rats (Fig. 1C and D). To confirm our findings, 6-week normal and diabetic rat brains were sectioned and prepared for immunohistochemistry. BDNF staining was observed in the blood vessels of the cortex. BDNF levels appeared to be lower in diabetic endothelium compared with normal vessels (Fig. 2).

**AGE-BSA treatment decreases BDNF levels in brain endothelial cells.** Our in vivo data suggested that endothelial BDNF was suppressed in diabetic endothelium. To assess the mechanisms involved, we switched to an in vitro experimental model using AGE-BSA to mimic endothelial stress triggered during diabetes. Human microvascular brain endothelial cells were incubated with AGE-BSA for 48 h in serum-free media. This treatment caused a change in cell morphology, with changes in cell shape and loss of cell–cell contact (Fig. 3A).

After 48 h, BDNF protein levels in the cell lysates were assessed by Western blotting. AGE-BSA clearly induced a dose-dependent reduction in BDNF levels (Fig. 3B). Compared with normal BSA controls, BDNF levels were significantly reduced in the AGE-BSA–treated endothelial cells (Fig. 3C and D). No changes in cell viability were noted, suggesting that these reductions in BDNF were not indirectly caused by nonspecific cytotoxicity (Fig. 3E).

Immunostaining confirmed our Western blot findings. In normal human brain endothelial cells, cytoplasmic BDNF staining was observable in the perinuclear zone and in vesicles being trafficked to the plasma membrane (Fig. 4A). In AGE-BSA–treated endothelial cells, there was a clear reduction in BDNF staining compared with untreated controls (Fig. 4A). Consistent with these immunostaining observations, AGE-BSA affected the secretion of BDNF into extracellular space. Standard enzyme-linked immunosorbent assays confirmed that conditioned media from brain endothelial cells contained BDNF. AGE-BSA–treated endothelial cells showed a significant decrease in secreted BDNF compared with untreated cells or controls treated with normal BSA (Fig. 4B).

**AGE-BSA–induced reduction of BDNF is dependent on ERK/MAP kinase signaling.** AGEs can trigger many intracellular signaling pathways. Because ERK/mitogen-activated protein (MAP) kinase is one of the major mechanisms that allow endothelial cells to respond to extracellular stimuli, we asked whether this signaling pathway might be involved in the phenomenon of AGE-BSA–induced down-regulation of BDNF. Human brain endothelial cells were exposed to AGE-BSA for 48 h, and then cell lysates were probed for changes in ERK and phospho-ERK. Levels of phospho-ERK were significantly elevated in AGE-BSA–treated cells with no change in total ERK (Fig. 5A and B). Next, we tested the effects of the potent MEK/ERK inhibitor U0126 to provide pharmacologic evidence of causality. As expected, AGE-BSA decreased BDNF expression in brain endothelial cells. Blockade of ERK signaling with U0126 decreased phospho-ERK levels and significantly prevented this AGE-BSA–induced suppression of BDNF (Fig. 5C and D). Concomitantly, blockade of ERK signaling also interfered with the ability of AGE-BSA to decrease the secretion of BDNF into conditioned media (Fig. 5E). Taken together, these data suggest that the ability of AGE-BSA to suppress endothelial BDNF requires ERK/MAP kinase signaling.

**BDNF-mediated neuroprotection is lost after AGE-BSA treatment in brain endothelial cells.** Because AGE-BSA decreased the production of BDNF, we hypothesized that this would mean that “diabetic” endothelium would lose the ability to trophically protect neurons. First, we confirmed that AGE-BSA does not directly kill neurons (Fig. 6A). Next, media transfer experiments were performed whereby brain endothelial-conditioned media were added to primary mouse neurons subjected to hypoxia for 24 h. As expected, hypoxia killed neurons (Fig. 6B and C), and, as previously reported, conditioned media from normal healthy brain endothelial cells were significantly neuroprotective (Fig. 6B and C). In contrast, conditioned media from AGE-BSA–treated endothelial cells were no longer neuroprotective (Fig. 6A and B), consistent with their reduction in BDNF levels. Addition of exogenous BDNF back into the culture media restored protection and decreased neuronal death (Fig. 6B and C). Finally, the role of ERK signaling in the pathway was confirmed by U0126 experiments. Blockade of ERK with U0126 not only prevented endothelial BDNF suppression (Fig. 6D) but also restored neuroprotection (Fig. 6C).

**DISCUSSION**

Symptomatic strokes caused by large artery disease have garnered much attention in cerebrovascular investigations.

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**FIG. 2.** BDNF expression is reduced in the diabetic brain endothelium. Representative images of cortical sections (2-mm thick) from 6-week diabetic and age-matched nondiabetic rats immunostained for BDNF. Blood vessels (arrows) are visualized by CD31 staining (left). Cortex microvessels from a diabetic rat show decreased BDNF immunofluorescence when compared with those of a nondiabetic rat (right). Magnification 40×. (A high-quality digital representation of this figure is available in the online issue.)

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In contrast, small vessel dysfunction in the deeper layers of the brain cortex has received less emphasis, even though it comprises approximately one-third of all symptomatic strokes (26). This problem may be especially important for diabetic patients who present a higher incidence of lacunar stroke with recursive hemorrhagic episodes (6,27). Although the effects of acute hyperglycemia on brain injury are well documented in global and focal ischemia models (28), there is a bigger need to first study the effects of long-term diabetes on the brain. Emerging studies support the notion that preemptive vascular disease in diabetes affects ischemic brain injury before, during, and after stroke by modifying adaptive neovascularization responses and post-ischemic tissue remodeling (29,30). However, there is little clarity on baseline changes in cerebrovascular function in diabetes and the relative contribution of major diabetic stressors to cerebrovascular disease. Our findings suggest that cellular stress from AGEs leads to reduced cerebrovascular secretion of BDNF, a major mediator of neuroprotection.

A large body of evidence suggests that AGEs are central mediators of almost all diabetic vascular complications (31–34), beyond effects of prolonged hyperglycemia. A marked increase in deposition and accumulation of protein glycation end products in blood vessels has been linked to corresponding neuronal impairment, cognitive dysfunction, and dementia in several streams of investigation. In human brain tissue, increased cerebrovascular carboxymethyl lysine-AGE staining was observed in people with diabetes and clinical dementia, strengthening the argument that vascular accumulation of AGEs correspond with clinical presentations of neuronal injury (35). Notably, an accumulation of AGEs in microvessels along with its receptor, RAGE, is reported to drive microvascular AGE-RAGE-mediated chronic inflammation in Alzheimer pathologies (36). In addition, administration of AGE-BSA significantly increased cerebral infarct size in a rat model of focal cerebral ischemia, suggesting that increased severity of stroke associated with diabetes might be characterized by AGE accumulation (37).

In our study, treatment of primary brain microvascular cells with AGE-BSA significantly suppressed the production of BDNF via ERK/MAP kinase signaling pathways, whereas treatment with high glucose alone did not (data not shown). Subsequently, because of the loss of BDNF, endothelial cells exposed to AGE-BSA were no longer able to protect neuronal cultures against hypoxic injury. Although our in vitro model of AGE-BSA treatment cannot be equated to in vivo diabetic conditions, it is useful in assessing the direct contribution of AGEs to neurotrophic reduction observed in vivo.

We chose to study BDNF levels at 6 weeks and 6 months of diabetes as a suitable time window to characterize early chronic injury in diabetes. Several studies have focused on this early duration of diabetes to capture adaptive...
of trk receptors leads to widespread neuronal death in developing and adult DRG neurons (41). In vivo blockade (or other trophic factors) contributes to adult brain ho-
diabetic brain directly. Nevertheless, it is now accepted extrapolated, as yet, to BDNF dependence in the adult
able to a second insult. This cannot be unequivocally ex-
cortical embryonic neurons only provide proof of concept
previous studies. Our media transfer experiments with
mechanism underlying neuronal dysfunction observed in
support, as observed in our study, could be a molecular
in the diabetic brain. Reduced cerebrovascular BDNF
expression was decreased in the diabetic endothelium. Al-
though these findings point to endothelial dysfunction as a
mechanism for loss of neuroprotection in the diabetic
brain, they remain reductionist, given that other cell types
can secrete BDNF in the brain. The existence of compen-
satory mechanisms in the parenchyma that make up for
the microvascular deficit cannot be ruled out. To dissect
the singular contribution of the endothelium, targeted si-
lencing of the BDNF gene by conditional knockout exper-
iments or by small interfering RNA strategy will be required.
Nevertheless, there is reason to believe that in the deeper
cortical layers of the brain, with a high vessel-to-neuron
ratio, the endothelia serve as major life-supporting reposi-
tories of trophic growth factors.

Our data suggest that BDNF is a leading candidate of cerebrovascular trophic coupling mechanisms. However, the autocrine and paracrine functions of brain endothelium are likely to include many trophic signals. Further investigation is required to dissect the interactions with other neurotrophic factors. The diabetes-induced decrease of BDNF in cerebral microvessels seems to be mediated by AGEs via activation of the ERK signaling pathway. These findings are consistent with known receptor-mediated effects of AGEs; however, nonreceptor-mediated effects of AGEs cannot be ruled out, and more investigation is re-
quired to demonstrate a direct involvement of RAGE in this pathway. Although our in vitro model of AGE-BSA
treatment cannot be equated to in vivo diabetic conditions,
it is useful in assessing the direct contribution of AGEs to
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In conclusion, our study identified a vascular mecha-
nism that may explain why diabetes increases risk for
neurologic injury such as stroke. Strategies to preserve
neurovascular trophic coupling mechanisms may lead to
the development of novel preventive neuroprotective
therapy in diabetes.

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lowship from the American Heart Association.

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were reported.

D.N. designed and conducted experiments, analyzed
data, and wrote the manuscript. S.-z.G. provided technical
assistance and reviewed the manuscript. K.H. performed
and guided immunochemical procedures. X.W. provided
diabetic brain sections for study. C.G. provided technical
assistance and reviewed the manuscript. K.H. performed

and maladaptive events in diabetes (28). Degeneration
of endothelial cells and smooth muscle cells in cerebral
cortical arterioles was observable between 14 and 16 weeks
in the STZ model of diabetes (38). Increased capillary
basement membrane thickening, pericyte degeneration, and
decreased cortical capillary density were observed between
4 and 8 months of diabetes in the rats with STZ-induced
diabetes (39). A dramatic loss of neocortical neurons co-
incident with marked shortening of capillary network in the
neocortical tissue was observed after 1 year of diabetes
in the rat with STZ-induced diabetes by morphometric
quantification (40). Taken together, a progressive depletion
of microvascular neurotrophic support seems imminent
in the diabetic brain. Reduced cerebrovascular BDNF
support, as observed in our study, could be a molecular
mechanism underlying neuronal dysfunction observed in
previous studies. Our media transfer experiments with
cortical embryonic neurons only provide proof of concept
on how such a deficit might render neurons more vulnera-
table to a second insult. This cannot be unequivocally ex-
trapolated, as yet, to BDNF dependence in the adult
diabetic brain directly. Nevertheless, it is now accepted
that BDNF is not only important for neural development, it
(or other trophic factors) contributes to adult brain ho-
meostasis as well. BDNF is required for survival of both
developing and adult DRG neurons (41). In vivo blockade
of trk receptors leads to widespread neuronal death in
adult mouse brains (42), and a conditional BDNF knock-
out mouse shows disrupted striatal neuron survival and
function (43). In this context, our data provide a potential
mechanism that may underlie the increased neuronal vul-
nerability of diabetic brains.

Endothelial cells are a major source of neuroprotective
BDNF protein in the brain (44–46). In addition, BDNF has
unique systemic and metabotrophic functions (47). Our
findings also may be consistent with the clinical disease
literature. Cerebral output and plasma levels of BDNF are
reduced in individuals with type 2 diabetes (48–50). Be-
cause these changes occur in an insulin-dependent manner,
it suggests that glycemic memory and BDNF status might
be linked (49). In our study, we found that BDNF protein
levels were reduced in microvessel-enriched fractions of
6-month diabetic rat cortices and that BDNF protein ex-
pression was decreased in the diabetic endothelium. Al-
though these findings point to endothelial dysfunction as a
mechanism for loss of neuroprotection in the diabetic
brain, they remain reductionist, given that other cell types
can secrete BDNF in the brain. The existence of compen-
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neurovascular trophic coupling mechanisms may lead to
the development of novel preventive neuroprotective
therapy in diabetes.
diabetic samples, contributed to discussion, and edited the manuscript. E.H.L. supervised research design, analyzed data, and co-authored the manuscript.

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FIG. 6. BDNF-mediated neuroprotection is lost after AGE-BSA treatment of brain endothelial cells. A: AGE-BSA is not directly neurotoxic. Primary embryonic mouse neurons were treated with AGE-BSA (50 μg/mL) under normoxic conditions for 24 h. Cytotoxicity was assessed by MTT assay. B: Phase-contrast images of primary mouse neurons after 24 h of hypoxia with different treatments. Hypoxia kills neurons. Conditioned media from normal untreated brain endothelial cells reduce neurotoxicity. Conditioned media from AGE-BSA-treated brain endothelial cells are no longer neuroprotective. Addition of exogenous BDNF rescues neurons again. C: Quantitative comparison of MTT cytotoxicity assays. *P < 0.05 normoxic neurons vs. hypoxic neurons and normoxic neurons vs. hypoxic neurons in E-CM collected after AGE-BSA treatment. #P < 0.05 hypoxic neurons vs. hypoxic neurons in E-CM and hypoxic neurons in E-CM collected after AGE-BSA treatment vs. hypoxic neurons in E-CM collected after AGE-BSA treatment with exogenous BDNF added, and hypoxic neurons in E-CM collected after AGE-BSA treatment vs. hypoxic neurons in E-CM collected after AGE-BSA treatment with U0126. N = 5 per group.

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