Early effects of high-fat diet on neurovascular function and focal ischemic brain injury

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1Charlie Norwood Department of Veterans Affairs Medical Center, Augusta, Georgia; 2Department of Physiology, Medical College of Georgia, Georgia Regents University, Augusta, Georgia; 3Vascular Biology Center, Medical College of Georgia, Georgia Regents University, Augusta, Georgia; 4Institute of Molecular Medicine and Genetics, Medical College of Georgia, Georgia Regents University, Augusta, Georgia; 5Program in Clinical and Experimental Therapeutics, Department of Clinical and Administrative Pharmacy, College of Pharmacy, University of Georgia, Augusta, Georgia; and 6Department of Pharmacology, School of Medicine of Ribeirao Preto, University of Sào Paulo, Ribeirao Preto, São Paulo, Brazil

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Li W, Prakash R, Chawla D, Du W, Didion SP, Filosa JA, Zhang Q, Brann DW, Lima VV, Tostes RC, Ergul A. Early effects of high-fat diet on neurovascular function and focal ischemic brain injury. Am J Physiol Regul Integr Comp Physiol 304: R1001–R1008, 2013. First published April 10, 2013; doi:10.1152/ajpregu.00523.2012.—Obesity is an independent risk factor for acute ischemic stroke and focal ischemic brain injury. Early effects of high-fat diet (HFD) on neurovascular function and ischemic stroke outcomes remain unclear. The goal of this study was to test the hypotheses that HFD beginning early in life 1) impairs neurovascular coupling, 2) causes cerebrovascular dysfunction, and 3) worsens short-term outcomes after cerebral ischemia. Functional hyperemia and parenchymal arteriole (PA) reactivity were measured in rats after 8 wk of HFD. The effect of HFD on basilar artery function after middle cerebral artery occlusion (MCAO) and associated O-GlcNAcylation were assessed. Neuronal cell death, infarct size, hemorrhagic transformation (HT) frequency/severity, and neurological deficit were evaluated after global ischemia and transient MCAO. HFD caused a 10% increase in body weight and doubled adiposity without a change in lipid profile, blood glucose, and blood pressure. Functional hyperemia and PA relaxation were decreased with HFD. Basilar arteries from stroke HFD rats were more sensitive to contractile factors, and acetylcholine-mediated relaxation was impaired. Vascular O-GlcNAcylated protein content was increased with HFD. This group also showed greater mortality rate, infarct volume, HT occurrence rate, and HT severity and poor functional outcome compared with the control diet group. These results indicate that HFD negatively affects neurovascular coupling and cerebrovascular function even in the absence of dyslipidemia. These early cerebrovascular changes may be the cause of greater cerebral injury and poor outcomes of stroke in these animals.

Cerebral ischemia; high-fat diet; hemorrhagic transformation; neurovascular coupling; vascular dysfunction

Obesity is an independent risk factor for acute ischemic stroke (AIS) (19, 36). An alarming recent report showed that the prevalence of AIS dramatically increased in children and young adults, which positively correlated with increases in risk factors including obesity, lipid disorders, and diabetes (13). Clinical studies also suggest that obesity is an independent predictor of unfavorable functional outcome and mortality in AIS patients treated with tissue plasminogen activator (tPA), the only therapeutic option these patients have (39, 40). Given that stroke is the leading cause of disability and that the obesity epidemic is on the rise these clinical and social problems are expected to get worse, and therefore early interventions are necessary. While experimental studies in genetic or diet-induced obesity models have shown increased cerebral infarct size and poor outcomes of stroke (7, 25, 32, 33), the early impact of a high-fat diet (HFD) before the development of obesity on AIS injury and functional outcomes is not known. It is known that the brain relies heavily on constant blood flow for proper function. Two important mechanisms that contribute to the regulation of cerebral blood flow are autoregulatory behavior of cerebral vessels and functional hyperemia upon increased neuronal activity (11, 16, 20). HFD can negatively affect vascular function, as demonstrated by increased myogenic tone and endothelial dysfunction in diet-induced as well as genetic models of obesity (7, 8, 24, 32, 33). The effect of a HFD on neurovascular coupling and cerebrovascular reactivity after an ischemic insult especially in the absence of metabolic abnormalities is unknown. To address this key deficit in our knowledge, the present study tested the hypotheses that HFD 1) impairs neurovascular coupling, 2) causes cerebrovascular dysfunction, and 3) worsens outcomes after cerebral ischemia, even in the absence of obesity.

METHODS

Animals. This study was conducted in accordance with the National Institutes of Health guidelines for the care and use of animals in research and was approved by the Division of Laboratory Animal Services at the Georgia Health Sciences University. Male Wistar rats (Harlan Laboratories, Indianapolis, IN; 4–5 wk old, n = 64) were fed either an isocaloric control diet (CD, 10% fat) or a HFD (45% fat; Research Diets, New Brunswick, NJ) for 8 wk ad libitum. Blood pressure was measured by tail cuffs (Kent Scientific, Torrington, CT), and blood glucose levels were measured with a glucometer (FreeStyle, Abbott Diabetes Care, Alameda, CA).

Metabolic parameters. At death, blood was collected and processed for plasma analyses. Adipose tissue from the subcutaneous, perirenal, and epididymal depots was collected and weighed separately. Total adiposity (all depots combined) was normalized to body weight and expressed as percent body weight. Plasma insulin (ALPCO Diagnostics, Salem, NH), triglycerides, and cholesterol (Wako USA, Richmond, VA) were measured.

Measurement of functional hyperemia. Functional hyperemia was assessed 2 days prior to ischemia injury by measuring the cerebral blood flow (CBF) change in the somatosensory cortex upon whisker stimulation (21, 22). Animals were anesthetized with ketamine-xylazine (100 and 10 mg/kg) injection, and trimmed contralateral whiskers were gently stroked at a frequency of 2.5 Hz with a cotton tip attached to a vortex. The PIM3 laser Doppler scanning system (LDS, Perimed, http://www.ajpregu.org

http://ajpregu.physiology.org/ Downloaded from http://ajpregu.physiology.org/ on October 14, 2017
Ardmore, PA) was programmed to scan an area covering somatosen-
sory cortex, which is supplied by the middle cerebral artery (MCA),
without tissue contact. CBF changes were expressed as percent
increase relative to resting levels.

Brain slice preparation. Parenchymal arteriole (PA) function was
assessed with a well-established brain slice preparation (4, 5, 15).
After death, the brain was removed and 300-μm-thick coronal slices
were cut in ice-cold artificial cerebrospinal fluid (aCSF) containing
(mM) 3 KCl, 120 NaCl, 1 MgCl2, 26 NaHCO3, 1.25 NaH2PO4, 2
CaCl2, 10 glucose, and 0.4 L-ascorbic acid, equilibrated with 95%
O2-5% CO2. Ascobic acid was added to reduce cell swelling
associated with oxidative stress. An aCSF with identical composition
was used for bath perfusion in all experiments, except for those
assessing the effects of high external K+ concentration ([K+]o), in
which control aCSF contained 4.2 mm KCl and KCl replaced NaCl to
increase [K+]o to 10 mM. Osmolality of aCSF was ~290 mosmoll
kgH2O. After the slicing procedure, slices were kept at room temper-
ature in aCSF equilibrated with 95% O2-5% CO2 (pH ~7.45) until
use.

Video microscopy. Diameter changes in cortical arterioles (<30-μm
internal diameter) were recorded with an upright Zeiss Axioplan 2FS
microscope (Carl Zeiss USA, Thornwood, NY) equipped with infrared-
differential interference contrast (IR-DIC) optics, a water-immersion
objective, and an EMCCD camera (iXon+885, Andor Tech, South
Windsor, CT). Images were acquired at 1 frames/s and visualized and
stored with IQ software (Andor Tech). The slices were perfused with
aCSF (35 ± 2°C) gassed with 95% O2-5% CO2 and were allowed to
equilibrated for ≥10 min prior to the beginning of recording. Only one
arteriole per slice was recorded. Slices were perfused with the thrombox-
ane A2 receptor agonist U-46619 to induce vasoconstriction, and test
solutions were applied in the constant presence of U-46619 after a stable
preconstriction was attained. Vessels that did not respond to U-46619
were not included in the analysis. Data from arteriolar diameter (IR-DIC)
experiments were analyzed with custom software created by Dr. Adrian
D. Bonev (Univ. of Vermont). Changes in the internal (luminal) diameter
of arterioles were determined from averaged measurements taken from
multiple points across the arteriolar lumen. Baseline diameter (repre-
sented as 100%) was determined during the first ~10 min of sampling,
before any experimental stimulation. All arteriolar diameter values are
expressed as percentage relative to baseline. Vascular tone is expressed as
degree of constriction relative to baseline.

Models of ischemia. Focal cerebral ischemia (FCI) was induced by
transient MCA occlusion (MCAO) as previously described (10).
Briefly, all animals were anesthetized with 2% isoflurane via inhalation.
The right MCA was occluded for 3 h with a 19- to 21-mm 3-0
surgical nylon filament, which was introduced from the external
carotid artery lumen into the internal carotid artery to block the origin
of the MCA. The rectal temperature was maintained at 37°C with a
heating pad (Fine Science Tools, Foster City, CA). The cerebral
perfusion was monitored with LDS to confirm successful occlusion or
reperfusion. In a subset of animals, global cerebral ischemia (GCI)
was induced (10 min occlusion, 7-day reperfusion) as an alternative
method of ischemia. For GCI, all animals (except sham control
animals) underwent four-vessel occlusion performed as described
previously (43). Briefly, 24 h after electrocautery of the vertebral
arteries, the common carotid arteries (CCAs) were occluded with
aneurysm clips to induce 10-min forebrain ischemia. Animals that lost
their righting reflex within 30 s and whose pupils were dilated and
unresponsive to light during occlusion were selected for the experi-
ments. The clips were then removed, and the blood flow through the
CCAs was confirmed before the wound was sutured. The animals of the
sham group underwent identical procedures except that the CCAs
were not occluded. Rectal temperature was maintained at 36.5–37.5°C
throughout the experiment with a thermal blanket.

Isolated vessel studies. At 24 h after FCI, 2-mm basilar artery
segments were isolated and mounted for myography for isometric
tension recordings as described previously (27). Concentration-re-

RESULTS

Metabolic parameters. Eight-week HFD significantly increased body weight and adiposity without affecting plasma lipids (Table 1). Adipose tissue in all depots (subcutaneous, peritoneal, and epididymal) was increased. There were no differences in blood glucose, blood pressure, or plasma insulin levels.

Effect of HFD on cerebrovascular function. The effect of HFD on cerebrovascular function was assessed by several methods looking at vessels of different caliber. First, functional hyperemia was measured to evaluate the response of smaller arterioles by using the relative change in CBF upon whisker stimulation. As shown in Fig. 1, A and B, HFD animals displayed blunted change in CBF, indicating impaired neurovascular coupling.

Next, the tone and relaxation properties of PAs were measured in slice preparations. We previously showed that the degree of tone in PAs dictates the polarity of the vascular response to vasoactive signals released by activated astrocytes, with decreased tone favoring constrictions and increased tone favoring dilations (3). To determine whether the HFD induced any change in vascular tone, cortical PAs were exposed to 150 nM U-46619 to induce arteriolar constriction. While no statistically significant differences were achieved, arterioles from the HFD group showed lower baseline tone (23.9 ± 4.8%, n = 11) compared with the control group (35.7 ± 9.9%, n = 6). The values of the control group were comparable to those previously reported by us in Sprague-Dawley rats fed chow diet (3). In agreement with our previous observations, reduced tone such as that observed in the HFD group resulted in a reduced vasodilatory response to 10 mM K+ (Fig. 1C).

Third, the contractile and dilatory responses of basilar arteries before and after focal ischemic injury were determined. There was no effect of HFD on these functions if the animals were not subjected to stroke (data not shown). However, when basilar arteries were tested at 24 h after MCAO, the concentration-response curves to several vasoconstrictors including 5-HT, ET-1, and U-46619 were left-shifted, indicating enhanced sensitivity, as well as greater maximum responses (Fig. 2, A–C). Endothelium-dependent relaxation was also significantly impaired in the HFD group (Fig. 2D). O-GlcNAc levels in the basilar arteries of HFD-fed animals were significantly greater, suggesting that this posttranslational modification can be the underlying mechanism of increased contractility in basilar arteries (Fig. 3).

Effect of HFD on neurovascular injury after ischemia-reperfusion. When focal ischemic injury was induced by 3-h MCAO and 21-h reperfusion, the percent drop in CBF after occlusion (40 ± 5% in CD and 38 ± 4% in HFD compared with baseline) or recovery after reperfusion (17 ± 3% in CD and 20 ± 11% in HFD compared with occlusion) was similar in both groups, but infarct size was higher in the HFD group than in the control group (Fig. 4A). Mortality rate was 11% (2 of 18) and 33% (6 of 18) in CD and HFD groups, respectively (P = 0.09). When ischemic injury was induced by 10-min GCI followed by 7-day reperfusion, mortality was 50% in the HFD group. Hippocampal CA1 sections were collected from animals that survived the surgery, and TUNEL staining was performed to assess apoptotic cell death. There was no difference in apoptotic cell death between sections from CD and HFD rats (Fig. 4B). In the focal ischemia model, there was no difference in edema between the groups but the incidence of macroscopic HT as well as tissue Hb levels were increased in the HFD group (Fig. 5).

Effect of HFD on functional outcome after ischemia-reperfusion. A composite score derived from Bederson’s score and beam walking showed poorer HFD rat performance on the behavioral tests compared with the CD group (Fig. 6A; 7.8 ± 1.3 in CD vs. 4.0 ± 0.8 in HFD, P < 0.05). However, there was no difference on grip strength (Fig. 6B; 1.11 ± 0.07 kgF in CD vs. 0.90 ± 0.08 kgF in HFD, P = 0.07).

Table 1. Metabolic parameters of CD and HFD groups

<table>
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<tr>
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<th>CD (n = 18)</th>
<th>HFD (n = 18)</th>
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<tbody>
<tr>
<td>Body wt, g</td>
<td>452 ± 9</td>
<td>494 ± 9*</td>
</tr>
<tr>
<td>Adiposity, % body wt</td>
<td>5.2 ± 0.5</td>
<td>9.3 ± 1.2*</td>
</tr>
<tr>
<td>Triglyceride, mg/dl</td>
<td>57 ± 4</td>
<td>69 ± 9</td>
</tr>
<tr>
<td>Cholesterol, mg/dl</td>
<td>49 ± 3</td>
<td>61 ± 8</td>
</tr>
<tr>
<td>Insulin, ng/ml</td>
<td>1.4 ± 0.2</td>
<td>1.2 ± 0.2</td>
</tr>
<tr>
<td>SBP, mmHg</td>
<td>112 ± 2</td>
<td>115 ± 3</td>
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Values are means ± SE for n rats. CD, control diet; HFD, high-fat diet; SBP, systolic blood pressure. *P < 0.05.
DISCUSSION

This study provides novel information about the early impact of HFD on cerebrovascular function and stroke outcomes in the absence of overt metabolic changes. First, HFD impairs communication between neurons and penetrating arterioles even in the absence of an ischemic insult. Second, ischemic injury serves as a second hit and causes large-artery dysfunction in stroked HFD rats that is not otherwise detectable in HFD-alone animals. Third, stroke in HFD-fed animals that do not have obesity or metabolic derangement worsens neurovas-

![Diagram](image1)

Fig. 2. Effect of HFD on basilar artery function after focal cerebral ischemia [middle cerebral artery occlusion (MCAO)]-reperfusion. HFD increased the contractile response to multiple agonists (A–C) and also reduced endothelium-dependent relaxation (D). Experimental values of contraction were calculated relative to the contractile response produced by 120 mM KCl, which was taken as 100% (n = 8/group). Values are means ± SE. *P < 0.05.

![Diagram](image2)

Fig. 3. O-GlcNAcylation in basilar artery after focal cerebral ischemia-reperfusion. An increase in total O-GlcNAc-protein content was seen in the HFD-fed group after MCAO (n = 6/group). A representative Western blot image of O-GlcNAc-modified proteins and actin control is given in A, and cumulative data are summarized in B. Representative images were selected from the same membrane, and splices are indicated by dashed lines. Values are means ± SE. *P < 0.05, n = 4.
cular injury and functional outcomes. Collectively, these data suggest that detrimental effects of HFD start early in the disease process and preventive measures should be implemented as early as possible.

HFD or obesity is a major risk factor for vascular dysfunction. It was realized several decades ago that high intake of saturated fat in the diet significantly enhanced the development of the atherosclerotic and autoimmune lesions in aorta of the autoimmune-prone B/W mice, which were known to develop severe glomerulonephritis and vasculitis (12). Numerous studies thereafter demonstrated that HFD impaired the structure and function and increased the lesion in different vascular beds (18, 31, 37, 42). Recent studies that focused on the cerebral vasculature have found that the dilator response to ACh was impaired in cerebral arterioles of HFD-fed apoE−/− mice (24) or in basilar artery of HFD-fed peroxisome proliferator-activated receptor (PPAR)-γ knockdown mice (2). In the present study, we found that relatively short-term administration of a nonatherogenic HFD impaired the ability of smaller arterioles to dilate and altered the contractile and dilatory properties of basilar arteries only after ischemic injury. Interestingly, these detrimental changes in cerebrovascular function were in the absence of overt obesity. There is no definition of obesity in animal models such as it is clearly defined in humans as body mass index (BMI) > 30. A person has traditionally been considered to be obese if he or she is >20% over ideal weight. In our animals total body weight increased by 10%, and this was mainly adipose mass. Thus the changes we observed in this model are mainly the effect of HFD and not obesity per se.

Cerebral vascular function is closely regulated by central nervous system activity, especially astrocytes whose processes are in direct contact with both synapses and blood vessels (20). Previous reports demonstrated the contribution of astrocytes in neurovascular coupling through K⁺ signaling (3, 9). In the present study, we evaluated whether K⁺-mediated vasodilation is disrupted after HFD treatment. We found that whisker stimulation-induced functional hyperemia (in vivo) and K⁺-induced vasodilation (in vitro) are reduced in the HFD group. The data suggest that PAs from the HFD group had impaired vascular function. Given the lack of increased blood flow.

Fig. 4. Effect of HFD on neuronal injury in different models of cerebral ischemia. Focal ischemia (A) induced by 3-h MCAO and 21-h reperfusion increased infarct size in the HFD group, but 10-min global ischemia (B) did not impact neuronal death in the hippocampus (n = 10–18/group). Values are medians in A and means ± SE in B. *P < 0.05.

Fig. 5. Effect of HFD on vascular function after focal cerebral ischemia-reperfusion. The balanced edema percentage (A) was not significantly higher, but the occurrence rate (C) and the severity (B) of hemorrhagic transformation (HT) determined by excess Hb in the brain were greater in the HFD group (n = 18/group). Values are medians in A and means ± SE in B. *P < 0.05.
response following whisker stimulation, future studies addressing the role of astrocytes in activity-dependent vascular responses are needed to better define whether HFD only affected vascular function or if it also altered the activity of upstream mechanisms such as that of K⁺ signaling by astrocytes.

In the present study we found no significant effect of HFD on surviving neuronal cell number in the GCI model even with different methods (NeuN staining, data not shown), which is consistent with another report that used 60-day Western HFD in Sprague-Dawley rats and also found no effect of HFD on neuronal cell death or survival after GCI (1). While we did not assess functional end points after GCI in our study, the study by Arvanitidis et al. (1) did assess functional outcome with the Morris water maze and found no significant effect of HFD, a finding consistent with the lack of effect of HFD on neuronal cell death or survival in both our and their studies. In a preliminary study, we utilized an even longer HFD period of 10 wk, with the thought that a longer duration may be needed to observe an effect in the GCI model. However, 10-wk HFD also had no significant effect on neuronal cell death/survival after GCI. It is not clear as to why HFD increased neuronal damage in the FCI but not GCI model of cerebral ischemia. It is known that the pathophysiological mechanisms differ between the two models (e.g., a more delayed neuronal cell death occurring in vulnerable brain regions after GCI), which might contribute to the difference. In addition, the duration of ischemia is also quite different between the two models (3 h in FCI vs. 10 min in GCI), which might contribute to differences in effects. While the mechanisms underlying the differential effect of HFD on neuronal cell death/survival in the two ischemia models requires further study, the significant effect of HFD observed in the FCI model is of potential translational importance. This is especially true considering that, of the two ischemia models, the FCI (MCAO) model is generally accepted as the most translationally relevant model of ischemic stroke, as >75% of strokes in humans involve occlusion of the MCA.

Obesity is an independent risk factor and may affect other risk factors for stroke such as hypertension, diabetes, and hyperlipidemia. Experimental studies have shown that either HFD or genetically induced obesity was accompanied by increased cerebrovascular remodeling, promoted hypertension, and increased infarct size in either transient or permanent focal ischemia models (7, 32). HFD-fed apoE−/− mice with hyperlipidemia also had increased infarct volume (23). However, another report showed that 1-mo HFD had no effect on the cerebral ischemia outcome (26). In the present study, 8-wk HFD resulted in significantly larger infarct volume after transient focal ischemia induced by suture occlusion of MCA, which is comparable to previous reports. When a global ischemia model was employed, there was no difference in hippocampal neuronal death between the groups, which was also reported by another group (1). These findings suggest that the duration of the diet and the method of ischemia are important for the extent and localization of neuronal injury. While we do not know the potential mechanisms contributing to greater neurovascular injury and poor outcomes in our model, it is possible that proper regulation of cerebral perfusion after stroke contributes to unfavorable outcomes. Since large arteries like the basilar artery contribute significantly to total cerebrovascular resistance and are major determinants of microvascular pressure, dysregulation of basilar artery function may worsen stroke injury by altering cerebral perfusion after stroke.

In this context, it is highly possible that exacerbated release of vasoactive factors, such as ET-1, released into the circulation may be mediating this response. In a recent elegant study from Dr. Cipolla’s group, investigators showed that plasma from stroked hyperglycemic animals can affect cerebrovascular function through peroxynitrite generation and ET-1 (34). In another study, we showed that stroke decreases the dilatory ability of basilar arteries in regular chow-fed animals compared with sham treatment (6), and administration of atrasentan, an ET receptor antagonist, at reperfusion prevented this response.

While the experimental conditions of that particular study were different, maximum relaxation observed in sham-treated rats (~50%) was reduced to ~25% and this was normalized by ET receptor antagonism. In the present study, we do not have a sham treatment group, but it is possible that even CD-fed animals may be displaying some degree of dysfunction and this is exacerbated in HFD. We have previously shown that HFD increases plasma ET-1 (38). Given these findings, the ET system may play a role in exacerbated stroke injury in our model and will be further pursued.

Along the same lines, in light of our recent studies showing that augmented O-GlcNAcylation increases vascular reactivity to ET-1 (28), we next assessed whether this posttranslational modification is a potential downstream mechanism contributing to HFD-induced vascular dysfunction. As recently reviewed, there are multiple targets that are regulated by
O-GlcNAcylation in the vasculature (30). A positive correlation between phosphorylation of the MAPK cascade (ERK1/2 and p38) and nuclear O-GlcNAcylation was observed in fetal human cardiac myocytes exposed to high glucose (14). Previous work from our group has shown that O-GlcNAcylation-induced increased reactivity of aorta to PE was prevented by a PKC inhibitor or a Rho kinase inhibitor, respectively (17, 29). Our present finding of increased O-GlcNAc levels in basilar arteries of HFD-fed animals after stroke merits further studies to determine the mechanisms linking HFD to increased O-GlcNAcylation as well as linking O-GlcNAcylation to cerebrovascular dysfunction. In a preliminary study, we found that HFD alone caused a small increase (1.5 fold) in O-GlcNAc levels compared with a fourfold increase observed in this study with HFD + MCAO. It is of great interest to determine whether blockade of increased O-GlcNAc levels prevents vascular dysfunction and improves stroke outcomes.

Perspectives and Significance

In the present study, the important findings of impaired neurovascular communication, large-artery dysfunction, and augmented vascular injury suggest that even short-term HFD without obesity or metabolic imbalance may be detrimental to the cerebrovasculature and exacerbate the response to cerebral ischemia. We recognize that there are limitations to this study such as evaluation of the outcome only at 24 h and inclusion of only male rats. Given that AIS has dramatically increased in children and young adults, which is positively correlated with increases in risk factors including obesity, lipid disorders, and diabetes (13), further studies are needed to explore the underlying mechanisms by which HFD worsens short- and long-term stroke outcome in both female and male animal models.

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