Research Article

The Traditional Herbal Medicine, Dangkwisoo-San, Prevents Cerebral Ischemic Injury through Nitric Oxide-Dependent Mechanisms

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Dangkwiso-San (DS) is an herbal extract that is widely used in traditional Korean medicine to treat traumatic ecchymosis and pain by promoting blood circulation and relieving blood stasis. However, the effect of DS in cerebrovascular disease has not been examined experimentally. The protective effects of DS on focal ischemic brain were investigated in a mouse model. DS stimulated nitric oxide (NO) production in human brain microvascular endothelial cells (HBMECs). DS (10–300 μg/mL) produced a concentration-dependent relaxation in mouse aorta, which was significantly attenuated by the nitric oxide synthase (NOS) inhibitor L-NAME, suggesting that DS causes vasodilation via a NO-dependent mechanism. DS increased resting cerebral blood flow (CBF), although it caused mild hypotension. To investigate the effect of DS on the acute cerebral injury, C57/BL6J mice received 90 min of middle cerebral artery occlusion followed by 22.5 h of reperfusion. DS administered 3 days before arterial occlusion significantly reduced cerebral infarct size by 53.7% compared with vehicle treatment. However, DS did not reduce brain infarction in mice treated with the relatively specific endothelial NOS (eNOS) inhibitor, N5-(1-iminoethyl)-L-ornithine, suggesting that the neuroprotective effect of DS is primarily endothelium-dependent. This correlated with increased phosphorylation of eNOS in the brains of DS-treated mice. DS acutely improves CBF in eNOS-dependent vasodilation and reduces infarct size in focal cerebral ischemia. These data provide causal evidence that DS is cerebroprotective via the eNOS-dependent production of NO, which ameliorates blood circulation.

1. Introduction

Stroke is the main cause of adult disability and the third leading cause of death in the world [1]. Despite decades of intense research, the treatment of acute stroke remains limited. Therapies that restore cerebral blood flow (CBF) are efficacious in acute stroke, suggesting that CBF is a critical determinant of final stroke outcome. Endothelium-derived nitric oxide (NO) regulates CBF and mediates vascular response and prevents ischemic stroke by increasing collateral flow to the ischemic area [2, 3]. Thus, conditions that enhance endothelial NO synthase (eNOS) activity could have beneficial effects on stroke.

Herbal medicine may be useful for the treatment of stroke [4]. Traditional Korean medicine is based on natural plants and has many herbal prescriptions for treating stroke, but its therapeutic efficacies as well as its mechanisms are unclear. Dangkwisoo-San (DS) is used in traditional Korean medicine for the treatment of traumatic ecchymosis and pain by promoting blood circulation and relieving blood stasis. Traditional Korean medications usually contain many compounds that affect multiple targets [5, 6]. The combination of multiple drugs is thought to maximize therapeutic efficacy by facilitating synergistic actions and preventing potential adverse effects. DS contains nine species of herbal plants (Angelicae gigantis Radix, Paeoniae Radix, Linderae...
Radix, Sappan Lignum, Cyperi Rhizoma, Carthami Flos, Persicae Semen, Cinnamomi Cortex, and Glycyrrhizae Radix et Rhizoma) that have various pharmacological effects on the cardiovascular system [7–9]. However, no report has described the effects of DS on stroke in an animal model.

The present study examined the effects of DS on cerebral infarct, blood flow, blood pressure, and eNOS signaling in response to ischemia. To determine the physiological relevance of eNOS regulation by DS, DS was administered to control and N^G^-(1-iminoethyl)-L-ornithine (L-NIO)-treated mice for 3 days before subjecting them to middle cerebral arterial occlusion. The findings suggest that DS has vascular protective action for acute cerebral ischemic damage through an eNOS-dependent mechanism.

2. Methods

2.1. Preparation of DS Extract. DS was purchased from Kwangmyungdang Natural Pharmaceutical (Ulsan, Korea). The herbal components were identified by one of the authors (Su In Cho). The mixture (60 g) of the nine constituent dried plants (Table 1) was boiled in 1 L of distilled water using an herb extractor (Dae-Woong, Korea) for 2 h. The final extract volume of 200 mL was centrifuged, and the supernatant was evaporated under reduced pressure at low temperature and stored in a freezer at −20°C. The extract samples were dissolved in dimethyl sulfoxide (DMSO, Sigma-Aldrich, St. Louis, MO) at concentrations of 30, 100, and 300 μg/mL DS at the plateau of the phenylephrine-induced contraction. Finally, endothelial-dependent relaxation was tested by subsequent application of acetylcholine (1 μmol/L). Changes in isometric tension were computationally recorded using a model FT03 force-displacement transducer (Grass, Quincy, MA) connected to a PowerLab ML 118 system 400 (AD Instruments, Medford, MA). Relaxations were expressed as the percentage of relaxation of phenylephrine-induced tone.

2.2. Determination of NO Production in Human Brain Microvascular Endothelial Cells (HBMECs). A membrane-permeable fluorescent indicator for NO (4-amino-5-methyl-10′-difluorofluorescein diacetate; DAF-FM; Molecular Probes, Eugene, OR) was utilized to detect DS-induced changes of the NO production. DAF-FM DA is converted via a NO-specific mechanism to an intensely fluorescent changes in response to a tail pinch. Rectal temperature was kept at 36.5–37.5°C using a Panlab thermostatically controlled heating mat (Harvard Apparatus, Holliston, MA). The aortic rings were suspended at a tension of 1.3 ± 0.6 g was maintained by adding phenylephrine (1 μmol/L). The vasodilatory effect of DS was studied by cumulative addition of 10, 30, 100, and 300 μg/mL DS at the plateau of the phenylephrine-induced contraction. Finally, endothelial-dependent relaxation was tested by subsequent application of acetylcholine (1 μmol/L). Changes in isometric tension were computationally recorded using a model FT03 force-displacement transducer (Grass, Quincy, MA) connected to a PowerLab ML 118 system 400 (AD Instruments, Medford, MA). Relaxations were expressed as the percentage of relaxation of phenylephrine-induced tone.

2.3. Isolated Vessel Experiments. Male C57BL/6 mice weighting 20–25 g were housed under diurnal lighting conditions and allowed food and tap water ad libitum. All animal procedures were in accordance with the institutional guidelines for animal research and were approved by the Institutional Animal Care and Use Committee. Anesthesia was achieved by face mask-delivered isoflurane (2% induction and 1.5% maintenance in 70% nitrous oxide and 30% O_2). The carotid artery and femoral vein were catheterized for the measurement of mean arterial blood pressure using a MLT844 physiological pressure transducer (AD Instruments) and the infusion of DS or saline. The depth of anesthesia was checked by the absence of cardiovascular changes in response to a tail pinch. Rectal temperature was kept at 36.5–37.5°C using a Panlab thermostatically controlled heating mat (Harvard Apparatus, Holliston, MA). The data were continuously recorded using a PowerLab data acquisition and analysis system (AD Instruments) and were stored in a computer. Mean arterial blood pressure, arterial blood gases, and pH were measured after a 3-day treatment of DS (i-Stat System, Abbott Laboratories, Abbott Park, IL). The physiological parameters were within the normal limits (Table 2).

2.4. General Surgical Preparation. Male C57BL/6] mice weighing 20–25 g were housed under diurnal lighting conditions and allowed food and tap water ad libitum. All animal procedures were in accordance with the institutional guidelines for animal research and were approved by the Institutional Animal Care and Use Committee. Anesthesia was achieved by face mask-delivered isoflurane (2% induction and 1.5% maintenance in 70% nitrous oxide and 30% O_2). The carotid artery and femoral vein were catheterized for the measurement of mean arterial blood pressure using a MLT844 physiological pressure transducer (AD Instruments) and the infusion of DS or saline. The depth of anesthesia was checked by the absence of cardiovascular changes in response to a tail pinch. Rectal temperature was kept at 36.5–37.5°C using a Panlab thermostatically controlled heating mat (Harvard Apparatus, Holliston, MA). The data were continuously recorded using a PowerLab data acquisition and analysis system (AD Instruments) and were stored in a computer. Mean arterial blood pressure, arterial blood gases, and pH were measured after a 3-day treatment of DS (i-Stat System, Abbott Laboratories, Abbott Park, IL). The physiological parameters were within the normal limits (Table 2).
were removed 24 h after MCA occlusion. Cerebral infarct size was determined on 2,3,5-triphenyltetrazolium chloride- (TTC-) stained, 2-mm-thick brain sections. Infarction areas were quantified with iSolution full image analysis software (BD Biosciences, San Jose, CA), anti-Akt and anti-phospho-Akt (Ser 473) antibodies (Cell signaling, Danvers, MA), anti-nNOS and anti-iNOS antibodies (Santa Cruz Biotechnology, Santa Cruz, CA) followed by incubation with secondary antibody conjugated with horseradish peroxidase. The intensity of chemiluminescence was measured using an ImageQuant LAS 4000 apparatus (GE Healthcare Life Sciences, Uppsala, Sweden). The membrane was reprobed with an anti-β-actin antibody (Sigma-Aldrich, St. Louis, MO) as an internal control.

2.8. Chemicals. Acetylcholine chloride, L-NAME, and phenylephrine hydrochloride were purchased from Sigma-Aldrich. L-NIO was purchased from Tocris Bioscience (Bristol, UK), and all other chemicals were reagent grade. The solid form of the extract was dissolved in distilled water.

2.9. Data Analysis. The data were expressed as mean ± SEM. Statistical comparisons were performed using paired or unpaired Student’s t-test and one-way analysis of variance (ANOVA) or two-way ANOVA for repeated measures followed by Fisher’s protected least significant difference test. P < .05 was considered statistically significant.

3. Results

3.1. DS Stimulates NO Production in HBMEC. DAF-FM DA, a fluorescent NO-sensitive dye, was used to measure DS-induced NO release in HBMECs. The effect of the NOS inhibitor, L-NAME, was also assessed to determine whether the NO increase was attributable to NOS activity-derived de novo synthesis. NO production was rapid, being observed within 5 min of 30 μg/mL DS addition, and reached a maximum at 10 min in HBMECs (data not shown). Treatment of HBMECs with 30 μg/mL DS for 10 min induced NO production, which was abrogated by pretreatment with 100 μmol/L L-NAME (Figure 1). Similar results were obtained in endothelial cells from mouse thoracic aorta (data not shown). This result was consistent with the suggestion that the increase in NO production after DS treatment was mediated by increased NOS activity.

### Table 1: Composition of Dangkwisoo-San.

<table>
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<tr>
<th>Scientific name</th>
<th>Herbal name</th>
<th>Amount (g)</th>
</tr>
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<tbody>
<tr>
<td>Angelica gigas Nakai</td>
<td>Angelicae gigantis Radix</td>
<td>5.625</td>
</tr>
<tr>
<td>Paeonia lactiflora Pall</td>
<td>Paeoniae Radix</td>
<td>3.750</td>
</tr>
<tr>
<td>Lindera strichnifolia Fernández-Villar</td>
<td>Linderae Radix</td>
<td>3.750</td>
</tr>
<tr>
<td>Caesalpinia sappan L.</td>
<td>Sappan Lignum</td>
<td>3.750</td>
</tr>
<tr>
<td>Cyperus rotundus L.</td>
<td>Cyperi Rhizoma</td>
<td>3.750</td>
</tr>
<tr>
<td>Carthamus tinctorious L.</td>
<td>Carthami Flos</td>
<td>3.000</td>
</tr>
<tr>
<td>Prunus persica Batsch</td>
<td>Persiceae Semen</td>
<td>2.655</td>
</tr>
<tr>
<td>Cinnamomum cassia Presl</td>
<td>Cinnamomi Cortex</td>
<td>2.250</td>
</tr>
<tr>
<td>Glycyrrhiza uralensis Fisch</td>
<td>Glycyrrhize Radix et Rhizoma</td>
<td>1.875</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>30.405</td>
</tr>
</tbody>
</table>

Values are mean ± SEM. MABP (mean arterial blood pressure), pO2, and pCO2 are expressed in mmHg.

### Table 2: Physiological parameters.

<table>
<thead>
<tr>
<th></th>
<th>Control (N = 7)</th>
<th>DS (N = 7)</th>
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<tr>
<td>MABP</td>
<td>80.6 ± 2.2</td>
<td>84.2 ± 2.0</td>
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<tr>
<td>pH</td>
<td>7.32 ± 0.01</td>
<td>7.36 ± 0.04</td>
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<tr>
<td>pCO2</td>
<td>41.1 ± 2.0</td>
<td>39.4 ± 2.5</td>
</tr>
<tr>
<td>pO2</td>
<td>143.8 ± 10.5</td>
<td>148.0 ± 6.0</td>
</tr>
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</table>

Values are mean ± SEM. MABP (mean arterial blood pressure), pO2, and pCO2 are expressed in mmHg.
Figure 1: Effects of DS on NO production in HBMEC. HBMECs were loaded DAF-FM (50 μmol/L) with DS (30 μg/mL), in the absence or presence of the NOS inhibitor, L-NAME (100 μmol/L). Acetylcholine (Ach, 30 μmol/L) was used to validate our measurements. DS increased NO production, which was abrogated by L-NAME. The scale bar represents 200 μm.

Figure 2: Effects of DS on phenylephrine-induced aortic contraction. (a) Representative tracings showing that cumulative addition of DS (10, 30, 100, and 300 μg/mL; arrows) relaxed mouse aorta in a concentration-dependent manner in vessel segments preconstricted with phenylephrine (PE, 1 μmol/L). (b) Average of data from four preparations showing that incubation with 100 μmol/L L-NAME abolished the DS-mediated relaxation. *P < .05 versus control, two-way ANOVA for repeated measures. Error bars indicate standard errors and are shown unidirectionally for clarity.

3.2. DS Causes Vasorelaxation in Isolated Mouse Aorta. DS concentrations of 10–300 μg/mL relaxed isolated mouse aorta in a concentration-dependent manner with a maximum value of 30.02 ± 10.39% at a concentration of 300 μg/mL. This relaxation was abolished by the NOS inhibitor L-NAME (100 μmol/L) (Figure 2), confirming the NO-mediated nature.

3.3. Effects of DS on Blood Pressure and Resting CBF. DS caused mild hypotension (81.5 ± 2.1 mmHg versus
3.4. Protective Actions of DS on Cerebral Ischemic Injury. To determine whether DS could protect against ischemic stroke, DS was administered to mice for 3 days before MCAO. DS decreased cerebral infarct volume (167.0 ± 38.2 mm$^3$) as compared with vehicle treatment (89.7 ± 34.0 mm$^3$; $P < .05$, $N = 6$; Figures 4(a) and 4(b)). Focal cerebral ischemia followed by reperfusion produced significant motor incoordination ($P < .01$, $N = 5$) in mice measured by rotarod test as compared to that of sham group animals. DS markedly prevented ischemia-reperfusion induced motor incoordination ($P < .05$, $N = 5$; Figure 4(c)). To examine the contribution of eNOS signaling to the cerebroprotective action of DS, an experiment tested the impact of DS on ischemic injury in mice treated with the relatively specific eNOS inhibitor, L-NIO. In contrast to control, DS treatment failed to reduce infarct volume in L-NIO-treated mice (Figure 4(b)).

3.5. DS Protects against Ischemic Stroke through eNOS-Dependent Signaling. To further assess the impact of DS on eNOS signaling during ischemia, the phosphorylation of Akt at Ser473 and eNOS at Ser1177 in brain tissues was assessed by Western blotting. DS treatment promoted Akt and eNOS phosphorylation in both ischemic and nonischemic regions of the brain compared with control. However, total Akt, eNOS, iNOS, and nNOS protein levels did not differ between the DS-treated and control mice (Figure 5).

4. Discussion

DS, an herbal extract, is widely used in traditional Korean medicine to treat traumatic ecchymosis and pain by promoting blood circulation and relieving blood stasis. However, the effect of DS in cerebrovascular disease has not been examined experimentally. The present study provides evidence that DS protects the brain from acute ischemic injury in a mouse model of MCAO. DS increased NO production, which led to vasodilation, improved CBF, and decreased cerebral infarction size. The cerebroprotective effect of DS was mediated by eNOS, given that DS had no beneficial effect on cerebral infarction size in mice treated with L-NIO. Indeed, phosphorylated eNOS was increased in brain tissue after DS treatment. The present observations indicate that DS exerts a cerebroprotective action through an eNOS-dependent mechanism.

When DS was administered 3 days before subjecting mice to MCAO, cerebral infarct volume was significantly decreased (Figure 4). However, it is not known whether this was due to a vasodilator effect on cerebral vessels leading
Figure 4: DS reduces cerebral ischemic injury. (a) Representative photographs of coronal brain sections stained with 2,3,5-triphenyltetrazolium chloride in saline- (Con, left)—and DS-treated mice (right). Mice were orally administered saline or 600 mg/kg DS twice per day for 3 days before the ischemic insult. Mice were subjected to 90 min of MCAO followed by 22.5 h of reperfusion. White indicates the infarct area. (b) Effect of DS on infarct volume in saline- and L-NIO-treated mice at 24 h after ischemia. Infarction volume was calculated by an indirect measurement. DS significantly reduced cerebral infarct size; however, it did not affect brain infarction in L-NIO-treated mice. (c) Effect of DS on ischemia and reperfusion induced impairment of motor coordination. DS markedly prevented ischemia-reperfusion induced motor incoordination. Data are expressed as means ± SEM of six separate experiments. *P < .05 versus control; ##P < .01 versus Sham group.

to an acute augmentation of CBF or other mechanisms such as a direct neuroprotective action [14, 15]. Presently, DS caused vasodilation and improved CBF, even it caused mild hypotension. The endothelial and smooth muscle mechanisms of vasodilation mediated by DS appear to be differentially active in systemic and cerebral circulation. Therefore, the direct smooth muscle relaxant effect of DS mildly decreased systemic resistance, but not cerebrovascular resistance. In light of the potential detrimental effect of systemic vasodilation and hyperemia on CBF in acute stroke, DS may be more efficacious in stroke therapy.

Therapies that restore CBF to ischemic regions are efficacious in acute stroke, suggesting that CBF is a critical determinant of stroke outcome. NO constitutively produced by eNOS regulates CBF and mediates vascular response and protects against ischemic stroke by mediating vasodilation and hence increases blood flow to the damaged brain area [3, 16, 17]. Several lines of evidence indicate that NO donor or L-arginine improves blood flow and reduces tissue damage after focal cerebral ischemia [18, 19]. Several therapeutic modalities to upregulate and/or active eNOS might mediate NO-dependent stroke-protective effects [20]. The beneficial effects of DS on ischemic injury are due at least in part to its vascular protective actions, which involve eNOS-dependent mechanisms, because the cerebroprotective actions of DS are abolished in a relatively specific eNOS inhibitor [21], L-NIO-treated mice. Consistent with these findings, Akt and eNOS phosphorylation was presently increased in the brains of DS-treated mice. Endothelial NO release is enhanced through direct phosphorylation of eNOS by the protein kinase Akt downstream of PI3K [22]. In contrast, total Akt, eNOS, iNOS, and nNOS expression level did not differ between vehicle- and DS-treated mice. Together, the present results clearly demonstrate that DS regulates eNOS signaling to modulate vascular function under ischemic conditions, protecting against cerebral injury after stroke.

DS represents a mixture of nine herbal medicines, consisting of Angelicae gigantis Radix, Paeoniae Radix, Linderae Radix, Sappan Lignum, Cyperi Rhizoma, Carthami Flos, Persicae Semen, Cinnamomi Cortex, and Glycyrrhizae Radix et Rhizoma. Most traditional therapeutic formulations consist of a combination of several drugs. Bioactivity from each drug may collectively act to block multiple targets underlying ischemic pathophysiology, although little is known about the mechanisms for their pharmacological activities [5, 6]. The combination of multiple drugs is thought to maximize therapeutic efficacy by facilitating synergistic actions and preventing potential adverse effects. However, little is known concerning the compounds responsible for the protective effect of DS. It will be important to perform additional experiments to identify the efficient compounds from DS.

In summary, DS increases NO production, vasodilation and improvement of CBF, which protects against cerebral ischemia. The DS-mediated cerebroprotective effects are
absent in mice treated with a relatively specific eNOS inhibitor, L-NIO, and eNOS phosphorylation is increased in the brains of mice treated with DS, indicating the obligatory role of endothelium-derived NO in mediating these beneficial effects.

Acknowledgment

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References


