

Effect of Short-Term Phytoestrogen Treatment in Male Rats on Nitric Oxide-Mediated Responses of Carotid and Cerebral Arteries: Comparison with 17β -Estradiol

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ABSTRACT

The use of estrogen for protection against vascular dysfunction is limited due to its effects on the reproductive system, particularly in males. We postulated that daidzein, an isoflavone with estrogen-like effects on the systemic vasculature but not the reproductive system, might enhance nitric oxide (NO)-mediated cerebral vasodilatation. Male rats were administered vehicle, 17β -estradiol (0.1 mg/kg s.c.), or daidzein (0.2 mg/kg s.c.) daily for 7 days. Basal and acetylcholine-stimulated NO release was assessed in vitro via carotid arterial rings or in vivo by measuring changes in basilar artery diameter. Levels of protein expression of endothelial NO synthase (eNOS), caveolin-1, and calmodulin were assessed in carotid arteries using Western analysis. Plasma NO levels were doubled by daidzein or 17β -estradiol. NO production and endothelium-dependent contraction in response to the NOS inhibitor N^G -nitro-L-arginine (L-

NNA; 100 μ M) was enhanced by 50 to 100% in carotid arteries from rats treated with daidzein or 17β -estradiol. Acetylcholine-induced relaxation was selectively enhanced in carotid arteries from rats treated with daidzein. Similarly, constrictor responses of the basilar artery to L-NNA in vivo were selectively augmented by \sim 100% by 17β -estradiol treatment and tended to be \sim 50% greater in daidzein-treated rats. Expression of caveolin-1 was decreased, and calmodulin was increased, in vessels from daidzein- or 17β -estradiol-treated rats. eNOS expression was unaffected by the treatments. These data suggest that short-term administration of daidzein or 17β -estradiol modulates cerebral artery reactivity in males by enhancing synthesis and release of endothelium-derived NO. Isoflavone therapy may therefore be a feasible approach to protect against cerebrovascular disease and stroke.

Death and morbidity from cardiovascular disease is substantially lower in premenopausal women compared with age-matched men (Barrett-Connor and Bush, 1991). After menopause, the incidence of cardiovascular mortality and morbidity, including the incidence of stroke, dramatically increases in females to levels comparable with those of males similar in age (Penotti et al., 1993). The increased incidence of vascular disease in postmenopausal women has been attributed to the absence of the hormone estrogen, specifically the predominant form, 17β -estradiol.

In experimental stroke, normal female or 17β -estradiol-treated ovariectomized rats suffer less ischemic damage than males or untreated ovariectomized rats after cerebral artery

occlusion (Alkayed et al., 1998; Zhang et al., 1998; Wang et al., 1999). Furthermore, chronic 17β -estradiol treatment enhances acetylcholine-induced cerebral vasodilatation (Pelligrino et al., 2000; Watanabe et al., 2001) in ovariectomized female rats. A major mechanism of the beneficial effects of 17β -estradiol is thought to involve increased expression and/or activity of endothelial nitric oxide synthase (eNOS) and consequently increased synthesis of endothelium-derived NO (McNeill et al., 1999).

Nevertheless, it is presently uncertain to what extent, if any, hormone replacement therapy (HRT) with estrogen may be beneficial in preventing clinical heart disease and stroke. More than 30 observational studies have reported up to 50% reduced risk of cardiovascular disease among postmenopausal women who use HRT (Hurn and Brass, 2003). However, in the Heart and Estrogen-Progestin Replacement Study, the first prospective, double-blind, randomized, placebo-controlled trial of HRT in postmenopausal women with known coronary heart disease, HRT did not reduce risk of stroke (Simon et al., 2001; Hurn and Brass, 2003). Moreover,

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ABBREVIATIONS: eNOS, endothelial nitric-oxide synthase; NO, nitric oxide; HRT, hormone replacement therapy; KPSS, high K^+ -containing physiological saline solution; PBZ, phenoxybenzamine; NO_x , nitrite + nitrate; L-NNA, N^G -nitro-L-arginine; PBS, phosphate-buffered saline; mAb, monoclonal antibody; ANOVA, analysis of variance.

with regard to cerebrovascular health, postmenopausal estrogen use has been associated with either increased or decreased risk of stroke, or no net benefit for stroke prevention (Baron et al., 1998; Simon et al., 2001; Beral et al., 2002; Rossouw et al., 2002; Hurn and Brass, 2003).

Regardless of any potential protective actions of 17 β -estradiol on cerebral and peripheral vasculature, this agent causes feminization in men and increased incidence of breast cancer and endometrial hyperplasia in women. Thus, it is desirable that therapies be identified that mimic the vasoprotective actions of 17 β -estradiol without affecting the reproductive system and other nonvascular tissue (Lissin and Cooke, 2000). This goal has led to the increased study of phytoestrogens, plant-derived compounds such as daidzein, a major isoflavone mainly derived from soybean, which seems to have estrogen-like activity on the cardiovascular system without effects on the reproductive system or on tyrosine kinase activity (Lissin and Cooke, 2000; Belcher and Zsarnovszky, 2001; Mitchell et al., 2001). Like 17 β -estradiol, chronic treatment with isoflavones may enhance vascular NO synthesis or activity (Squadrito et al., 2000). However, the effects of isoflavones on cerebral vascular function are largely unknown. The major aim of this study was therefore to determine the effect of short-term treatment with daidzein on cerebral vascular reactivity *in vitro* and *in vivo*. Because of the effects daidzein shares with 17 β -estradiol in the peripheral vasculature, we also were interested to compare the effects of both agents in the cerebral circulation. We chose to administer daidzein subcutaneously in light of an emerging concept that intestinal metabolism of isoflavones by bacterial flora of the gut produces metabolites that may contribute to the vascular actions of isoflavones (Setchell et al., 2002). Importantly, at least in humans, there seems to exist significant individual variation in the presence of such bacterial flora (Setchell et al., 2002). Thus, subcutaneous administration avoids the functional effects of potential variation in such gastrointestinal metabolism.

Materials and Methods

General Procedures. Male Sprague-Dawley rats were studied (250–300 g; $n = 75$). The study was approved by the Institution's Animal Experimentation Ethics Committee. Rats were treated with daily subcutaneous injections of vehicle (10% dimethyl sulfoxide/90% H₂O), daidzein (0.2 mg/kg), or 17 β -estradiol (0.1 mg/kg) for 7 days, and then killed by exposure to 80% CO₂/20% O₂. The dose of 17 β -estradiol has previously been shown to improve endothelial function after 7 days of treatment in ovariectomized female rats (Andersen et al., 1999). Testicular weights were measured and expressed relative to body weight. The common carotid arteries were removed and placed in Krebs bicarbonate solution composed of 118 mM NaCl, 4.7 mM KCl, 1.18 mM MgSO₄, 1.2 mM KH₂PO₄, 25 mM NaHCO₃, 11.1 mM D-glucose, and 1.6 mM CaCl₂, bubbled with 5% CO₂ in O₂ at 37°C. Arteries were cleaned of fat and connective tissue and from each was cut two rings 3 to 4 mm in length. For experiments requiring endothelium-denuded vessels, the intimal surface of each ring was gently rubbed using fine forceps. Rings were each mounted in a 5-ml chamber of a four-channel myograph (model 610M, Multi-Myograph; J.P. Trading, Copenhagen, Denmark) containing Krebs bicarbonate solution. Passive tension was adjusted to 15 mN over 60 to 90 min and recorded on a chart recorder (model 3721; Yokogawa, Tokyo, Japan). Once resting tension had stabilized, rings were exposed to an isotonic high K⁺-containing physiological saline solution (KPSS), in which Na⁺ in Krebs' solution was replaced by K⁺ ([K⁺]_{KPSS} = 124

mM). After several washouts and return to 15 mN, phenylephrine (0.01–0.1 μ M) was added to induce precontraction to ~50% of the KPSS response. Relaxation (>80% of precontraction tone) in response to acetylcholine (10 μ M) confirmed the endothelium to be functionally intact. After further washouts and return to 15 mN, rings were again precontracted to 50% of the KPSS response using phenylephrine, and concentration-response curves were performed for acetylcholine or sodium nitroprusside. One or two such curves were typically performed per ring. Before some acetylcholine concentration-response curves, rings were briefly treated with phenoxybenzamine (PBZ, 0.5 μ M, 30 min). PBZ was used to alkylate muscarinic receptors, thereby reducing muscarinic receptor reserve and mimicking endothelial dysfunction (Martin et al., 1992). PBZ reduced the response to acetylcholine by ~50%. Thus, up-regulated eNOS-mediated signaling could be detected by augmented responses to acetylcholine after the short-term treatment protocols. Rings were washed to remove unbound PBZ, treated with nifedipine (100 nM) for 10 min to minimize spontaneous activity, and then precontracted to 50% of the KPSS response using the thromboxane A₂ mimetic U46619, instead of phenylephrine, because PBZ also alkylates α_1 -adrenoceptors.

Effect of Short-Term Treatment with Daidzein or 17 β -Estradiol on Basal NO Activity. We used two approaches to assess the effect of short-term treatment with daidzein or 17 β -estradiol on basal NO activity. First, we measured the level of NO metabolic byproducts (NO_x, i.e., nitrite + nitrate) in plasma, and their production by isolated carotid artery. Plasma samples were stored at –20°C until assayed. Carotid artery rings were incubated under sterile conditions in a humidified chamber with 5% CO₂, 95% O₂ at 37°C for 48 h in cell culture medium (Dulbecco's modified Eagle's medium). The concentration of NO_x was measured in samples of plasma or culture medium after converting all nitrate to nitrite with nitrate reductase. Total nitrite levels were measured in duplicate by absorbance at 560 nm using the Griess reagent of 50% *N*-(1-naphthyl)ethylenediamine hydrochloride/50% sulfanilamide in 100 ml of 5% (v/v) orthophosphoric acid added to 100 ml of medium. Sodium nitrite was used as a standard. Second, contraction in response to the isoform nonselective NOS inhibitor N^G-nitro-L-arginine (L-NNA; 100 μ M) was measured. Endothelium-intact and endothelium-denuded rings were precontracted to ~20% of the contraction to KPSS using phenylephrine, and L-NNA was added to the tissue once a stable level of contraction was obtained. Arterial rings were allowed to reach maximum contraction (~30 min). The response to L-NNA was expressed as a percentage of the contraction to KPSS (not including the precontracted tone).

Basilar Artery Diameter *In Vivo*. Rats were anesthetized with pentobarbitone (50 mg/kg i.p.) for study of basilar artery reactivity *in vivo* using a cranial window as described previously (Sobey and Quan, 1999). Anesthesia was supplemented throughout the experiment at 10 to 20 mg/kg/h i.v. Arterial blood gases were maintained within normal levels (pH of 7.39 \pm 0.01; pCO₂ = 37 \pm 3 mm Hg; and pO₂ = 186 \pm 11 mm Hg). The cranial window was continuously suffused at 2 ml/min with artificial cerebrospinal fluid. Cerebrospinal fluid sampled from the cranial window was pH of 7.41 \pm 0.02, pCO₂ = 35 \pm 4 mm Hg, and pO₂ = 126 \pm 3 mm Hg. Diameter of the basilar artery was monitored using a microscope equipped with a TV camera coupled to a video monitor and was continuously measured using a computer-based tracking program (Diamtrak; Montech Clayton, Australia). After the craniotomy was prepared, the artery was allowed 30 min to equilibrate before application of vasoconstrictors, which were applied topically. Serotonin (0.1 μ M) was applied until a steady-state change in diameter was attained, which usually occurred within 5 to 6 min. The basilar artery was then allowed to recover for at least 30 min. To determine the effect of short-term daidzein or 17 β -estradiol on basal NO activity in the basilar artery, L-NNA (100 μ M) was similarly applied topically for 30 min.

Western Analysis of NOS, Caveolin-1, and Calmodulin. Sections of carotid arteries that were not used in functional experiments

were frozen, homogenized, and subsequently used for Western analysis. Briefly, identical amounts of protein were separated on 7.5, 12, and 15% SDS-polyacrylamide gel electrophoresis, and transferred to nitrocellulose with a Trans-blot (Bio-Rad, Hercules, CA) overnight. Blots were blocked with 5% (w/v) skim milk in phosphate-buffered saline (PBS) for 1 h at room temperature. Blots were then incubated overnight at 4°C with the primary antibodies, anti-eNOS, anti-caveolin-1 (mAb 1:1000; BD Transduction Laboratories, Lexington, KY) and anti-calmodulin (mAb 1:1000; Auspep, Melbourne, Australia) diluted in 3% bovine serum albumin/PBS. Membranes were then incubated with the sheep anti-mouse secondary antibody (1:1000; Silenus, Boronia, Australia) diluted in 3% bovine serum albumin/PBS for 1 h at room temperature followed by five washes with 0.1% Tween in PBS. The specific bands were detected using enhanced chemiluminescence reagents and exposed to film (Amersham Biosciences, Piscataway, NJ) before development (X-ray developer and fixer; Ilford, Cheshire, UK). Protein bands detected were quantified by densitometry (Kodak Image Station 440CF; PerkinElmer Life and Analytical Sciences, Boston, MA).

Drugs. All drugs were purchased from Sigma-Aldrich (St. Louis, MO), except acetylcholine perchlorate (BDH, Poole, Dorset, UK), daidzein (4',7-dihydroxyisoflavone; Indofine, Hillsborough, NJ), U46619 (9,11-dideoxy-9 α ,11 α -epoxymethano-prostaglandin F_{2 α} ; Cayman Chemical, Ann Arbor, MI), and phenoxybenzamine HCl (MP Biomedicals, Irvine, CA). Daidzein and 17 β -estradiol were dissolved in 10% dimethyl sulfoxide (vehicle). With the exception of U46619, nifedipine, and phenoxybenzamine, which were dissolved in absolute ethanol, all other drugs were dissolved in distilled water. All subsequent dilutions were made in distilled water except phenoxybenzamine, which was diluted in 50% absolute ethanol/50% saline, and then saline alone.

Analyses and Statistics. Concentration-response data were fitted to a sigmoid plot using GraphPad Prism version 3.0a (GraphPad Software Inc., San Diego, CA), which estimated the pEC₅₀ value. Relaxation responses are presented as percentage of inhibition of the precontracted level of tone. Each *n* represents the number of animals per group. Statistical analysis was carried out using Student's unpaired *t* test or a one-way ANOVA followed by Dunnett's multiple comparisons test (as appropriate). *P* < 0.05 was considered statistically significant. All values are mean \pm S.E.M.

Results

In comparison with vehicle-treated rats, plasma NO_x levels were approximately doubled in rats treated with either daidzein or 17 β -estradiol (Fig. 1a; both *P* < 0.05). Similarly, NO_x production by carotid arteries from daidzein- or 17 β -estradiol-treated rats was also ~2-fold greater than the amount produced by vessels from vehicle-treated rats (Fig. 1b; both *P* < 0.05). During the 7-day treatment period, the body weight gained by vehicle- and daidzein-treated rats was similar (20 \pm 1 versus 21 \pm 2 g; *P* > 0.05), whereas 17 β -estradiol-treated rats gained slightly less weight (16 \pm 1 g; *P* < 0.05 versus vehicle-treated rats). However, there was no significant effect of the treatments on testicular weight [(in grams per kilogram of body weight) vehicle-treated, 7.3 \pm 0.6; daidzein-treated, 8.9 \pm 0.6; and 17 β -estradiol-treated, 10.1 \pm 0.6].

Acetylcholine and sodium nitroprusside each induced concentration-dependent relaxation of carotid artery rings. These responses were similar in vehicle-, daidzein-, and 17 β -estradiol-treated rats (Table 1). To simulate responses in the presence of impaired endothelial function, acetylcholine-induced relaxation also was assessed in the presence of PBZ. In comparison with responses of carotid arteries from vehicle-treated rats, acetylcholine caused greater relaxation of arter-

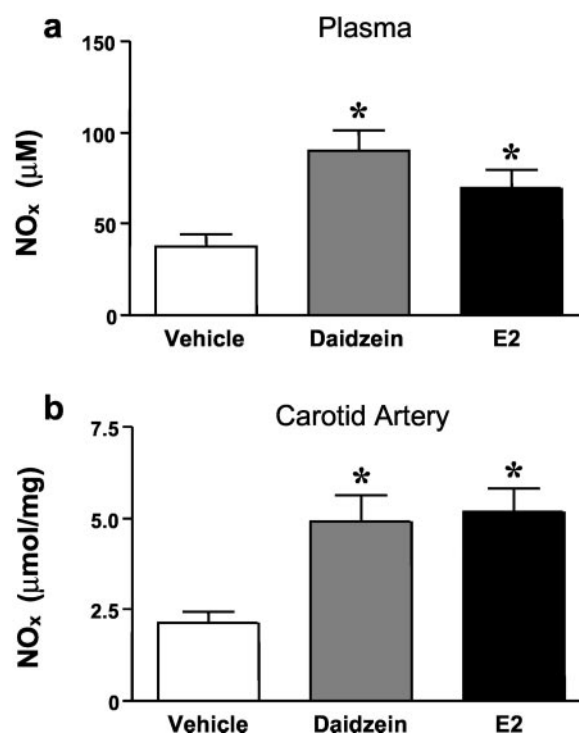


Fig. 1. Levels of NO_x measured in plasma (a) or generated by isolated carotid arteries from rats treated with vehicle, daidzein, or 17 β -estradiol for 7 days (b) (all *n* = 5). Data are mean \pm S.E.M. *, *P* < 0.05 versus vehicle (ANOVA and Dunnett's test).

ies from rats treated with daidzein (Fig. 2, *P* < 0.05; Table 1). Acetylcholine-induced relaxation of rings from 17 β -estradiol-treated rats also tended to be greater than those from vehicle-treated rats, but this difference did not reach statistical significance (Fig. 2; Table 1).

In endothelium-intact carotid artery rings precontracted to 20% of the KPSS-induced level using phenylephrine, contractions by L-NNA were significantly greater in vessels from rats treated with either daidzein or 17 β -estradiol (Fig. 3). L-NNA had no significant effect on contractile tone in endothelium-denuded arterial rings (data not shown).

In cranial window preparations, L-NNA (100 μ M) caused marked vasoconstriction in vivo in all three groups of rats (Fig. 4a). However, vasoconstrictor responses to L-NNA were approximately 50% greater in daidzein-treated rats (*P* > 0.05) and 100% greater in 17 β -estradiol-treated rats compared with responses in vehicle-treated rats (*P* < 0.05; Fig. 4a). By contrast, serotonin caused equivalent vasoconstrictor responses in all three groups (Fig. 4b).

Molecular expression of eNOS was similar in carotid arteries from all three treatment groups (Fig. 5a). Expression of caveolin-1 was ~50% lower in both daidzein-treated and 17 β -estradiol-treated arteries than in arteries from vehicle-treated rats (Fig. 5b). Expression of calmodulin was increased by 60–70% in daidzein-treated and 17 β -estradiol-treated arteries (Fig. 5c).

Discussion

This is the first study to investigate effects of short-term phytoestrogen treatment on vascular responses, expression of NO-related proteins or generation of NO in cerebral arteries. Our findings indicate that, similar to the effects of 17 β -

TABLE 1

Response to acetylcholine (ACh) after treatment with PBZ (0.5 μ M for 30 min), and sodium nitroprusside (SNP) in carotid artery rings from male rats treated with vehicle, daidzein, or 17 β -estradiol (E2) for 7 days

Data are mean \pm S.E.M. *n* is number of experiments.

Agonist	Vehicle			Daidzein			E2		
	<i>n</i>	pEC ₅₀	R _{max} %	<i>n</i>	pEC ₅₀	R _{max} %	<i>n</i>	pEC ₅₀	R _{max} %
ACh	7	7.66 \pm 0.24	97 \pm 1	7	7.29 \pm 0.16	98 \pm 1	7	7.74 \pm 0.11	98 \pm 2
ACh after PBZ	5	5.94 \pm 0.07	48 \pm 7	7	5.97 \pm 0.06	74 \pm 3*	7	5.88 \pm 0.10	64 \pm 6
SNP	6	8.66 \pm 0.08	102 \pm 1	7	8.59 \pm 0.11	102 \pm 2	6	8.93 \pm 0.30	98 \pm 2

* $P < 0.05$, Dunnett's test compared with vehicle.

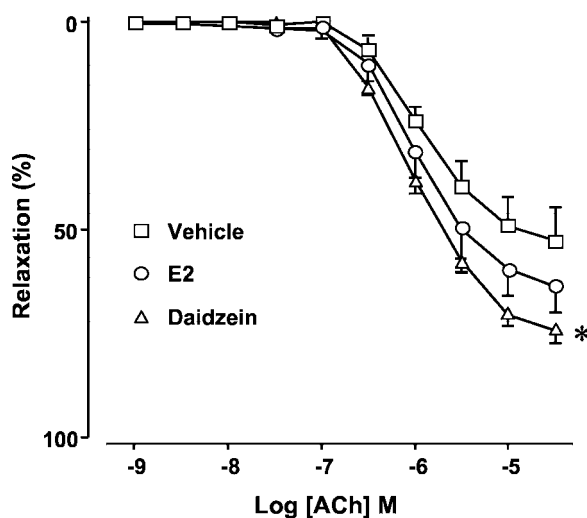


Fig. 2. Concentration-response curves to acetylcholine (ACh) in phenoxylbenzamine-treated aortic rings from male rats treated for 7 days with vehicle ($n = 5$), 17 β -estradiol (E2; $n = 7$), or daidzein ($n = 7$). Data are mean \pm S.E.M. Daidzein significantly enhanced the maximum response to acetylcholine; *, $P < 0.05$ versus vehicle (ANOVA and Dunnett's test).

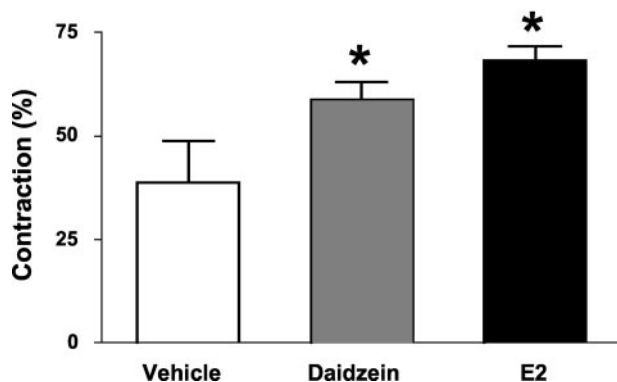


Fig. 3. Contractile responses to L-NNA (100 μ M) in aortic rings from male rats treated for 7 days with vehicle, daidzein, or 17 β -estradiol (E2) (all $n = 7$). Data are mean \pm S.E.M. *, $P < 0.05$ versus vehicle (ANOVA and Dunnett's test).

estradiol treatment, administration of daidzein for 7 days enhances NO production and consequent vasodilatation in cerebral arteries. Evidence supporting this conclusion is that production of NO metabolites, vasoconstriction by L-NNA, and vasorelaxation by acetylcholine are all augmented in carotid arteries of rats treated with either daidzein or 17 β -estradiol in comparison with arteries from vehicle-treated rats. Further findings suggested that basal NO activity in the basilar artery in vivo was also higher in daidzein- and 17 β -estradiol-treated rats. These effects are not due to increased

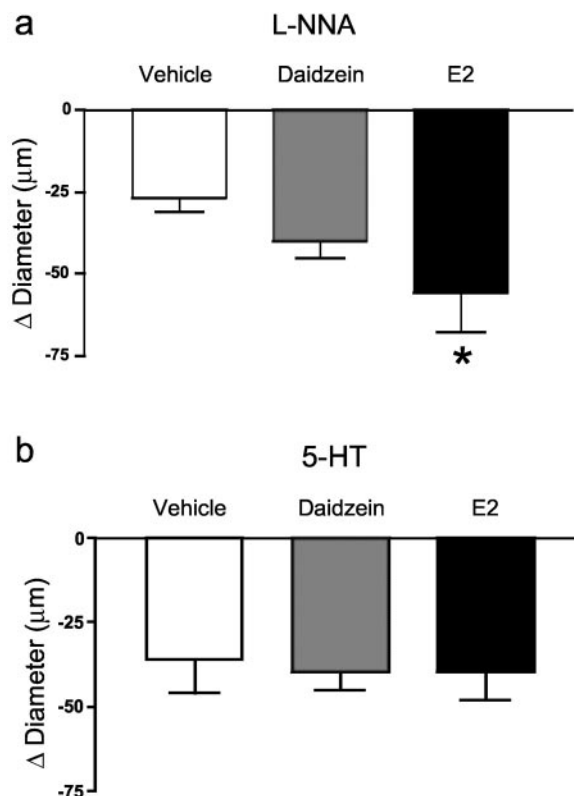


Fig. 4. Change in basilar artery diameter of male rats treated with vehicle ($n = 8$, baseline diameter = 221 \pm 12 μ m), daidzein ($n = 8$, baseline diameter = 236 \pm 8 μ m), or 17 β -estradiol (E2; $n = 5$, baseline diameter = 242 \pm 4 μ m) in response to L-NNA (100 μ M) (a) or serotonin (5-HT; 0.1 μ M) (b). Data are mean \pm S.E.M. *, $P < 0.05$ versus vehicle (ANOVA and Dunnett's test).

expression of eNOS protein directly, but they are associated with altered levels of two eNOS-modulating proteins, specifically, decreased expression of caveolin-1 and increased expression of calmodulin.

Treatment with daidzein or 17 β -estradiol for 7 days enhanced contraction in response to the NOS inhibitor L-NNA both in vitro and in vivo. Because this indicated an increase in basal NO activity, it was somewhat surprising that the relaxant response to acetylcholine was unaffected by either treatment. We considered two possible explanations for the apparently divergent results. Could daidzein or 17 β -estradiol treatment selectively enhance basal rather than stimulated NO activity? Alternatively, is stimulated NO activity near-maximal under normal conditions, and thus there is little or no capacity within the system for further increase? To address the second possibility, we acutely exposed the isolated carotid arteries to PBZ to alkylate some of the muscarinic

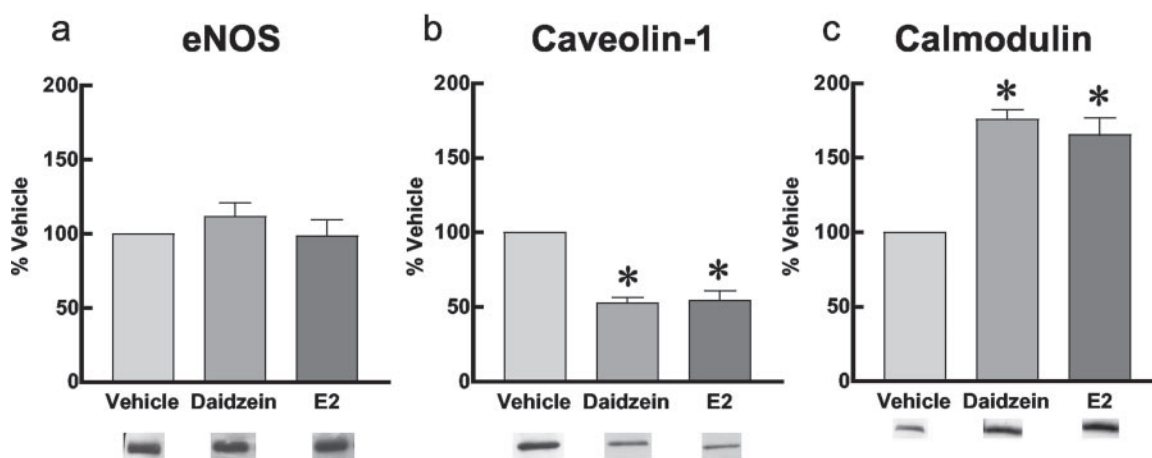


Fig. 5. Protein levels of eNOS (a), caveolin-1 (b), and calmodulin (c) in carotid arteries from male rats treated with vehicle, daidzein, or 17 β -estradiol (E2). Levels of each protein in daidzein- and E2-treated rats are expressed relative to the level in vehicle-treated rats. All groups are $n = 3$. Data are mean \pm S.E.M. *, $P < 0.05$ versus vehicle (ANOVA and Dunnett's test). Representative examples of individual blots are shown below each bar.

receptors and hence reduced both the potency and efficacy of acetylcholine (Martin et al., 1992). We then found that in the presence of PBZ, the relaxant responses to acetylcholine were enhanced by short-term treatment with either daidzein or 17 β -estradiol. Thus, the ability of daidzein and 17 β -estradiol to enhance endothelial function is most apparent when there is an impairment of stimulated NO release, emphasizing the potential for isoflavones to enhance endothelium-dependent relaxation impaired by vascular disease. At present, we also cannot exclude the possibility that an up-regulation of endothelium-derived hyperpolarizing factor activity contributed to this enhancement of the vasorelaxant response to acetylcholine (Woodman and Boujaoude, 2004).

Therapeutic Use of Estrogen. The risk of cardiovascular disease, including stroke, is lower in premenopausal women than in age-matched men, but this difference progressively diminishes after the onset of menopause (Hurn and Macrae, 2000; Hurn and Brass, 2003). These different, gender-related profiles in the clinical incidence of cardiovascular disease are thought to be due to differences, or changes, in the plasma level of estrogen. However, despite substantial experimental evidence that estrogen can improve vascular function, recent large clinical trials investigating the effects of HRT, using estrogen plus progesterone or estrogen alone, report no benefit on the incidence of coronary artery disease or stroke (Simon et al., 2001; Beral et al., 2002; Grady et al., 2002; Hurn and Brass, 2003). Moreover, other significant impediments to the therapeutic use of estrogen include the development of breast and endometrial cancers in women and unacceptable effects on reproductive function in men. Hence, development of a vascular-selective alternative to estrogen therapy is clearly desirable, and this goal has led to considerable interest in the actions of plant-derived estrogen mimetics, such as the isoflavones.

Vascular Effects of Isoflavones. In the present study, and in others where a direct comparison has been made, the vascular effects of isoflavones mimic those of 17 β -estradiol (Squadrito et al., 2000; Belcher and Zsarnovszky, 2001; Walker et al., 2001). Isoflavones such as genistein and daidzein are abundant in some foods, particularly soybean and legumes. It has been postulated that the relatively lower incidence of cardiovascular disease in Asian populations compared to Western societies, and reports that Japanese women

suffer significantly fewer menopausal symptoms (Nestel et al., 1999) may be associated with the larger consumption of isoflavones in Asian diets compared with Western diets. Indeed, soy isoflavones are known to enhance endothelium-dependent coronary vasodilatation in atherosclerotic monkeys (Honore et al., 1997) and to enhance aortic endothelial function in ovariectomized rats (Squadrito et al., 2000). Isoflavones also acutely dilate human forearm vasculature (Walker et al., 2001) and enhance systemic vascular compliance (Walker et al., 2001). In healthy age-matched men and postmenopausal women, consumption of a soy protein isolate was reported to decrease arterial pressure (Teede et al., 2001). In contrast to endogenous estrogens, however, isoflavones do not seem to affect reproductive function and are more selective for vascular and other nonreproductive tissues (Lissin and Cooke, 2000; Belcher and Zsarnovszky, 2001). We found that neither daidzein nor 17 β -estradiol reduced testicular weight, thus the vascular effects of these treatments did not seem to be associated with inhibitory effects on the reproductive system during this short-term study. Similarly, a recent study in humans has found that in male volunteers, 2 months of dietary phytoestrogen supplementation high in daidzein also had no effect on endocrine measurements, testicular volume, or semen parameters (Mitchell et al., 2001).

Estrogen-Like Effects of Daidzein on Expression of NOS-Related Proteins. A major protective effect of estrogen against vascular disease may occur via increasing the bioactivity of vascular NO (i.e., by increasing NO synthesis and/or stability). NOS enzymes are subject to transcriptional and post-translational regulation, and there is evidence that estrogen affects both of these processes (Papapetropoulos et al., 1999). Experimental 17 β -estradiol treatment has variously been reported to increase expression of each of the three NOS isoforms (Binko and Majewski, 1998; Pelligrino et al., 1998, 2000; McNeill et al., 1999; McNeill et al., 2002; Mershon et al., 2002). By contrast, 17 β -estradiol may increase NO synthesis in aorta of male rats (M. Boujaoude and O. L. Woodman, unpublished observations) and of ovariectomized mice (Darblade et al., 2002) without changing expression of any NOS isoform. Although NO production and activity was also higher in the carotid artery after daidzein or 17 β -estradiol treatment in the present experiments, we found that levels of eNOS expression also were not altered in

this vessel. Because L-NNA had no constrictor effect in endothelium-denuded arteries, it seems that the greater levels of basal NO release after daidzein or 17 β -estradiol treatment were not due to upregulation of expression of inducible NOS in vascular smooth muscle (Binko and Majewski, 1998; Mershon et al., 2002).

Two proteins that are also critical in the regulation of eNOS activity are caveolin-1 (inhibitory) and calmodulin (activating), which compete for the same binding domain on eNOS. Altered expression of these modulatory proteins could have profound effects on vascular NO synthesis and contractile tone. It has been reported that 17 β -estradiol treatment reverses the increase in caveolin-1 expression in female rat pial arterioles that occurs after ovariectomy (Pelligrino et al., 2000). Two important novel findings of the present study are that short-term treatment with either daidzein or 17 β -estradiol decreases caveolin-1 expression and increases calmodulin expression in carotid arteries of normal males. Such findings support the hypothesis that, similar to effects of estrogen, post-translational modulation of NOS activity via altered expression of eNOS modulatory proteins may be an important target for isoflavones to increase NO activity in the cerebral circulation.

Although estrogen and the isoflavones can exert rapid, acute effects directly on vascular tone, it is likely that the actions of 17 β -estradiol and daidzein observed here were mainly genomic, because remarkably similar degrees of altered caveolin-1 and calmodulin protein expression due to the modulation of gene transcription were observed. In further support of this proposition is the fact that daidzein and 17 β -estradiol have similar transactivational potencies at an estrogen responsive element, whereas daidzein has 1000 and 200 times less binding affinity than 17 β -estradiol at the estrogen receptors ER α and ER β , respectively (Belcher and Zsarnovszky, 2001).

In summary, the results of the present study demonstrate that short-term treatment with daidzein mimics the effect of 17 β -estradiol in augmenting NO synthesis and activity in carotid and basilar arteries of male rats. These effects are associated with no change in eNOS expression but with increased calmodulin and decreased caveolin-1 expression in the carotid arteries. Thus, estrogen-like effects in the cerebral circulation can be achieved using isoflavones, which increases activity of endothelium-derived NO, probably via altered expression of key proteins which modulate eNOS activity.

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