Estrogen-induced contraction of coronary arteries is mediated by superoxide generated in vascular smooth muscle

Richard E. White,1 Guichun Han,1 Christiana Dimitropoulou,1 Shu Zhu,1 Katsuya Miyake,3 David Fulton,1,2 Shaylee Dave,1 and Scott A. Barman1

1Department of Pharmacology and Toxicology, 2Vascular Biology Center, and 3Institute of Molecular Medicine and Genetics, Medical College of Georgia, Augusta, Georgia

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White, Richard E., Guichun Han, Christiana Dimitropoulou, Shu Zhu, Katsuya Miyake, David Fulton, Shaylee Dave, and Scott A. Barman. Estrogen-induced contraction of coronary arteries is mediated by superoxide generated in vascular smooth muscle. Am J Physiol Heart Circ Physiol 289: H1468–H1475, 2005; doi:10.1152/ajpheart.01173.2004.—Although previous studies demonstrated beneficial effects of estrogen on cardiovascular function, the Women’s Health Initiative has reported an increased incidence of coronary heart disease and stroke in postmenopausal women taking hormone replacement therapy. The objective of the present study was to identify a molecular mechanism whereby estrogen, a vasodilatory hormone, could possibly increase the risk of cardiovascular disease. Isometric contractile force recordings were performed on endothelium-denuded porcine coronary arteries, whereas molecular and fluorescence studies identified estrogen signaling molecules in coronary smooth muscle. Estrogen (1–1,000 nM) relaxed arteries in an endothelium-independent fashion; however, when arteries were pretreated with agents to uncouple nitric oxide (NO) production from NO synthase (NOS), estrogen contracted coronary arteries with an EC50 of 7.3 ± 4 nM. Estrogen-induced contraction was attenuated by reducing superoxide (O2−), whereas molecular and fluorescence studies identified estrogen signaling molecules in coronary smooth muscle. Estrogen (1–1,000 nM) relaxed arteries in an endothelium-independent fashion; however, when arteries were pretreated with agents to uncouple nitric oxide (NO) production from NO synthase (NOS), estrogen contracted coronary arteries with an EC50 of 7.3 ± 4 nM. Estrogen-induced contraction was attenuated by reducing superoxide (O2−), whereas molecular and fluorescence studies identified estrogen signaling molecules in coronary smooth muscle. Estrogen (1–1,000 nM) relaxed arteries in an endothelium-independent fashion; however, when arteries were pretreated with agents to uncouple nitric oxide (NO) production from NO synthase (NOS), estrogen contracted coronary arteries with an EC50 of 7.3 ± 4 nM.Estrogen-stimulated O2− production was detected in NOS-uncoupled coronary myocytes. Interestingly, only the type 1 neuronal NOS isoform (nNOS) was detected in myocytes, making this protein a likely target mediating both estrogen-induced relaxation and contraction of endothelium-denuded coronary arteries. Estrogen-induced contraction was completely inhibited by 1 μM nifedipine or 10 μM indomethacin, indicating involvement of dihydropyridine-sensitive calcium channels and contractile prostaglandins. We propose that a single molecular mechanism can mediate the dual and opposite effect of estrogen on coronary arteries: by stimulating type 1 nNOS in coronary arteries, estrogen produces either vasodilation via NO or vasoconstriction via O2−, nitric oxide; coronary circulation.

The women’s health initiative (WHI) trials indicate that postmenopausal hormone replacement therapy (HRT) bears a significant health risk, including a 29% increase in coronary heart disease and a 41% increase in stroke (30). However, these findings are in stark contrast to prior basic research studies demonstrating clear beneficial effects of estrogen on the cardiovascular and other systems, which had led to HRT becoming the second most prescribed medication in the United States. Despite the fact that estrogen produces favorable effects on plasma lipid profiles, increases fibrinolysis, and acts as a vasodilator to lower systemic blood pressure and increase organ blood flow (21, 33, 37), HRT has been increasingly discontinued in light of recent clinical trials. The obvious paradox is as follows: How could a hormone that produces such an array of salutary effects promote significant pathology and disease? Despite continued investigation, the cellular and molecular basis for these contradictory and confusing responses to estrogen continues to elude explanation.

Many effects of estrogen are mediated by nitric oxide (NO) via stimulation of nitric oxide synthase (NOS). It is generally believed that the primary target of estrogen in the cardiovascular system is type 3 NOS expressed in endothelial cells (eNOS), yet there are also endothelium-independent effects of estrogen on blood vessels or single vascular smooth muscle (VSM) cells mediated by NO (8, 11, 24, 38, 39). Interestingly, VSM cells express aromatase (i.e., estrogen synthase), indicating that estrogen may act acutely in a paracrine or even autocrine manner within the vascular wall (16). Thus direct action of estrogen on VSM might actually be more important in older women because the vascular endothelium becomes increasingly dysfunctional with age (10, 12, 41). Nonetheless, estrogen’s effects on NO production in VSM cells are often ignored. Our present findings now provide evidence for a mechanism of estrogen action that could, for the first time, shed significant light on the controversy of estrogen and HRT. We propose that both beneficial and harmful effects of estrogen can be mediated by the same biological target, type 1 neuronal NOS (nNOS), expressed in VSM cells. Depending on the microenvironment of this enzyme, estrogen exhibits a “yin-yang” influence on cellular function, producing either vasodilation via NO or vasoconstriction via superoxide (O2−), a powerful oxidant that can further decrease NO bioavailability. Thus, by acting on a single molecular target, estrogen can produce completely opposite effects in vascular and other target tissues and could thereby induce either physiological or pathophysiologic responses.

METHODS

Supply of coronary arteries. We obtained fresh porcine hearts from local abattoirs. We generally obtain hearts from castrated male pigs because females are typically conserved for breeding, but we have observed no sexual dimorphism in responses of arteries to estrogen (11, 38). The left anterior descending coronary artery was excised immediately and placed into ice-cold Krebs-Henseleit buffer solution of the following composition (in mM): 122 NaCl, 4.7 KCl, 15.5 NaHCO3, 1.2 KH2PO4, 1.2 MgCl2, 1.8 CaCl2, 1.15 glucose, pH 7.2. Arteries were kept on ice during transport to the laboratory.

Tension studies of intact coronary arteries. Arteries were placed under a dissecting microscope, and excess fat and connective tissue were removed in ice-cold buffer solution. Two-to-four 5-mm rings were obtained from each left anterior descending coronary artery, and...
prepared for isometric contractile force recordings as described previously (38). To control for possible indirect effects of endothelium-derived vasoactive factors, the endothelium was removed physically by rubbing the intimal surface and tested by observing the absence of acetylcholine-induced relaxation. Rings were mounted on two triangular tissue supports, with one support fixed to a stationary glass rod and the other attached to a force-displacement transducer. Isometric contractions or relaxations were recorded on a PC computer using MacLab software. The tissue bathing solution was the modified Krebs-Henseleit buffer described in *Supply of coronary arteries*. The solution was oxygenated continuously (95% O$_2$-5% CO$_2$) and maintained at 37°C. Coronary ring preparations were equilibrated for 90 min under an optimal resting tension of 2.0 g, and fresh bath solution was added to the tissue chamber every 30 min to prevent accumulation of metabolic end products. After the initial equilibration, preparations were exposed to maximally effective concentrations of a contractile agonist, e.g., PGF$_2$α, to ensure stabilization of the muscles. Pharmacological inhibitors were allowed to equilibrate with the arteries for at least 30 min before measurement of a complete estrogen concentration-response relationship (1–1,000 nM). The effects of 17α-estradiol, an “inactive” estrogen, were determined to control for possible vehicle artifact. Steroid vehicle was usually 50–75% ethanol, and this stock was diluted to a concentration of no more than 0.1% in the vessel chamber.

**Cell culture.** Human coronary artery smooth muscle cells (HCASMC) were purchased from Clonetics/Cambrex and were grown in phenol red-free smooth muscle growth medium with 5% FBS as described previously (39). Steroid hormones and growth factors were removed from FBS by charcoal stripping. Only short-term cultures (passage 3–5) were employed.

**Western blot analysis.** Arteries were obtained and prepared as described in *Tension studies of intact coronary arteries*. The endothelium was removed from some of the arteries by gentle rubbing of the luminal surface with a cotton swab. Tissues were stored in liquid nitrogen until immunoblots were to be performed. Frozen tissues were pooled and pulverized (Fisher Scientific). Protein concentrations were determined by Bio-Rad DC protein assay. ADP-sepharose beads were employed to affinity extract NOS proteins from lysates (3). Purified positive control proteins [nNOS and inducible (iNOS; pituitary extracts)] were purchased from Transduction Laboratories. Proteins were separated on SDS-polyacrylamide gels using a Mini Protein II (Bio-Rad) gel kit according to the manufacturer’s instructions. Proteins were then transferred to Hybond-ECL membrane (Amersham Pharmacia Biotech) using a Mini-Trans-Blot Electrophoretic Transfer Cell (Bio-Rad) at 100 V for 1 h. Blots were blocked with 5% nonfat milk overnight at 4°C. The membrane was then rinsed with Tris-buffered saline-TWEEN (TBST) three times for 15 min and two times for 5 min. Blots were then probed with primary antibodies (nNOS, eNOS, or iNOS; 1:1,000; BD Transduction Labs) in TBST containing 1% nonfat milk protein for 1 h. After being washed, the membrane was then incubated with anti-rabbit IgG conjugated to horseradish peroxidase and visualized with an enhanced chemiluminescence system (Amersham).

**Fluorescence studies.** The cell-permeable form of the O$_2$– fluorescence indicator dihydroethidium (DHE) was employed to examine production of O$_2$– within coronary myocytes. Cells were loaded with the fluorescent indicator during a 45-min incubation with 2 μM DHE (diluted from a 10 μM stock in DMSO) in Krebs solution (see *Supply of coronary arteries*) at 37°C. After the incubation, cells were washed with Krebs solution and placed on the stage of a Zeiss confocal laser microscope. A perfusion chamber was created by the addition of silicon grease to form in- and outflow chambers at each end of the coverslips inverted onto spacers glued to a slide. Drugs were then added to the cells, and fluorescence was measured. Cell imaging was conducted on a Zeiss 510 NLO laser scanning microscope operating in the confocal mode with a ×40 0.85 numerical aperture objective as described previously (20). Quantitative analysis of confocal images was under the control of Zeiss Physiology software.

**Statistical Analysis.** All data are means ± SE. Statistical significance between two groups was evaluated by Student’s t-test for paired data. Comparison between multiple groups was made by the One-Way ANOVA test, with a post hoc Tukey test performed for differences among data groups. A probability of <0.05 was considered to indicate a significant difference.

**RESULTS**

As we and others (8, 24, 38) have demonstrated previously, under normal conditions 17β-estradiol produces an endothelium-independent, concentration-dependent relaxation of precontracted arteries (Fig. 1A). For example, 300 nM 17β-estradiol induced an average relaxation of 41.6 ± 2.5% in endothelium-denuded coronary arteries precontracted with 10 μM PGF$_2$α (n = 4 arteries). But in contrast to this well known effect, when arteries were pretreated (20–30 min) with 100 μM of an inhibitor l-arginine analog, e.g., L$^6$-monomethyl-l-arginine (l-NAME), N$^ω$-nitro-l-arginine methyl ester (l-NNAME), or N$^ω$-propyl-l-arginine (l-NPA), to “uncouple” NO production from NOS and reduce NO bioavailability, estrogen now induced a concentration-dependent contraction of endothelium-denuded coronary arteries (Fig. 1B). Treating “NOS-uncoupled” arteries with the same concentrations of 17α-estradiol (a biologically less active steroid) had no effect on tension (n = 3 arteries; Fig. 1B), thus controlling for potential effects of vehicle (0.05% ethanol) or possible nonspecific steroid effects. After estrogen-induced coronary contraction had reached maximum levels, we found that reducing O$_2$− reversed this response. Estrogen-induced contraction was reversed by either 1 mM 4-hydroxy-2,2,6,6-tetramethylpiperidine 1-oxyl (Tempol, SOD mimetic, 70.3 ± 9%; n = 4 arteries; Fig. 1B) or 10 mM 4,5-Dihydroxy-1,3-benzenedisulfonic acid disodium salt (Tiron, O$_2$− scavenger, 70.0 ± 9.5%; n = 8 arteries; data not shown), suggesting that O$_2$− mediated the contractile response of estrogen.

The dependency of estrogen-induced vascular contraction on O$_2$– was further demonstrated by observing no response to estrogen when O$_2$– accumulation was prevented in coronary arteries. As predicted, estrogen had no effect on “NOS-uncoupled” arteries that had been pretreated with either 1 mM Tempol (0% increase in tension, n = 3 arteries, data not shown) or 10 mM Tiron (0% increase in tension, n = 4 arteries; Fig. 2A). In these same arteries, however, further addition of 10 μM PGF$_2$α induced a strong O$_2$−-independent contraction (Fig. 2A). In sum, these experiments indicate that estrogen can either relax or contract coronary arteries depending on whether NOS activity is coupled or uncoupled to NO production, with either NO or O$_2$–, respectively, exerting the predominate influence. A summary concentration-response relationship for estrogen-induced coronary artery contraction is illustrated in Fig. 2B, as is the total lack of a contractile effect when O$_2$– accumulation is prevented (i.e., in the presence of 10 mM Tiron). The calculated EC$_{50}$ for the contractile effect of estrogen is 7.3 ± 4 nM (n = 10 arteries).

These pharmacological studies on coronary arteries indicate that O$_2$− mediates the ability of estrogen to contract VSM when NO bioavailability is reduced. Additional evidence for this novel mechanism was obtained by observing estrogen-stimulated O$_2$– fluorescence in isolated HCASMC.
Fig. 1. Estrogen relaxes or contracts coronary arteries. Typical tracings from isometric contractile force recordings of endothelium-denuded porcine coronary arteries in response to cumulative addition of estrogen (1–1,000 nM). Periods of drug exposure are indicated by lines above traces. Baseline tension is indicated by dotted line. A: estrogen relaxes precontracted coronary arteries. Arteries were exposed to 10 μM PGF2a (10 min), and relaxation responses to increasing concentrations of 17β-estradiol were measured. B: estrogen contracts nitric oxide (NO) synthase (NOS)-uncoupled coronary arteries. Arteries were pretreated with 10–100 μM 1-NAME-propyl-l-arginine (l-NPA, 30–45 min) to reduce NO bioavailability. Cumulative addition of 17β-estradiol produced a concentration-dependent contraction, whereas 17α-estradiol had no effect over the same range of concentrations. 4-hydroxy-2,2,6,6-tetramethylpiperidine 1-oxyl (Tempol, 1 mM), a SOD mimetic, reversed the contractile effect of estrogen.

Single HCASMC were loaded with the cell-permeable fluorescent probe DHE, which is commonly used to detect generation of O2 in VSM (9, 22). The ability of estrogen to stimulate O2 production in coronary myocytes is illustrated in Fig. 3. Baseline fluorescence, before and 10 min after addition of 100 μM l-NMMA, is illustrated in Fig. 3A and indicates no spontaneous increases in O2 levels in the absence of estrogen over this brief time period (fluorescence intensity: control, 629.5 ± 28; l-NMMA, 691.7 ± 23; n = 6 cell groups; P > 0.12; Fig. 3A). In the absence of l-NMMA, 100 nM estrogen did not affect fluorescence intensity (10–30 min; data not shown). In contrast, in the presence of 100 μM l-NMMA, estrogen increased O2 production significantly after only 10 min (fluorescence intensity: l-NMMA, 688.5 ± 61; l-NMMA + E2, 887.6 ± 68; n = 6 cell groups; P < 0.001; Fig. 3B), with estrogen-stimulated O2 production reaching a plateau after 20–30 min (20 min, 985.6 ± 74; 30 min, 1,048 ± 83; n = 6 cell groups). There was no significant increase in O2 fluorescence intensity after 20 min (P > 0.05; n = 6 cell groups). These fluorescence studies on single coronary myocytes are entirely consistent with our functional studies on intact coronary arteries, and strongly support our hypothesis that estrogen stimulates O2 production in coronary myocytes to contract coronary arteries.

The next series of experiments demonstrated that the biochemical environment of NOS is a critical factor in determining the physiological response of coronary arteries to estrogen. In vitro contractile studies demonstrated that in the presence of only l-NMMA, 300 nM estrogen contracted coronary arteries by an average of 214.2 ± 136% (n = 5 arteries; Fig. 4A). In contrast, when arteries were pretreated with both 100 μM l-NMMA and 1 mM l-arginine (to increase NO availability and attenuate NOS-dependent O2 production), 300 nM estrogen now relaxed these nonprecontracted coronary arteries by an average of 172.4 ± 48% (n = 6 arteries; P < 0.02 compared with the l-NMMA-only group). In these same vessels, subsequent addition of exogenous O2 (i.e., 10 μM pyrogallol, a O2 donor) reversed the relaxation effect of estrogen and contracted arteries by an average of 141.5 ± 53% (n = 6 arteries; Fig. 4A). These findings support a critical role for NO activity in mediating effects of estrogen on coronary arteries. Identification of the type 1 nNOS isoform as a potential estrogen target molecule in coronary arteries was demonstrated by immunoblot studies that detected expression of only the nNOS isoform in coronary artery smooth muscle from either pigs or humans (Fig. 4B; n = 4 cell homogenates). In contrast, both nNOS and eNOS were detected in homogenates (i.e., muscle + endothelium) of porcine coronary arteries (data not shown). Therefore, it is most likely the nNOS isoform that mediates the dual effect of estrogen on coronary smooth muscle.

A final series of experiments was conducted to shed some light on the molecular basis of estrogen-induced coronary artery contraction. The mechanism(s) converting the expected estrogen relaxation response into a O2-mediated contractile effect is (are) unknown but would most likely involve an increase in activator calcium in smooth muscle. To test this hypothesis, we placed coronary arteries in a nominally calcium-free solution, uncoupled NOS activity, and then obtained a complete concentration-response relationship for estrogen-induced contraction. In the absence of extracellular calcium, estrogen, at any concentration, had no effect on vessel tension (Fig. 5A; n = 4 arteries), indicating that the contractile response to estrogen did not involve a significant release of calcium from intracellular stores. In contrast, when extracellular calcium was restored to normal (2 mM) levels, vessels...
Estrogen-stimulated NO production from the endothelium and within the vascular wall contributes to beneficial effects of estrogen on the cardiovascular system, as reflected by earlier clinical studies (13, 23, 31) demonstrating that estrogen reduces overall cardiovascular risk by ~50%. In contrast, the more recent WHI trials have reported deleterious effects of postmenopausal estrogen replacement on cardiovascular function (e.g., a nearly 30% increase in coronary heart disease) (30). The reasons for these discrepancies are not apparent. Interestingly, however, the conclusions of the WHI are based solely on findings from older (age range: 50–79; mean age, 63.3) postmenopausal women. One aspect of aging that the WHI did not take into account is the increasing evidence that as a woman ages there is a decline in factors critical for maintaining NOS in the “coupled” (i.e., NO-producing) state. NOS possesses both oxygenase and reductase domains with binding sites for several cofactors, and the disposition of the microenvironment around NOS will determine its primary product. For example, NO can catalyze an “uncoupled” NADPH oxidation to generate O$_2^-$ rather than NO (1), and O$_2^-$ has been suggested to play a role in age-related increased coronary vascular resistance due to its oxidative potential and ability to further reduce NO bioavailability (10).

There is evidence that the aging process could be associated with increased uncoupling of NOS activity. For example, aging reduces the levels of L-arginine and tetrahydrobiopterin (BH$_4$), both of which are cofactors required to sustain NO production from NOS activity. Serum L-arginine levels and NO production decrease with age (27, 28), which is associated with enhanced oxidative stress on the cardiovascular system (40). Moreover, recent studies (4) indicate that arginase activity is upregulated with our findings that nNOS is an estrogen target within the vascular wall, may form the basis of an explanation as to why the WHI observed mainly harmful effects of estrogen in postmenopausal women: HRT stimulated O$_2^-$ production.

There are several mechanisms whereby estrogen could increase O$_2^-$ production in VSM, such as by stimulating NADPH oxidase, xanthine oxidase, mitochondrial oxidase, and/or NOS. For example, NADPH oxidase is expressed in VSM and appears to be an important source of O$_2^-$ production (18, 34); however, estrogen inhibits NADPH oxidase activity in other
cell types (32) and decreases NADPH expression in endothelial cells (36). In the present study the response of coronary arteries to estrogen was critically dependent on an l-arginine balance; i.e., in the presence of l-arginine, estrogen relaxed arteries, but the addition of inhibitory l-arginine analogs converted estrogen into a coronary vasoconstrictor (see Figs. 1 and 4A). These findings point strongly to NOS as the source of estrogen-induced production of either O$_2^·$/H$_2$O$_2$ or NO in endothelium-damaged arteries. Whereas the present findings certainly cannot rule out other potential sources of estrogen-stimulated O$_2^·$/H$_2$O$_2$ production, potential contribution of O$_2^·$/H$_2$O$_2$ from NOS-independent sources would seem to play a minor role, if any, in mediating the vascular effects of estrogen in coronary arteries. l-arginine, it appears, is a sine qua non of estrogen-induced coronary relaxation. It seems doubtful that l-arginine would also play such a significant role in preventing O$_2^·$/H$_2$O$_2$ generation from NADPH oxidase or xanthine oxidase in the vascular wall. In contrast, l-arginine is highly effective in blunting estrogen-stimulated O$_2^·$/H$_2$O$_2$-mediated contraction of coronary arteries. Therefore, we conclude that the most likely molecular target mediating both estrogen-induced relaxation and contraction of endothelium-denuded coronary arteries is NOS expressed in VSM.

It remains unclear as to which NOS isoform could mediate the acute effects of estrogen on VSM. Interestingly, we found l-NPA to be highly effective in converting the “normal” relaxation effect of estrogen into vasoconstriction. Because l-NPA exhibits high (3,000-fold) selectivity for nNOS over iNOS and a 150-fold greater selectivity over eNOS (43), our studies implicate type 1 nNOS as mediating estrogen effects in coronary artery smooth muscle cells. The fact that our studies were performed in either endothelium-denuded vessels or myocytes in culture casts further doubt on eNOS as an estrogen target molecule in our experiments. Furthermore, immunoblot studies detected significant expression of only nNOS protein in coronary artery smooth muscle from either porcine or human vessels (whereas eNOS was detected only in endothelium-intact arteries). Therefore, consistent findings from this combination of functional and molecular approaches strongly suggest that it is the nNOS isoform that functions as novel estrogen target protein in both porcine and human coronary smooth muscle. Previous studies have demonstrated expression

Fig. 3. Estrogen stimulates generation of O$_2^·$/H$_2$O$_2$ in NOS-uncoupled, coronary artery myocytes. A: cellular fluorescence images of human coronary artery myocytes loaded with dihydroethidium (DHE, 2 μM; 45 min) to indicate O$_2^·$/H$_2$O$_2$ generation. In control (con) experiments fluorescence measurements were taken before and 10 min after treatment with 10 μM N$^\text{G}$-monomethyl-l-arginine (l-NMMA, middle and right, respectively). Mean fluorescence intensity from 6 experiments ± SE is illustrated in bar graph (left). There was no change in fluorescence intensity. B: estrogen-stimulated DHE fluorescence of human coronary artery myocytes. Myocytes were loaded with DHE as above and treated with 10 μM l-NMMA to uncouple NOS activity (middle). Treating same cells with 100 nM 17β-estradiol (E2, 10–30 min) enhanced O$_2^·$/H$_2$O$_2$-induced fluorescence. Average effect of estrogen in six experiments ± SE is illustrated in the bar graph (left). *$P<0.001$ indicates a significant increase in fluorescence in estrogen-treated cells. *$P<0.05$ indicates a further significant increase in fluorescence at 20–30 min exposure to estrogen compared with 10-min exposure time. There was no significant change in fluorescence intensity between 20 and 30 min ($n=6$ cell groups).
molecule, nNOS, can mediate either estrogen-induced coronary artery smooth muscle (81.5%) loss of GTP-cyclohydrolase-I immunoreactivity in the brain. Interestingly, Chen et al. (7) have reported a dramatic and other tissues leading to greater oxidative stress. This model proposes that how estrogen influences the critical balance of NO and O2− might have important implications on normal cellular function in a variety of systems and explain, at least in part, the controversies concerning the complicated physiology and pharmacology of estrogens, HRT, and aging. Our findings also raise the very intriguing question: If estrogen is indeed a stimulator of oxidative stress in older women, do traditional concepts of menopause need to be reconsidered? In other words, could age-related loss of ovarian function actually be an adaptive mechanism to reduce estrogen-stimulated pathologies due to elevated ROS production as NO becomes increasingly uncoupled with age?  

Our findings pose the intriguing possibility that a single molecule, nNOS, can mediate either estrogen-induced coronary artery dilation (via NO) or constriction (via O2−). Fluorescence studies support this hypothesis, as we previously reported estrogen-stimulated NOS activity in HCASMC under normal (i.e., “NOS-coupled”) conditions (39) and now report estrogen-stimulated O2− generation in NOS-uncoupled HCASMC (Fig. 3B). Therefore, it appears very likely that nNOS expressed in coronary artery smooth muscle influences vascular reactivity, and we speculate that this endothelium-independent mechanism could be especially important in older women with increasingly damaged or dysfunctional endothelium so often seen in aging, atherosclerosis, and/or diabetes (12, 41). In addition, estrogen should also modulate vascular reactivity in men. Aromatase is expressed in VSM (16), thus providing a local mechanism for de novo synthesis of estrogen in the vasculature of both males and females. Our findings now provide a novel molecular mechanism whereby intravascular synthesis of estrogen could impact cardiovascular function in both women and men to produce either physiological or pathophysiological effects. 

Estrogen stimulates nNOS activity in hippocampal neurons (15), and early studies suggested beneficial effects of estrogen on brain function; however, WHI findings (26) suggest potentially deleterious consequences of the steroid on global cognitive function in older women. As in the vasculature, it is unclear how estrogen could produce such opposite effects in the brain. Interestingly, Chen et al. (7) have reported a dramatic (81.5%) loss of GTP-cyclohydrolase-I immunoreactivity in brains of aged vs. young humans and other primates. This enzyme is rate-limiting for the synthesis of BH4, and loss of this co-factor should accelerate NOS uncoupling in the brain and other tissues leading to greater oxidative stress. This model is remarkably consistent with our present findings of dual and opposite effects of estrogen in coronary arteries. Therefore, we propose that how estrogen influences the critical balance of NO vs. O2− might have important implications on normal cellular function in a variety of systems and explain, at least in part, the controversies concerning the complicated physiology and pharmacology of estrogens, HRT, and aging. Our findings also raise the very intriguing question: If estrogen is indeed a stimulator of oxidative stress in older women, do traditional concepts of menopause need to be reconsidered? In other words, could age-related loss of ovarian function actually be an adaptive mechanism to reduce estrogen-stimulated pathologies due to elevated ROS production as NO becomes increasingly uncoupled with age?

Fig. 4. Type 1 neuronal NOS (nNOS) is a likely target of estrogen action in coronary artery smooth muscle. A: average effect of estrogen (E2, 300 nM) on isometric tension of endothelium-denuded porcine coronary arteries. Estrogen contracted arteries pretreated (20–30 min) with 100 μM L-NMMA (n = 5 arteries; *P < 0.05). In contrast, estrogen relaxed arteries pretreated with both 100 μM L-NMMA and 1 mM L-arginine (L-Arg, n = 6 arteries). These same arteries addition of 10 μM pyrogallol (PYRO), a O2− donor, reversed relaxation effect of estrogen and induced further contraction (n = 6 arteries). Period of drug exposure is indicated by lines above the graph. Each bar represents contractile response mean ± SE. B: typical immunoblots of NOS isoform expression detected in porcine coronary artery homogenate and human coronary myocytes. Presence of endothelium is as indicated for porcine arteries. iNOS, inducible NOS; + con, lanes containing exogenous purified protein controls. In endothelium-denuded vessels or single myocytes, nNOS was the only isoform detected.

Fig. 5. Estrogen-induced coronary artery contraction involves calcium influx. A: arteries were incubated in a nominally calcium-free solution with 100 μM L-NAME to uncouple NOS activity (30 min); 17β-estradiol (1–1,000 nM) had no effect on contractile activity. Restoration of extracellular [Ca2+] to 2 mM evoked an immediate contraction in presence of estrogen. B: average contractile response to 30 nM 17β-estradiol (E2; 100 μM L-NPA pretreatment; n = 10 arteries). This contractile effect of estrogen was prevented by pretreating arteries with either 1 μM nifedipine (Nif; 30 min) or 10 μM indomethacin (Indo; 30 min). Each bar represents contractile response mean ± SE.
The fact that estrogen cannot contract arteries in the absence of extracellular calcium or in the presence of nifedipine (with normal extracellular calcium) indicates a dependency on an influx of calcium through dihydropyridine-sensitive calcium channels. In contrast, previous findings (19, 42) suggest that estrogen inhibits calcium channel activity in neurons and A7r5 vascular cells. The present findings, however, indicate a stimulatory effect of estrogen on calcium channels in "NOS-uncoupled" vessels, thereby leading to contraction. Moreover, it is most likely not O$_2$ that opens calcium channels directly; rather, our results with indomethacin suggest that estrogen and O$_2$ generate production of a contractile prostaglandin which then induces contraction. Interestingly, we had demonstrated previously that indomethacin also inhibits the contractile effect of another oxidant, H$_2$O$_2$, which also can either contract or relax coronary arteries (2). Because O$_2$ is readily converted to H$_2$O$_2$ via SOD, it is possible that the observed contractile effect of estrogen might involve local production of H$_2$O$_2$ (or another oxidant species) in coronary artery smooth muscle; however, further studies are needed to identify other ROS and prostaglandins that might play a role in estrogen-induced vascular contraction.

In summary, we propose that estrogen per se is neither "good" nor "bad" in terms of producing physiological effects. Rather, an important action of estrogen is to stimulate NOS activity. It is the disposition of NOS (either coupled or uncoupled) that will then determine which product predominates (NO or O$_2$, respectively) and, therefore, whether the overall effect of estrogen will be beneficial or harmful. Evidence from both clinical and basic research studies demonstrates that aging is associated with the depletion of cofactors essential to maintain NOS in the coupled state. We hypothesize, therefore, that NOS activity (particularly that of nNOS) would become increasingly uncoupled as women and men age, thereby increasing the predisposition to oxidative damage in the cardiovascular and other systems. Accordingly, HRT would tend to be harmful to older, postmenopausal women yet would tend to produce primarily salutary effects in younger women, which is often observed with oral contraceptive regimens.

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