17β-Estradiol inhibits cyclic strain-induced endothelin-1 gene expression within vascular endothelial cells

Shu-Hui Juan,1 Jin-Jer Chen,2,3,4 Cheng-Hsien Chen,5 Heng Lin,2 Ching-Feng Cheng,4 Ju-Chi Liu,5 Ming-Hsiung Hsieh,5 Yen-Ling Chen,4 Hung-Hsing Chao,6 Tso-Hsiao Chen,3 Paul Chan,3 and Tzu-Hurung Cheng.17β-Estradiol inhibits cyclic strain-induced endothelin-1 gene expression within vascular endothelial cells. Am J Physiol Heart Circ Physiol 287: H1254–H1261, 2004. First published May 6, 2004; 10.1152/ajpheart.00723.2003.—It has been well documented previously that 17β-estradiol (E2) exerts a protective effect on cardiovascular tissue. The possible role of E2 in the regulation of endothelin-1 (ET-1) production has been previously reported, although the complex mechanisms by which E2 inhibits ET-1 expression are not completely understood. The aims of this study were to examine whether E2 was able to alter strain-induced ET-1 gene expression and also to identify the putative underlying signaling pathways that exist within endothelial cells. For cultured endothelial cells, E2 (1–100 nM), but not 17α-estradiol, inhibited the level of strain-induced ET-1 gene expression and also peptide secretion. This inhibitory effect elicited by E2 was able to be prevented by the coincubation of endothelial cells with the estrogen receptor antagonist ICI-182,780 (1 μM). E2 also inhibited strain-enhanced NADPH oxidase activity and intracellular reactive oxygen species (ROS) generation as measured by the redox-sensitive fluorescent dye 2′,7′-dichlorodihydrofluorescein diacetate and the level of extracellular signal-regulated kinase (ERK) phosphorylation. Furthermore, the presence of E2 and antioxidants such as N-acetylcysteine and diphenylene iodonium were able to elicit a decrease in the level of strain-induced ET-1 secretion, ET-1 promoter activity, ET-1 mRNA, ERK phosphorylation, and activator protein-1 binding activity. In summary, we demonstrated, for the first time, that E2 inhibits strain-induced ET-1 gene expression, partially by interfering with the ERK pathway via the attenuation of strain-induced ROS generation. Thus this study delivers important new insight regarding the molecular pathways that may contribute to the proposed beneficial effects of estrogen on the cardiovascular system.

Cardiovascular diseases are the leading cause of mortality for postmenopausal women in industrialized countries, accounting for >30% of deaths (30). Conflicting results existed in the literature regarding actions of estrogen on the cardiovascular system (3, 19, 32, 35). A better understanding of the effects of estrogen on vascular cells might contribute to optimization of the role of estrogen in cardiovascular system. Literature provides the evidence that estrogen inhibits endothelin (ET)-1 production (17, 45). However, a shortcoming of previous work is that investigations were carried out in static cultures, which is not typical for blood vessels (47). Therefore, this study examines the mechanism by which estrogen modulates ET-1 in the conditions of cyclic strain, simulating the environment in the vasculature.

Endothelial cells are constantly under the influence of mechanical forces, including cyclic strain, as a consequence of blood vessel contraction and relaxation. The activation of several signal transduction systems has previously been demonstrated to arise as a consequence of hemodynamic forces within endothelial cells (18, 38, 39). Recently, it has been proposed that a function of reactive oxygen species (ROS) is as second messengers within cells exposed to various stimuli (13, 18, 26, 37). Studies have further demonstrated that intracellular ROS levels are elevated within endothelial cells after cyclic strain treatment (5, 48). We have also found that ROS mediate cyclic strain-induced ET-1 expression via a Ras/Raf/extracellular signal-regulated kinase (ERK) signaling pathway within endothelial cells (6), although it is not yet clear as to whether estrogen inhibits strain-induced ET-1 expression within vascular endothelial cells.

17β-Estradiol (E2) is the terminal, biologically active, natural estrogen with the highest affinity for the estrogen receptor (9). Our study was conducted to examine whether E2 inhibits strain-induced ET-1 gene expression and also to identify signaling protein kinase cascades that may be responsible for the putative effect of estrogen in cardiovascular system. In the present study, we clearly demonstrate that E2 inhibits strain-induced ET-1 gene expression, activator protein-1 (AP-1) binding activity, and ERK phosphorylation in part via the attenuation of strain-induced ROS generation within endothelial cells. Thus this study delivers important new insight into the molecular pathways that may contribute to the proposed beneficial effects of estrogen in regard to cardiovascular disease.

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**MATERIALS AND METHODS**

**Materials.** Imubind ET-1 ELISA kits were purchased from Biochemica (ENDOTHELIN, Biomedica). ET-1 cDNA was obtained from a human endothelial cell cDNA library as previously described (41). A full length of the ET-1 promoter region (4.4 kb) was fused to the chloramphenicol acetyltransferase (CAT) reporter gene (6). PBLCAT2 (containing CAT reporter gene with its promoter) and PBLCA3 (containing the CAT gene only) were constructed as previously described (7). 2′,7′-Dichlorofluorescein diacetate (DCF-DA) was obtained from Molecular Probes (Eugene, OR). H2O2 was purchased from Acros Organics (Pittsburgh, PA). E2, N-acetylcysteine (NAC), and all other reagent-grade chemicals, were purchased from Sigma Chemical (St. Louis, MO). ICI-182,780 was purchased from Tocris Cookson (Ballwin, MO).

**Endothelial cell culture.** To avoid gender-related differences in the response to estrogen, human umbilical vein endothelial cells (HUVECs) were isolated from freshly collected umbilical cords of newborn females as described previously (6). After 3 days of culture in medium 199 (GIBCO-BRL) containing 20% fetal calf serum, endothelial cells (2.0×10^6 cells/well) were seeded on the flexible membrane base of a culture well (Flex 1, Flexcell; Mckeesport, PA). They were cultured for a further 3 days until the monolayer became confluent. The medium for the cultured endothelial cells was then changed to the same medium containing 2% fetal calf serum, and the cells were incubated overnight before the conduct of the experiment. The transformed human endothelial cell line ECV304 (ATCC CRL-1998) was purchased from the American Type Culture Collection (Bethesda, MD) and maintained in culture in DMEM supplemented with 10% fetal calf serum, penicillin (100 U/ml), and streptomycin (100 μg/ml) before subculture.

**In vitro cyclic strain on cultured endothelial cells.** Endothelial cells cultured on the flexible membrane base were subjected to cyclic strain produced by a computer-controlled application of sinusoidal negative pressure as described previously (6).

**Measurement of ET-1 concentration.** The ET-1 concentration in culture medium was assayed with Imubind-ET-1 ELISA kits (6). Briefly, the supernatant was mixed with an assay buffer, and the samples were processed according to the assay buffer manufacturer’s instructions. The samples were measured in duplicate, and the ET-1 concentration was obtained by comparing the ELISA results with a standard curve.

**RNA isolation and Northern blot hybridization.** Preparation of total RNA and Northern blot analyses of ET-1 and 18S RNA were performed as described previously (6). Transfections, chloramphenicol acetyltransferase assays, and β-galactosidase assays. ECV304 cells were transiently transfected with different expression vectors by the calcium phosphate method as described previously (6). The CAT and β-galactosidase assays were performed as described previously (6).

**NADPH oxidase activity assay and detection of intracellular ROS.** NADPH oxidase was measured in HUVECs as described previously (4). Measurement of intracellular ROS formation in HUVECs was recorded by monitoring changes in DCF fluorescence as described previously (6).

**Western blot analysis.** Rabbit polyclonal anti-phospho-specific ERK antibody was purchased from New England Biolabs (Beverly, MA). Anti-ERK antibody was purchased from Santa Cruz Biotechnology (Santa Cruz, CA). Western blot analysis was performed as previously described (6).

**Electrophoretic mobility shift assay and luciferase assay.** The electrophoretic mobility shift assay was performed as described previously (24). ECV304 cells were plated onto Flexcell culture dishes that had been transfected with the luciferase reporter construct possessing consensus AP-1 binding sites (AP-1-Luc; Stratgene; La Jolla, CA). Subsequent to incubation of ECV304 cells for a period of 24 h in 2% serum DMEM, ECV304 cells were cultured under various different conditions as indicated for a period of 48 h. ECV304 cells were assayed for luciferase activity using a luciferase reporter assay kit (Stratgene). The specific firefly luciferase activity, as was the case for the specific AP-1 transcriptional activity, was normalized for transfection efficiency to its respective β-galactosidase activity and expressed as activity relative to the control.

**Statistical analysis.** Data are presented as means ± SE. Statistical analysis was performed using one-way ANOVA or the unpaired Student’s t-test. P values <0.05 at difference were considered to represent statistical significance.

**RESULTS**

**Effects of E2 on strain-induced ET-1 expression.** HUVECs experiencing cyclic strain for a period of 48 h were observed to

![Fig. 1](http://ajpheart.physiology.org/)
demonstrate an increase in their ET-1 secretion into the culture medium to a level of about double that of the unstrained control analog (Fig. 1A). The preincubation of HUVECs with E2 at physiological concentrations (1–100 nM) for a period of 12 h before strain treatment for 48 h resulted in a concentration-dependent decrease in strain-induced ET-1 protein secretion (Fig. 1A). Unlike E2, 17α-estradiol (100 nM) appeared to elicit no effect on strain-induced ET-1 secretion, whereas the preincubation of HUVECs with the estrogen receptor antagonist ICI-182,780 (1 μM) prevented the E2-mediated downregulation of strain-induced ET-1 secretion (Fig. 1B).

To determine whether E2 inhibits strain-induced ET-1 gene expression, HUVECs were pretreated with E2 (1–100 nM) for a period of 12 h followed by a 6-h period of cyclic strain. HUVECs experiencing cyclic strain for 6 h demonstrated a significant increase in the ET-1 mRNA level compared with unstrained controls (Fig. 2A). Pretreatment of HUVECs with E2 (1–100 nM) significantly reduced the strain-induced ET-1 mRNA levels. Unlike E2, pretreatment of HUVECs with 17α-estradiol (100 nM) resulted in no effect on strain-induced ET-1 mRNA levels, whereas preincubation of HUVECs with the estrogen receptor antagonist ICI-182,780 (1 μM) prevented the E2-mediated downregulation of strain-induced ET-1 mRNA levels (Fig. 2B). To further investigate whether the effect of E2 on strain-induced ET-1 gene expression is a transcriptional event, a plasmid containing an ET-1 upstream sequence in a CAT reporter construct (~4.4 k CAT) was cotransfected with pSV-β-galactosidase into ECV304 endothelial cells. As shown in Fig. 2C, increased ET-1 promoter activity was observed in endothelial cells experiencing cyclic strain for 24 h. For endothelial cells pretreated with E2 (1–100 nM), the strain-induced ET-1 promoter activity appeared to have been significantly reduced (P < 0.05; Fig. 2C). Consistently, 17α-estradiol (100 nM) exerted no effect on strain-induced ET-1 promoter activity, whereas preincubation with the estrogen receptor antagonist ICI-182,780 (1 μM) prevented the E2-mediated downregulation of strain-induced ET-1 promoter activity (Fig. 2D).

Effects of E2 on strain-increased NADPH oxidase and intracellular ROS levels. Previous studies have shown that cyclic strain increases NADPH oxidase activity (4, 24, 25) and ROS formation in endothelial cells (4, 5, 24, 48). As a consequence, we examined whether E2 prevents the observed strain-increased NADPH oxidase activity and intracellular generation of ROS. HUVECs were treated with E2 (1–100 nM) in the absence or presence of strain treatment. The preincubation of E2 (1–100 nM) with cultured endothelial cells significantly inhibited strain-induced NADPH oxidase activity and ROS levels as measured after strain treatment for a period of 1 h (Fig. 3, A and B). The pretreatment of cultured endothelial cells

![Fig. 2. E2 inhibits strain-induced ET-1 gene expression in endothelial cells. The results shown are means ± SE; n = 3, *P < 0.05 vs. control; #P < 0.05 vs. strain-treated cells (by ANOVA). A: inhibition of strain-induced ET-1 mRNA by E2. HUVECs were either untreated controls (lane 1) or treated with various different concentrations of E2 (1–100 nM) in the absence (lanes 2–4) or presence of strain treatment (lanes 6–8). 18S RNA was used to normalize the RNA applied to each lane. Data are presented as the proportional (percent) change determined for experimental groups compared with untreated controls. B: effects of the ER antagonist ICI on the E2-mediated downregulation of strain-induced ET-1 mRNA and the corresponding absence of any effect from α-E administration to endothelial cells before strain-induced ET-1 mRNA. Cells were preincubated with α-E (100 nM), E2 (100 nM), or the combination of E2 plus the ER antagonist ICI (1 μM) and then stimulated with cyclic strain for a period of 6 h vs. no strain application. C: E2 (1–100 nM) inhibits strain-induced ET-1 promoter activity. ECV304 cells were pretreated with E2 (1–100 nM) for 12 h and then treated with cyclic strain for 24 h. C, no drugs; chloramphenicol acetyltransferase (CAT)2 and CAT3 are shown as positive and negative controls. CAT activity subsequent to normalization relative to that of β-galactosidase activity is shown as relative activity compared with corresponding values for control groups. D: effects of the ER antagonist ICI on the E2-mediated downregulation of strain-induced ET-1 promoter activity and the relative absence of any effect of α-E on strain-induced ET-1 promoter activity. Cells were preincubated with α-E (100 nM), E2 (100 nM), or the combination of E2 plus the ER antagonist ICI (1 μM) and then stimulated with cyclic strain for a period of 24 h vs. no cyclic strain.](http://ajpheart.physiology.org/ "Downloaded from http://ajpheart.physiology.org/ by 10.20.33.4 on October 30, 2017")
Effects of E2 on strain-induced AP-1 transcriptional activity within endothelial cells. To evaluate the effect of E2 on strain-increased AP-1 activation, which is involved in ET-1 gene induction (7, 15, 24), we used an electrophoretic mobility shift assay. The extent of AP-1 binding to the consensus AP-1 binding sequence was assayed for HUVECs that had undergone strain treatment for a period of 6 h (Fig. 5A). Pretreating these cells with E2, NAC, or DPI attenuated the strain-stimulated AP-1 binding activity. The effects of E2 on strain-induced AP-1 functional activity were also assessed in a reporter gene assay. Cyclic strain appeared to exert no effect on the luciferase activity of the background vector containing no AP-1 binding site (data not shown). Contrasting this, however, cyclic strain significantly increased AP-1-luciferase activity in a time-dependent manner (data not shown). Furthermore, we examined the effects of E2, NAC, and DPI on AP-1 activity and noted that E2 (100 nM), NAC (10 mM), or DPI (10 μM) significantly attenuated the level of strain-induced AP-1 reporter activation (Fig. 5B); such results suggest that E2 inhibits strain-increased AP-1 activation.

Effects of E2 on strain-activated ERK phosphorylation within endothelial cells. To gain insight into the mechanism of action of E2, we thus examined whether E2 affects intracellular protein kinase signaling pathways. Given that the ERK signaling pathway is involved in strain-induced ET-1 expression (6), we further investigated whether E2 inhibits the ERK pathway for strain-treated HUVECs. We examined the phosphorylation of ERK in endothelial cells exposed to E2 (1–100 nM) in either the absence or the presence of strain treatment. As shown in Fig. 4A, endothelial cells that were exposed to strain treatment for 30 min rapidly activated phosphorylation of ERK, although endothelial cells pretreated with E2 (1–100 nM) exhibited a significant reduction in strain-induced ERK phosphorylation compared with their non-E2-pretreated analogs. Endothelial cells pretreated with E2 (100 nM), NAC (10 mM), or DPI (10 μM) all revealed a significant decrease in strain-induced ERK phosphorylation.

Effects of E2 on strain-increased NADPH oxidase activity and ROS generation within HUVECs. The results shown are means ± SE; n = 6. *P < 0.05 vs. control; #P < 0.05 vs. strain-treated cells (by ANOVA). A: effect of E2 (1–100 nM) on strain-increased NADPH oxidase activity. Cells were preincubated with E2 (1–100 nM) for 12 h and then stimulated with cyclic strain for a period of 1 h vs. no strain application. B: effect of E2 (1–100 nM) on strain-induced ROS generation. Cells were preincubated with E2 (1–100 nM) for 12 h and then stimulated with cyclic strain for a period of 1 h vs. no strain application. C: effects of the ER antagonist ICI or antioxidants on E2-mediated downregulation of strain-induced ROS generation. Cells were preincubated with E2 (100 nM) or the combination of E2 plus the ER antagonist ICI (1 μM) and the antioxidants N-acetylcysteine (NAC; 10 mM) or diphenylene iodonium (DPI; 10 μM) and then stimulated with cyclic strain for a period of 1 h or not at all. H2O2 (25 μM) was used as a positive control.

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E2 attenuation of strain-increased ET-1 gene expression that is compatible with antioxidants. To further determine whether E2 influences the strain-induced ET-1 gene expression that is compatible with antioxidants, the effect of E2 on strain-induced ET-1 gene expression was compared with the effects of antioxidants such as NAC and DPI. As demonstrated in Fig. 6, pretreatment of HUVECs with E2 or NAC or DPI alone did not appear to produce any significant effect on the basal ET-1 mRNA level and associated promoter activity (Fig. 6, A and B). Preincubation of endothelial cells with E2 (or NAC or DPI) did result in a significant inhibition of strain-increased intracellular levels of ET-1 mRNA and promoter activity. Furthermore, E2 (or NAC or DPI) alone exerted no significant effect on the basal level of ET-1 secretion. Preincubation of endothelial cells with E2 (or NAC or DPI) also significantly inhibited strain-increased ET-1 secretion. Endothelial cells exposed to exogenous oxidative stress (25 μM H2O2) also responded with a significant increase in ET-1 expression compared with the control analog (Fig. 6, A–C). These data implicate that E2 affects the strain-induced ET-1 gene expression that is compatible with antioxidants within endothelial cells.

DISCUSSION

Important vascular proteins such as ET-1 have been previously suggested to promote the development of cardiovascular diseases (31). Estrogen regulates the production of ET-1 as a potential novel mechanism in the prevention of the development of vascular disease among women (29). Estrogen may regulate prepro-ET-1 at the transcriptional level within cultured porcine endothelial cells (43). Estrogen is able of inhibiting ET-1 production via negative transcriptional regulation.
Dynamic forces including shear flow can induce endothelial cell ROS generation at the molecular level (40), which leads to the suppression of strain-induced ET-1 gene expression. The effects of E2 on strain-induced ET-1 gene expression and ROS generation could be reversed by antioxidant pretreatment of endothelial cells (6). The major new finding of this work is that E2 inhibits strain-induced ET-1 gene expression within human endothelial cells (summarized in Fig. 7). It is supported by the observations that E2 inhibits strain-induced ET-1 protein secretion and mRNA level and the promoter activity, in part, via the attenuation of strain-increased NADPH oxidase activity and ROS generation within endothelial cells. The effects of E2 on strain-induced ET-1 gene expression and ROS generation could be reversed by application of the nonselective estrogen receptor antagonist ICI-182,780, indicating that these potentially atheroprotective effects of the estrogen are indeed estrogen receptor mediated.

Previous studies, including ours, have indicated that hemodynamic forces including shear flow (49) and pressure-induced strain (6, 42) can stimulate the level of ET-1 gene expression. Our collaborative research and that from the work of others has demonstrated that cyclic strain treatment of endothelial cells can induce intracellular ROS generation (5, 25, 48). There appear to be binding elements within the ET-1 promoter (6, 29) that bind gene-specific enhancer elements. The mechanistic regulation of the transcriptional activity and expression of the ERK cascade, which leads to the activation of AP-1 transcriptional activity. The inhibitory effect of estrogen on ROS formation within endothelial cells has recently been shown that estrogen exposure could greatly impact cellular oxidative stress by regulating phase II enzyme activity through an antioxidant/electrophile response element-mediated pathway, thereby helping to explain why estrogen exposure is a risk factor for the induction of certain types of cancer (2). However, the data presented here and by others (40) have shown that E2 can exert antioxidative effects by inhibiting expression of NADPH oxidase in human endothelial cells, thereby inhibiting NADPH oxidase activity and ROS formation. Furthermore, recently, several lines of evidence suggest that hormone replacement therapy might be more effective in statin users (8, 21). Lipid profiles are more favorable in women on both statins and hormone replacement therapy than in women on either treatment alone (14). Estrogen and statins, although structurally unrelated to each other, both seem to possess similar action(s) on the inhibition of intracellular ROS generation at the molecular level (40, 44), which
may contribute to their vasoprotective effects. However, additional studies are needed regarding the mechanisms of hormone replacement therapy might be more effective in statin users.

Within the past decade, it has been repeatedly suggested that oxidative stress is related to, and may be a cause of, endothelial dysfunction in cases of atherosclerosis (12). The present study delivers important new insights into the molecular mechanisms of action of E2 for endothelial cells. Moreover, we show that E2 acts in part via the suppression of the ERK pathway to reduce strain-induced ET-1 gene expression. It is plausible that the strain-activated signaling pathway investigated herein consists of a number of redox-sensitive steps and that E2 treatment of endothelial cells could be involved in the modulation of the redox state of the cell. In summary, our data show that E2 inhibits strain-induced ET-1 gene expression, in part, via the attenuation of ROS formation and thereafter the suppression of the ERK pathway within endothelial cells. These findings support the suggested beneficial effects of estrogen on the cardiovascular system.

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cellular signal-regulated kinase pathway in neonatal rat cardiomyocytes.


