The Expanding Complexity of Estrogen Receptor Signaling in the Cardiovascular System

Sara Menazza, Elizabeth Murphy

Abstract: Estrogen has important effects on cardiovascular function including regulation of vascular function, blood pressure, endothelial relaxation, and the development of hypertrophy and cardioprotection. However, the mechanisms by which estrogen mediates these effects are still poorly understood. As detailed in this review, estrogen can regulate transcription by binding to 2 nuclear receptors, ERα and ERβ, which differentially regulate gene transcription. ERα and ERβ regulation of gene transcription is further modulated by tissue-specific coactivators and corepressors. Estrogen can bind to ERα and ERβ localized at the plasma membrane as well as G-protein–coupled estrogen receptor to initiate membrane delimited signaling, which enhances kinase signaling pathways that can have acute and long-term effects. The kinase signaling pathways can also mediate transcriptional changes and can synergize with the ER to regulate cell function. This review will summarize the beneficial effects of estrogen in protecting the cardiovascular system through ER-dependent mechanisms with an emphasis on the role of the recently described ER membrane signaling mechanisms. (Circ Res. 2016;118:994-1007. DOI: 10.1161/CIRCRESAHA.115.305376.)

Key Words: estrogens ■ MAP kinase signaling pathways ■ PI3 kinases ■ receptors, G-protein–coupled ■ signal transduction

Sex differences in cardiovascular disease are well documented. Premenopausal women have reduced cardiovascular disease, and the occurrence increases after menopause.1,2 Furthermore, many studies in animal models have reported less hypertrophy and less ischemia–reperfusion (I/R) injury in females compared with males.3,4 Additional studies with ovariectomized females have also shown that addition of estrogen reduces hypertension and I/R injury.5 Figure 1 summarizes the cardiovascular effects associated with estrogen. Large randomized clinical trials did not show a benefit with hormone-replacement therapy.6,7 However, a recent update of the woman health initiative examined different age groups and concluded that hormone-replacement therapy “has a harmful effect on health initiative examined different age groups and concluded that hormone-replacement therapy “has a harmful effect on health initiative examined different age groups and concluded that hormone-replacement therapy “has a harmful effect on health initiative examined different age groups and concluded that hormone-replacement therapy “has a harmful effect on health initiative examined different age groups and concluded that hormone-replacement therapy “has a harmful effect on health initiative examined different age groups and concluded that hormone-replacement therapy “has a harmful effect on health initiative examined different age groups and concluded that hormone-replacement therapy “has a harmful effect on health initiative examined different age groups and concluded that hormone-replacement therapy “has a harmful effect on health initiative examined different age groups and concluded that hormone-replacement therapy “has a harmful effect on

DOI: 10.1161/CIRCRESAHA.115.305376

Circulation Research is available at http://circres.ahajournals.org
to this 1 receptor, which acted as a ligand regulated transcription factor. The complexity of estrogen signaling has grown over the past 20 years. There are now 3 ERs (ERα, ERβ, and an orphan G-protein–coupled estrogen receptor, now known as GPER), as well as several splice variants, and ER signaling occurs via the traditional regulation of transcription as well as by activating membrane signaling cascades.

The need for a better understanding of the mechanisms of estrogen signaling is clearly emphasized by the recent findings, suggesting that there are sex differences in response to cardiovascular drug treatment and the suggestion that the failure of some small clinical trials could be related, at least in part, to sex differences in response to the drug.9,10 In fact, the National Institutes of Health has recently called for the inclusion of both sexes in preclinical trials.11 Without a better understanding of the complexity of estrogen signaling in the heart, it will be difficult to unravel the mechanisms by which estrogen might be involved in protection in premenopausal females and why it fails to protect in late postmenopausal women. This lack of understanding can also complicate the design and interpretation of clinical trials.

Nonstandard Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Akt</td>
<td>activation of protein kinase B</td>
</tr>
<tr>
<td>EC</td>
<td>endothelial cells</td>
</tr>
<tr>
<td>EDC</td>
<td>estrogen–dendrimer conjugate</td>
</tr>
<tr>
<td>eNOS</td>
<td>endothelial nitric oxide synthase</td>
</tr>
<tr>
<td>ER</td>
<td>estrogen receptor</td>
</tr>
<tr>
<td>ERE</td>
<td>estrogen response element</td>
</tr>
<tr>
<td>GPER</td>
<td>G-protein–coupled estrogen receptor 1</td>
</tr>
<tr>
<td>I/R</td>
<td>ischemia–reperfusion</td>
</tr>
<tr>
<td>MAPK</td>
<td>mitogen-activated protein kinase</td>
</tr>
<tr>
<td>PI3K</td>
<td>phosphatidylinositol-3-OH kinase</td>
</tr>
<tr>
<td>VSMCs</td>
<td>vascular smooth muscle cells</td>
</tr>
</tbody>
</table>

Estrogen Initiates Acute and Chronic Effects by Binding to ERs

The physiological effects of estrogen are mediated by estrogen binding to ERs. With classical ER signaling, estrogen binding to ERα or ERβ initiates translocation to the nucleus where the ER–estrogen complex acts as a ligand gated transcription factor initiating changes in gene expression. However, estrogen can also bind receptors localized at the plasma membrane, leading to the activation of acute signaling pathways often referred to as nongenomic or membrane-delimited signaling. However, the term nongenomic is somewhat misleading because activation of acute signaling pathways at the membrane can also indirectly lead to changes in gene expression. Recent studies have demonstrated that post-translational modifications of ERα and ERβ can influence their cell localization and activity.12–14 In addition to ERα and ERβ, GPER has been shown to localize to membranes and activate acute signaling pathways after estrogen binding.

Genomic Estrogen Action

ERα and ERβ are localized in both the cytosol and the nucleus and on binding estrogen they can translocate to the nucleus, bind to DNA and modulate gene expression. ERα and ERβ are highly homologous; they share >95% homology in their DNA-binding domains, but their ligand-binding domains share only 56% of amino acid sequence identity.15 Estrogen-activated ERs alter gene expression by (1) directly binding to DNA, (2) indirectly binding DNA through other transcription factors, or (3) ligand-independent binding (Figure 2). Estrogen binding to ERα promotes receptor dimerization and facilitates receptor binding to the consensus estrogen response element (ERE) in the DNA sequence, thus mediating its genomic effects. Coactivators and corepressors are recruited to activate or inhibit gene expression16 (Figure 2A). Estrogen can also alter gene expression via non-ERE regulatory mechanisms. ERs can tether to activator protein-1 and specificity protein-1 regulating gene expressions. Burns et al17 showed that mutation of a region of ER inhibits binding between ERs and transcription factors and blocks this signaling. Also consistent with the concept that ER binding via transcription factors is independent of EREs, Jakacka et al18 reported that an ERE is not necessary for activation and inactivation of API-dependent transcription (Figure 2B). Interestingly, activation of kinase signaling pathways by growth factors or estrogen activation of membrane ERs can lead to phosphorylation of ER and trigger its binding to DNA, thereby modulating of transcription. A specific serine phosphorylation site on ER has been shown to be important for ligand-independent activation of transcription19 or for binding to ERE (Figure 2C and 2D). This mechanism was elucidated when it was observed that growth factor activation of uterine proliferation was lost in mice that lacked ERα.20 Before these studies, it was not appreciated that ER was required for growth factor–dependent proliferation of the uterus.20 These results led to the concept that phosphorylation of ER can lead to its ligand-independent effects on transcription.

Estrogen has been shown to regulate the expression of a large number of cardiac genes.21–34 Overall, different genes are found to be regulated in different studies, and it is difficult...
to draw general conclusions. Gene regulation depends on the context of the cell, thus the estrogen-dependent changes in transcription might vary with age, sex, disease, and tissue. To address some of these issues, Devanathan et al. developed a mouse model of cardiomyocyte-specific deletion of ERα to characterize the role of ERα in the heart independent of systemic effects. Microarray data revealed differential variations in the expression of 208 genes compared with wild-type heart. A genome-wide expression profiling of estrogen-treated cardiomyocyte from men and women showed that 36 estrogen-dependent genes are regulated in a sex-specific manner confirming that estrogen effects are tissue and sex specific.

ERα Versus ERβ

To further complicate the analysis of ER-regulated genes, ERα and ERβ differentially regulate gene expression, and there can be tissue and temporal variations in the protein levels of ERα and ERβ. Also, the expression of coactivators and corepressors can differ and the recruitment of coregulators depends in part on the ligand bound. For example, tamoxifen recruits coactivators in endometrium, but it is an antagonist in breast recruiting corepressors. Hall et al. provide a more detailed review on genomic ER signaling, and Rosenfeld and Glass discuss the roles of coactivators and corepressors in ER signaling. In mouse aorta, O’Lone et al. reported that ERα and ERβ regulate a distinct set of genes. They reported that estrogen activation of ERα primarily results in upregulated gene expression, whereas ERβ primarily enhances downregulation of gene expression. In contrast to the study of O’Lone et al., a gene array study in ovariectomized female mice showed that perfusion of the heart for 2 hours with an ERβ selective agonist primarily led to the upregulation of gene expression with only a few genes downregulated. These conflicting results might be because of differences in aorta versus ventricular myocytes (eg, differences in levels of corepressors and coactivators) or because of different durations of estrogen treatment; as mentioned, estrogen can act in a time- and tissue-dependent manner. For example, in endothelial cells, ERα upregulates endothelial nitric oxide synthase (eNOS), whereas in cardiac muscle, ERβ mediates upregulation of eNOS. Also, studies in vascular smooth muscle cells (VSMCs) showed that inducible NOS expression is enhanced by ERβ and repressed by ERα. Furthermore, ERβ blocks inducible NOS gene upregulation in endothelial cells. ERα and ERβ can also synergize to regulate protein and enzyme activity. For example, in vascular endothelial cells (ECs), ERα regulates activation of superoxide dismutase 2, whereas ERβ regulates basal expression. Superoxide dismutase 2 upregulation results in a decrease in reactive oxygen species generation with lower mitochondrial dysfunction and vascular damage. The Table summarizes the known functions associated with ERα and ERβ gene regulations.

Overall, estrogen regulation of gene expression is complex; ERα upregulates some genes, whereas others are unaffected or downregulated by ERβ and vice versa. Also, the relative levels of ERα and ERβ and the corepressors and coactivators can change.
with sex, age, disease, and tissue thereby altering the response to estrogen. Additional studies are needed to better characterize the factors that contribute to tissue-specific ER regulation of gene expression in the cardiovascular system. Furthermore, although there are many studies examining ER regulation of gene expression, few studies have examined sex differences or estrogen-mediated differences in protein expression. There are many studies showing that changes in gene expression do not always translate to changes in protein expression, and therefore it is important to characterize the effects of sex and estrogen at the protein level. In addition to regulating mRNA transcription, estrogen is likely to regulate RNA processing, splicing, mRNA and protein stability, and protein post-translational modifications. We have just begun to understand that these sex differences in protein levels and additional studies are needed.

**Membrane-Delimited (Nongenomic) Signaling**

A rapid response to estrogen was first reported in the 1960s. Pietras and Szego showed that estrogen increased the cAMP concentration within minutes, paving the way for recent studies on the nongenomic response of estrogen. It is established that physiological concentrations of estrogen can have rapid effects, which occur independent of protein synthesis or gene activation, and it is generally accepted that these acute effects of estrogen are transmitted by signaling pathways through activation of ERs localized at the plasma membrane. In addition to the plasma membrane, ERs have also been localized to organelles including mitochondria and endoplasmic reticulum; however, the effects of ERs in mitochondria and endoplasmic reticulum are poorly understood and will not be discussed here.

Investigations of nongenomic estrogen action and its contribution to cellular function have been facilitated by the development of an estrogen conjugated to BSA. However, the cross-link between estrogen and BSA was through a key binding site for ERs making the experiments problematic as the conjugation inhibited the physiological effects of estrogen binding. Recently, Harrington et al developed an estrogen–dendrimer conjugate (EDC), an estrogen–macromolecule conjugate in which estrogen is attached to a large and positively charged polyamidoamine dendrimer. EDC provides a new tool to investigate the non-nuclear signaling mechanisms of estrogen.

**ERα and ERβ: Membrane Delimited**

**ERα and ERβ Both Localize to the Plasma Membrane**

It is estimated that 5% to 10% of total ERs are localized to the plasma membrane. The relative amount of ERα and ERβ at the plasma membrane can differ among cell types; for example, in breast cancer cells, ERα is found to be less than ERβ, meanwhile in reproductive tissue, ERα is more abundant than ERβ. ERs distribution is poorly studied in cardiovascular tissue; however, both the ERα and ERβ are found to be present at the plasma membrane of vascular ECs. ERα and ERβ are tethered to the plasma membrane by a mechanism involving post-translational modifications such as palmitoylation, which has been shown to increase association of the receptor with the plasma membrane.

Several laboratories have conducted investigations to confirm the localization of ERα to the plasma membrane. Using 3 different ERα antibodies, Chambless et al found ERα in EC plasma membranes, and they further demonstrated the presence of the ERα protein in a plasma membrane fraction isolated from the cell. They were also able to detect ERα in the caveolae using subfractions of caveolae and non caveolae. The same group later reported that ERα and eNOS colocalized in the caveolae. This group also found that ERβ is present in caveolae from EC and has a nongenomic signaling response, through eNOS stimulation. Chambliss and Shaul further confirmed that the same isoform of ERα (or ERβ) was present in purified plasma membranes and in the nucleus. Finally, Razandi et al confirmed in human breast cancer cells, using a mass spectrometry approach, that membrane and nuclear ERs are the same protein.

Several sites have been identified on ERα, which are involved in its localization to the plasma membrane. The interaction between ERα and caveolin-1 requires Ser522, located in the ligand-binding domain, which has been reported to facilitate the binding of ERα to caveolae. Also, palmitoylation of Cys447 on the ligand-binding domain of ERα has been demonstrated to be crucial for ERα localization to the membrane. Finally, immunoprecipitation studies demonstrated that amino acids 251 to 260 and 271 to 595 of ERα bind directly to Gαi and Gβγ. These modifications and their role in specific cell types will be discussed later.

The full-length ERα seems to be the predominant form associated with the plasma membrane and has been shown to initiate rapid actions of estrogen. However, an N-terminal–deleted splice variant, ERα 46, has been shown to colocalize with caveolin-1 in caveolae, and it seems to have a reduced transcriptional activity when compared with the full-length ERα. ERα 46 has been found coimmunoprecipitated with eNOS leading to eNOS activation and nitric oxide release.

**Trafficking to the Plasma Membrane**

As mentioned above, Ser522 is important for physical association of ERα with caveolin-1, and subsequent translocation to the plasma membrane. Indeed, 1 study showed that ERα localization at the plasma membrane is lost in caveolin-1 null cells, and ERα is only found in the nucleus. However, another study reported that the mutation of Ser522 in Chinese hamster ovary cells is not sufficient to block the ERα translocation to the

**Table. Summary of Known Genomic Function Associated With ERα and ERβ**

<table>
<thead>
<tr>
<th>ERα Function</th>
<th>ERβ Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increases left ventricular mass and volume</td>
<td>Reduces pathological cardiac hypertrophy</td>
</tr>
<tr>
<td>Reductions of infarct size after myocardial infarction</td>
<td>Prevents increases mortality in chronic heart failure</td>
</tr>
<tr>
<td>Cardioprotection against ischemia–reperfusion injury</td>
<td>Cardioprotection against ischemia–reperfusion injury</td>
</tr>
<tr>
<td>Regulates GLUT4 expression</td>
<td>Regulation of vascular function and blood pressure</td>
</tr>
<tr>
<td>Regulates cardiac growth</td>
<td>Modulates sex-specific response of the heart to exercise</td>
</tr>
<tr>
<td></td>
<td>Decreases inflammatory response</td>
</tr>
</tbody>
</table>

ER indicates estrogen receptor; and GLUT4, glucose transporter type 4.
plasma membrane, suggesting that Ser522 is not the only residue responsible for membrane association. Acconcia et al found that Cys447 of human ERα is a site for palmitoylation and this modification promotes the association of ERα with caveolin-1. Mutation of this site blocked ERα translocation to the plasma membrane in cancer cell lines. In 2007, Levin’s group identified a highly conserved amino acid motif in the estrogen-binding domain of both human and mouse ERα and ERβ that mediates membrane translocation via palmitoylation, and Cys447 is part of this motif. Therefore, palmitoylation of Cys447 is essential for caveolin-1 interaction and membrane translocation. However, additional sequences flanking this cysteine residue are needed for optimal palmitoylation. Mutation of key residues of ER for palmitoylation, such as phenylalanine or tyrosine at position-2, significantly reduces membrane localization and nongenomic actions of ER. Palmitoylation occurs only on ER monomers; therefore, enhancing ER dimerization, such as with estrogen binding, limits the available receptors that can undergo palmitoylation and translocate to the membrane. Because the percentage ERs localized at the plasma membranes are only 5% to 10% of the total amount present in the cell, it is important to define the proteins and mechanisms that regulate the ERs trafficking to plasma membrane. Heat shock protein 27 was identified by Razandi et al as a promoter of ER palmitoylation. Using a proteomic approach, they found that heat shock protein 27 binds to the palmitoylation site of ERα and promotes palmitoylation of ERα monomer. Another group found that ERα can localize to caveolae indirectly via the scaffold protein striatin, forming complexes with Gαi and Gα proteins.

**ERα and ERβ signaling**

ERα was first shown to localize to the plasma membrane and to activate phosphatidylinositol-3-OH kinase (PI3K) signaling. ERα and ERβ have been shown to play important roles in modulating cardiovascular disease. As discussed above, ERs localized at the plasma membrane initiate rapid signal transduction through kinase cascades involving PI3K, mitogen-activated protein kinase (MAPK), and eNOS activation. Rapid signaling by estrogen action was shown to lead to increased nitric oxide within minutes after addition of estrogen. Nitric oxide generation is involved in many beneficial effects on the cardiovascular system. Nitric oxide induces EC growth and migration, vasodilatation, and platelet inhibition, resulting in prevention of thrombus formation and leukocyte–EC adhesion.

**Endothelial Cells**

Endothelial homeostasis is important in cardiovascular health and endothelial dysfunction is associated with an increased cardiovascular risk. The rapid activation of eNOS is an important mechanism in vascular relaxation, EC migration, and proliferation. Initial studies showed that an estrogen–BSA conjugate stimulates eNOS phosphorylation in cultured EC. Estrogen can activate eNOS by multiple signaling pathways as illustrated in Figure 3A. Upon estrogen binding, membrane-localized ERα forms a complex with p85α, the regulatory subunit of PI3K and with SH2 domain of c-Src mediated by the phosphorylated Tyr-537 of ERα and by methylation of Arg260 of ERα. The formation of the ERα/PI3K complex leads to the activation of protein kinase B (Akt), extracellular-signal-regulated kinases 1/2, and phosphorylation and activation of eNOS. ERα can also activate MAPK and stimulate nitric oxide production by eNOS. Indeed, mice treated with estrogen showed increased eNOS activity and decreased vascular leukocyte accumulation after I/R injury, and this vascular protective effect of estrogen was abolished in the presence of inhibitors of PI3K or eNOS. ERα can also interact with the G proteins Gαi and Gβγ through amino acids 251 to 260, and this interaction activates eNOS and monocyte adhesion, as well as stimulating cell migration. A single alanine substitution generated within the Gαi-binding domain of ERα blocked the ability of estrogen to induce extracellular-signal-regulated kinases 1/2 and eNOS activation. Also, blocking formation of the ERα–Gαi complex prevented EC cell migration. Recently, Chambliss et al used EDC to demonstrate that EC proliferation and migration occurs via ERα–Gαi–Src kinase complex formation and resultant eNOS activation. They also demonstrated that EDC can attenuate the development of neointimal hyperplasia after vascular injury. Interestingly, EDC did not cause endometrial carcinoma cell growth in vivo or increase cell proliferation in breast cancer cells. The activation of PI3K on ERα–Gαi complex formation increases the activity and expression of the matrix metalloproteinase, matrix metalloproteinase 2 and matrix metalloproteinase 9, leading to epidermal growth factor receptor stimulation, which activates the MAPK kinase signaling pathway.

Immunoprecipitation experiments demonstrated that ERα can bind the adaptor striatin through amino acids 183 to 253 of ERα. Estrogen promotes the formation of a complex containing ERα, striatin, and Gαi leading to the activation of extracellular-signal-regulated kinases 1/2, Akt and eNOS pathways stimulating EC migration. Besides nitric oxide generation, the nongenomic ER signaling pathway also modulates intracellular calcium homeostasis at physiological estrogen concentration (10−9 mol/L) in human EC, causing a rapid increase in intracellular calcium. Treatment with estrogen conjugated to BSA caused a rise in calcium concentration in rat EC, whereas treatment with the ER antagonist ICI 182,780 blocked this effect. Taken together, estrogen activation of membrane ERs leads to rapid signaling mechanisms that target nitric oxide signaling, thus modulating EC proliferation, migration, and vascular relaxation.

**Vascular Smooth Muscle Cells**

The proliferation of VSMC plays a crucial role in vascular diseases, especially in atherosclerosis. Similar to EC, ERα and ERβ are associated with caveolin-1 at the plasma membrane of VSMCs. Several studies demonstrate that estrogen rapidly (within 30 minutes) inhibits VSMC proliferation. On estrogen treatment, ERα stimulates the activity and expression of several phosphatases, such as MAP kinase phosphatase-1, Src homology region 2 domain-containing phosphatase-1, phosphatase and tensin homolog, and protein phosphatase 2A. Activation of these phosphatases, which reverses phosphorylation, results in a decrease of cell growth and migration (Figure 3B). Consistent with these findings, a recent study showed that estrogen significantly blocks VSMC proliferation and decreases Akt phosphorylation because of enhanced protein phosphatase 2A activation mediated by a complex formed between ERα and protein phosphatase 2A. They also used
VSMC derived from a transgenic mouse line overexpressing a peptide that prevents ER trafficking to the plasma membrane and demonstrated that in this transgenic mouse, cell proliferation was not inhibited on addition of estrogen. Similar results were obtained by other groups using transgenic mice overexpressing a peptide that prevents ERα from interacting with striatin, a scaffold protein essential for ER binding to the caveolae. These studies demonstrated that the ability of estrogen to stimulate VSMC growth after carotid artery injury was lost in mice overexpressing the disrupting peptide. Microarray analysis of ex vivo aorta from these mice showed that the transcriptional response was greatly altered by blocking the nongenomic signaling. The genes showing different responses in the transgenic versus wild-type mice were associated with vascular function, indicating that acute estrogen signaling also plays a key role in physiological vascular gene regulatory
responses. Additional studies are needed to better understand the molecular mechanisms of nongenomic signaling and the effects on gene transcription. A better understanding of these mechanisms could contribute to the development of new treatments to improve vascular health.

Cardiomyocytes

There are few studies examining the nongenomic role of ERα and ERβ in cardiomyocytes. No studies have been done to distinguish genomic and nongenomic actions using transgenic models or extranuclear ER agonists. Estrogen was shown to have a role in cardioprotection against I/R injury. Short-term estrogen treatment (15 minutes before ischemia and 5 minutes at the beginning of reperfusion) improved heart function similar to that seen with pacing postconditioning.2,3,12 In addition, these beneficial effects of estrogen were not observed in the presence of a NOS inhibitor, suggesting that nitric oxide production via ER activation plays a key role in this process.12 Also, there are many studies showing that estrogen prevents cardiac hypertrophy, in particular, through ERβ.4,113 Pedram et al14 demonstrated that estrogen is not able to prevent angiotensin-induced hypertrophy and fibrosis in ERβ knockout mice. They provide data showing that rapid estrogen signaling acts on cardiac hypertrophy sequestering the transcription factors in the cytoplasm of cardiomyocytes to prevent target gene activation. Indeed, estrogen through ERβ can activate the modulatory calcineurin-interacting protein-1 gene blocking calcineurin activation in myocytes.22 Histone deacetylase are important in regulation of cardiac hypertrophy: class II is involved in signaling that inhibit this disorder, whereas class I promotes hypertrophy.115 Recently, Pedram et al116 demonstrated that angiotensin regulates gene and protein level of both class I and II histone deacetylases and rapid estrogen action through ERβ blocks these angiotensin actions. Angiotensin causes inhibition of calcium flux trough a G Protein-dependent mechanism, inhibiting Ca2+/calmodulin-dependent protein kinase II–induced class II histone deacetylase 4 phosphorylation and nuclear translocation. Also, angiotensin stimulates protein kinase C and D with consequent phosphorylation of class II HDACs, and estrogen is able to prevent these effects.116 In summary, these findings suggest an important role for estrogen in cardioprotection caused by rapid estrogen action. Additional studies should be conducted using the novel extranuclear ER agonists together with ER null transgenic mice to better understand the mechanisms involved in the protection against heart disease.

G-Protein–Coupled Receptor Signaling

G-Protein–Coupled Receptor Localization

It has recently been shown that estrogen can signal through an orphan G-protein–coupled receptor,72,117–119 also known as GPER. Two independent groups found that estrogen can directly bind to GPER at the membrane in monkey kidney fibroblast cells and breast cancer cells.2,118 Haas et al20 later discovered GPER expression in VSMC of human arteries and veins and confirmed that this novel receptor is regulated by estrogen. There is some debate on the cellular location of GPER. Revankar et al22 expressed green fluorescent protein-GPER in monkey kidney fibroblasts and images obtained using confocal fluorescence microscopy revealed that GPER is localized to the endoplasmic reticulum and the Golgi apparatus, but not to the plasma membrane. They also found that estrogen binding to GPER increases calcium mobilization by a signaling pathway involving epidermal growth factor receptor transactivation,117 rather than the more common mechanism involving ER activation of phospholipase C–dependent inositol 1,4,5-trisphosphate production. In contrast, other groups reported that GPER is localized to the plasma membrane.121–123 A possible explanation for these discrepant data has been proposed by Cheng et al124 which showed that GPER undergoes constitutive endocytosis resulting in a rapid (half-live of 30 minutes) downregulation. The recycled receptor that is present in the endosomes and endoplasmic reticulum levels might result from high levels of synthesis of the protein. In summary, GPER localization appears to be heterogeneous indicating that GPER can localize both at the plasma membrane and in specific intracellular sites. However, whether GPER is functionally active in the endoplasmic reticulum membrane is debated.

Vascular (EC and VSMC) Effects of GPER

Several studies investigated the role of GPER in vascular cells. Interestingly, the classical ERα and ERβ antagonist, ICI 182,780, was not able to attenuate estrogen-induced vasorelaxation in either canine coronary or small rat arteries.125–127 Although ICI 182,780 is an antagonist of ERα and ERβ, it is an agonist of GPER. Furthermore, removal of ERα and ERβ did not abolish estrogen-dependent responses in the cardiovascular system.128 These results led to the suggestion that activation of GPER might be responsible for the vasodilatory effects of estrogen. Several studies using the selective GPER agonist (G-1) were conducted confirming its ability to initiate vascular relaxation.129 Acute G-1 treatment induces relaxation on porcine coronary arteries,130 on rat aorta,131 and human internal mammary arteries.132 Infusion of G-1 to normotensive rats results in an acute reduction in blood pressure. Furthermore, GPER knockout mice did not exhibit a vascular response on addition of estrogen.132 Moreover, in hypertensive mRen2.Lewis rats, G-1 treatment leads to improved cardiac relaxation and reduced myocyte hypertrophy.133 Furthermore, GPER agonist treatment induces vasodilation in female rats.134 It has been suggested that G-1 results in 30% to 40% vasorelaxation in vivo135; however, the mechanism mediating this effect is poorly understood. There are data reporting actions of GRER via endothelium-dependent and endothelium-independent mechanisms. Estrogen binding to GPER leads to activation of eNOS, thus increasing the production of nitric oxide in coronary ECs to relax these arteries.125 Endothelium denudation or treatment with L-Nω-nitroarginine methyl ester, a NOS inhibitor, completely abolished the relaxation of porcine coronary arteries induced by G-1 action, consistent with a role for eNOS activation.123 In contrast, several other studies demonstrated that G-1 treatment can still have an effect on vasorelaxation in endothelium-denuded aorta131 and porcine coronary arteries.136 It was also shown that inhibition of eNOS does not affect this vasodilation response. Yu et al136 suggested that the endothelium-independent effect of coronary smooth muscle was mediated by a large conductance calcium-activated potassium channel in porcine and human arteries. Moreover, treatment with an eNOS inhibitor did not block the G-1–induced relaxation, but relaxation was inhibited by blocking the potassium channel. A scheme of these mechanisms is shown in Figure 4.
Studies suggesting that the activation of GPER alone mediates vasodilation contrast with studies suggesting that ERα and/or ERβ active NOS and mediate vasodilation. The reason for this discrepancy is unclear, but it may be because of differences in models, specificity of agonists and antagonists or cross talk between different receptors.

Normally, VSMC proliferation is slow; however, during stress, such as atherosclerosis or hypertension, these cells increase the rate of proliferation and migration. Estrogen decreases VSMC proliferation after injury. ERα has been clearly shown to mediate the antiproliferative effects of estrogen. There were initially reports using a first generation ERα knockout mouse, which was later found to express a truncated ERα protein which could mediate estrogen-dependent transcriptional activity, suggesting that ERα was not required to mediate the vascular injury response. However, later studies using an ERα knockout mouse, which is deficient in ERα, clearly demonstrated that ERα is required for the antiproliferative effects of estrogen. There are also some data, using GPER agonist, that suggest that activation of GPER can also play a role in the estrogen effect on vascular injury. Li et al recently demonstrated in coronary VSMCs that estrogen-GPER activation can decrease cell proliferation and migration. Estrogen also has a role in regulating proliferation of vascular ECs, thus preventing excessive EC proliferation that can occur during atherosclerosis. Treatment with G-1 reduced DNA synthesis and endothelial proliferation by blocking the transition between G2 and M phases of the cell cycle in mouse microvascular ECs and also in human umbilical vein ECs, again showing a role for GPER.

Cardiac Effects of GPER
In cardiomyocytes, Ullrich et al have shown that estrogen-dependent intracellular calcium signaling is independent of classic ERs: ERα and ERβ. They treated cardiomyocytes from ERα and ERβ knockout mice with serotonin and showed that the estrogen-mediated inhibition of Ca2+ influx and muscle contraction was not altered. Haas et al developed a GPER knockout mouse and confirmed that GPER stimulation is important for changing the intracellular Ca2+ concentration. Thus, estrogen may play a role through GPER by regulating the myofilament sensitivity to Ca2+ influx.

It has also been shown that estrogen-GPER activation protects against cardiac I/R injury. Deschamps and Murphy demonstrated that acute treatment of perfused rat heart with G-1 is cardioprotective, as it improved the contractile dysfunction after ischemia. The protection afforded by G-1 was shown to be dependent on PI3K signaling as a PI3K inhibitor blocked G-1-mediated cardiac protection. Also, GPER activation has been shown to inhibit mitochondria permeability transition pore opening after I/R injury, thereby protecting hearts from cell death. It was also reported that G-1 can reduce the inflammatory response in global ischemic injury. The discovery that GPER activation of acute signaling mechanisms results in myocardial protection provides the exciting possibility that GPER agonists can be used to initiate cardioprotection while avoiding the side effects of estrogen caused by nuclear ER stimulation in the uterus and breast.

GPER studies in the cardiovascular field have been growing rapidly, and overall these findings indicate a protective role of GPER in cardiovascular disease. Agonists of GPER...
are potential selective ER modulators and are likely to be good candidates for intervention in many cardiac dysfunctions. However, the molecular mechanisms downstream of GPER stimulation are still unclear, and future research needs to be done to clarify the signaling pathways involved and to understand the potentially beneficial effects of this receptor.

**ER Membrane and Genomic Collaboration for Regulation of Gene Expression**

Although nuclear and acute effects of estrogen can individually lead to changes in cell signaling, gene expression, and cell function, there is also cross talk between the nongenomic and genomic pathways that work together to modulate cell and organelle function. Estrogen acts synergistically, coordinating the activation of kinase signaling and the genomic signaling to regulate gene transcription. Mice lacking the ERα palmitoylation site, in which signaling is only via nuclear DNA binding and not via membrane signaling, were generated and offer insight into the collaboration between non-nuclear and nuclear ERα and ERβ signaling.149,150 Pedram et al149 found that nuclear ERα and ERβ alone are not able to maintain normal reproductive organ development; these mice showed infertility, abnormal ovaries, and pituitary hormone regulation. Overall, they also demonstrated that loss of membrane ERα compromises estrogen-induced expression of some important mRNAs in the uterus, mammary glands, and ovaries. Moreover, Pedram et al151 developed a mouse that expresses the ligand-binding domain of ERα that is targeted exclusively to the plasma membrane. After ovarietomy and treatment with an ERα agonist, they performed DNA microarray from liver mRNA. The majority of genes were regulated only by nuclear ERα; however, mRNAs for cholesterols, triglyceride, and fatty acid synthesis were comparably suppressed in membrane-only-ERα and wild-type mice and completely absent in ERα knockout mice. Several transcription factors are regulated by protein kinase–mediated phosphorylation. These transcription factors might regulate gene expression by ERs directly binding to DNA (Figure 2B). For example, activator protein-1 activity is regulated via MAPK-mediated phosphorylation.152 Estrogen can activate MAPK signaling that results in enhanced activator protein-1 DNA binding and lead to gene expression activation.153,154 Also, the activation of the PI3K-Akt signaling pathway by estrogen leads to nuclear factor κ-light-chain-enhancer of activated B cells phosphorylation and activation resulting in enhanced expression of genes that contain an nuclear factor κ-light-chain-enhancer of activated B cells binding site.153 The laboratory of Madak-Erdogan et al156 recently reported that ≈25% of estrogen-regulated genes are responsive with EDC treatment. Also, knockdown of ERα abolished gene expression caused by EDC treatment. Conversely, the knockdown of GPER showed no effect,156 indicating that in this study the cross talk between the nongenomic and genomic effects is mediated through ERs.

**ER Expression During Aging**

Premenopausal women have a lower incidence of cardiovascular disease when compared with age-matched men. However, this advantage for women gradually disappears after menopause with the cessation of ovarian function and reductions in estrogen levels. Both the ERα and ERβ have been localized in the cardiovascular system.157 The expression level of ERs seems to vary with the sex.38,158,159 Whether ER isoforms are distributed differently in cardiovascular system and whether they change with aging or sex is an important area for further investigation and would partially explain the clinical conflicting evidence of estrogen treatment in cardiovascular disease. However, changes in ER expression and signaling pathway are poorly investigated. Estrogen has been shown to positively regulate ER levels,160 and also other hormones such as progesterone and vitamin D negatively regulate ER levels.161 Measured by Western blotting, ERα and ERβ did not differ with age in aorta from spontaneously hypertensive rats.162 A study using immunofluorescence reported that vascular EC ERα expression in postmenopausal women is 33% lower than in the late follicular phase in premenopausal women.162,163 In astrocytes, using immunohistochemistry and Western blot analysis, Arimoto et al164 reported an increase in ERα levels with aging. Using immunofluorescence Wu et al165 also found an increase in ERα with age in the hypothalamus. Alterations in methylation of CpG islands, a cytosine and guanine-rich area in gene promoter regions, in the ER promoter have been reported to occur with age and disease, and these changes could be involved in altering ER levels. Methylation of the ER promoter has been reported to increase with atherosclerosis,166 but to decrease in brain after stroke.167 In future studies, it will be important to better define changes in expression and localization of ER with age, sex, and disease in the cardiovascular system.

**Conclusion**

Although estrogen signaling has been studied for years in reproductive tissues, it is only in the past decade or so that its role in the cardiovascular system has been appreciated. It has become apparent that estrogen has effects on cardiovascular tissues. Estrogen has important effects on lipid profile (such as low-density lipoprotein–lowering cholesterol), vascular remodeling, blood pressure, endothelial relaxation, development of hypertrophy and cardioprotection. However, the mechanisms by which estrogen mediates these effects are still poorly understood. As detailed in this review, estrogen can regulate transcription by binding to 2 nuclear receptors, ERα and ERβ, which differentially regulate gene transcription. These receptors are present at different ratios on different cells and their levels can change with time. ERα and ERβ regulation of gene transcription is also modulated by tissue-specific coactivators and corepressors. Taken together, estrogen can result in tissue- and temporal-specific regulation of gene transcription. Layered on the top of tissue-specific estrogen regulation of transcription, and adding to the complexity, is membrane-delimited signaling. Estrogen can bind to ERα and ERβ localized at the plasma membrane as well as GPER; estrogen binding enhances acute kinase signaling pathways that synergize with the ER to mediated transcriptional changes. In addition, acute signaling cascades can lead to phosphorylation of ERs that can lead to ligand-independent ER regulation of transcription (Figure 2). Understanding these complexities of estrogen-ER signaling is necessary to better understand why
premenopausal women have undergone cardiovascular disease but yet hormone-replacement therapy was not beneficial, at least in older menopausal women. Furthermore, a better understanding of what regulates ERα versus ERβ and how the nuclear ER transcriptional activation synergizes with acute membrane ER signaling will allow better design of selective estrogen modulator, which may provide beneficial effects of estrogen without unwanted side effects.

Sources of Funding
This work was supported by National Heart, Lung, and Blood Institute Intramural funds.

Disclosures
None.

References
beta mediate distinct pathways of vascular gene expression, including

...and estrogen receptor-alpha (ERalpha) messenger ribonucleic acid in the

...and estrogen receptor-beta (ERbeta) messenger ribonucleic acid in the


endothelial nitric oxide synthase via the PI3-kinase-Akt pathway in human


Monfared M, 10.1038/35035131.


ER. Estrogen regulates histone deacetylases to prevent cardiac hypertro-
ments.


Heaps CL, Stallone JN, Han G. Activation of GPER induces differentia-

Submitted for publication.


Menazzza and Murphy  Cardiovascular Effects of Estrogen 1007


The Expanding Complexity of Estrogen Receptor Signaling in the Cardiovascular System
Sara Menazza and Elizabeth Murphy

Circ Res. 2016;118:994-1007; originally published online January 7, 2016;
doi: 10.1161/CIRCRESAHA.115.305376
Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2016 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the
World Wide Web at:
http://circres.ahajournals.org/content/118/6/994

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation Research can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation Research is online at:
http://circres.ahajournals.org//subscriptions/