β-Arrestin-2 Deficiency Attenuates Abdominal Aortic Aneurysm Formation in Mice

Darshini B. Trivedi, Charles D. Loftin, James Clark, Page Myers, Laura M. DeGraff, Jennifer Cheng, Darryl C. Zeldin, Robert Langenbach

Rationale: Abdominal aortic aneurysms (AAAs) are a chronic inflammatory vascular disease for which pharmacological treatments are not available. A mouse model of AAA formation involves chronic infusion of angiotensin II (AngII), and previous studies indicated a primary role for the AngII type 1a receptor in AAA formation. β-arrestin (βarr)-2 is a multifunctional scaffolding protein that binds G-protein–coupled receptors such as AngII type 1a and regulates numerous signaling pathways and pathophysiological processes. However, a role for βarr2 in AngII-induced AAA formation is currently unknown.

Objective: To determine whether βarr2 played a role in AngII-induced AAA formation in mice.

Methods and Results: Treatment of βarr2+/+ and βarr2−/− mice on the hyperlipidemic apolipoprotein E–deficient (apoE−/−) background or on normolipidemic C57BL/6 background with AngII for 28 days indicated that βarr2 deficiency significantly attenuated AAA formation. βarr2 deficiency attenuated AngII-induced expression of cyclooxygenase-2, monocyte chemoattractant protein-1, macrophage inflammatory protein 1α, and macrophage infiltration. AngII also increased the levels of phosphorylated extracellular signal-regulated kinase 1/2 in apoE−/−/βarr2−/− aortas, whereas βarr2 deficiency diminished this increase. Furthermore, inhibition of extracellular signal-regulated kinase 1/2 activation with CI1040 (100 mg/kg per day) reduced the level of AngII-induced cyclooxygenase-2 expression in apoE−/−/βarr2−/− mice to the level observed in apoE−/−/βarr2+/+ mice. AngII treatment also increased matrix metalloproteinase expression and disruption of the elastic layer in apoE−/−/βarr2−/− aortas, and βarr2 deficiency reduced these effects.

Conclusions: βarr2 contributes to AngII-induced AAA formation in mice by phosphorylated extracellular signal-regulated kinase 1/2–mediated cyclooxygenase-2 induction and increased inflammation. These studies suggest that for the AngII type 1a receptor, G-protein–independent, βarr2-dependent signaling plays a major role in AngII-induced AAA formation. (Circ Res. 2013;112:1219-1229.)

Key Words: aneurysm ■ angiotensin ■ β-arrestin-2 ■ cyclooxygenase-2

Abdominal aortic aneurysms (AAAs) are a common vascular condition associated with several risk factors, including advanced age, male sex, smoking, and hypercholesterolemia.1 AAA formation begins as an abnormal dilation of the aorta, which may gradually expand over a period of years followed by eventual weakening and rupture of the vessel wall, resulting in mortality in ≈90% of cases.2–4 The pathophysiology of AAAs can be roughly categorized into 2 processes: inflammation and extracellular matrix degeneration.5 Inflammation is exemplified by the release of inflammatory mediators such as monocyte chemoattractant protein-1 (MCP-1) and interleukin 6 and the resultant infiltration of inflammatory cells, particularly macrophages, into the vessel wall.5–9 Inflammatory cells are a major source of proteolytic enzymes such as matrix metalloproteinase (MMP) 2 and MMP9, which are known to disrupt the structural integrity of the vessel wall and to degrade the components of the extracellular matrix such as elastin and collagen.10–11 This extracellular matrix degeneration and vascular remodeling contribute to the progression and severity of the disease. Currently, there are no pharmacological treatments for AAAs, with endovascular or surgical repair being the only options.

A widely used mouse model of AAAs involves chronic infusion of angiotensin II (AngII), and this model displays multiple characteristics of human AAAs and has provided mechanistic insight into the formation and progression of the disease.12,13 AngII mediates many of its physiological and pathological effects by activating the G-protein–coupled
Nonstandard Abbreviations and Acronyms

- AAA: abdominal aortic aneurysm
- AngII: angiotensin II
- apoE: apolipoprotein E
- AT1a: angiotensin II type 1a
- βarr: β-arrestin
- COX-2: cyclooxygenase-2
- ERK1/2: extracellular signal-regulated kinase 1/2
- MAPK: mitogen-activated protein kinase
- MCP-1: monocyte chemoattractant protein-1
- MIP1α: macrophage inflammatory protein 1α
- MMP: matrix metalloproteinase
- p-ERK1/2: phosphorylated ERK1/2
- PGE₂: prostaglandin E₂

receptor AngII type 1 (AT1) in most species and the a subtype of AT1 (AT1a) in rodents. Genetic ablation of the AT1a receptor in mice or treatment of mice with the AT1 receptor antagonist, losartan, attenuates AngII-induced AAA formation, indicating a critical role for this receptor in AngII-induced AAA pathology. The traditional signaling pathway used by the AT1a receptor involves G-protein–mediated activation of phospholipase Cβ and the liberation of the second messengers, diacylglycerol and inositol-triphosphate, resulting in downstream signaling events. However, in recent years, it has become increasingly evident that AT1a is also involved in G-protein–independent signaling by binding to scaffolding proteins known as β-arrestins (βarr)-1 and βarr2. βarr1 and βarr2 are ubiquitously expressed multifunctional proteins that were previously thought to be important in termination of G-protein–coupled receptor signaling. However, studies over the past decade have demonstrated that βarr1 and βarr2 can mediate G-protein–independent signaling and contribute to various physiological and pathological conditions. The coupling of βarr1 and βarr2 with G-protein–coupled receptors is known to recruit signaling molecules such as the c-Src family kinases, protein kinase B (AKT), phosphotyrosyl protein kinase 3, and key players in the mitogen-activated protein kinase (MAPK) signaling pathway, including p38, c-Jun N-terminal kinase 3, and extracellular signal-regulated kinase 1/2 (ERK1/2). The ERK1/2 cascade is the best-studied example of βarr–activated signaling for the AT1a receptor. Studies have shown that βarr1 and βarr2 bind with equal affinity to AT1a; however, both isoforms demonstrate differential roles in ERK1/2 signaling, wherein βarr2 is thought to be the primary isoform responsible for ERK1/2 activation.

Cyclooxygenase-2 (COX-2) is an enzyme important in the synthesis of inflammatory mediators such as prostaglandin E₁ (PGE₁) and has been shown to contribute to human AAA formation. Using the AngII-induced AAA model, we previously reported that genetic or pharmacological inactivation of COX-2 attenuated AAA incidence and severity in mice. Furthermore, these studies showed that AngII treatment significantly induced COX-2 expression in the abdominal aorta during the initiation and progression of the disease. Studies also suggested that the increased COX-2 expression in smooth muscle cells may contribute to AAA formation by initiating macrophage infiltration into the aorta via the release of inflammatory chemokines, including MCP-1 and macrophage inflammatory protein 1α (MIP1α). Additionally, studies have shown that the genetic deficiency of microsomal PGE synthase 1, an enzyme known to couple with COX-2 and to convert COX-2–generated prostaglandin H₂ into PGE₂, or antagonism of the PGE₂ receptor, prostaglandin E₂ receptor 4, ablates AngII-induced AAA formation in mice. These studies provide further evidence for the role of COX-2–derived PGE₂ in AAA formation.

Cyclooxygenase-2 induction in response to AngII has been shown to occur via the activation of several signaling molecules, including components of the MAPK pathway such as ERK1/2. Furthermore, ERK1/2 activation has also been shown to be important in the formation of AngII-induced AAAs because inhibition of ERK1/2 activation impairs AAA formation in mice. These findings underscore the importance of COX-2 and ERK1/2 in AAA formation and suggest that activated phosphorylated ERK1/2 (p-ERK1/2) may contribute to COX-2 induction during AAA formation. Because βarr2 is important in AngII-AT1a–mediated ERK1/2 activation, in the present study, we investigated whether βarr2 played a role in AngII-induced AAA formation. Using both normolipidemic βarr2–deficient mice and hyperlipidemic apolipoprotein E–deficient (apoE−/−)βarr2−/− mice, we demonstrate that βarr2 deficiency significantly attenuates AAA formation. Furthermore, mechanistically, it seems that βarr2 mediates AngII-induced COX-2 expression via a p-ERK1/2–dependent pathway and increases the expression of inflammatory markers, thereby contributing to AAA formation.

Methods

Mice

Male, hyperlipidemic apoE−/−βarr2−/− and apoE−/−βarr2− mice at 8 to 10 weeks of age were used for measuring AngII-induced AAA incidence and severity and for mechanistic experiments. AngII-induced AAA incidence was also examined in 8-month-old male βarr2−/− and βarr2− mice on a normolipidemic C57BL/6 background. Please refer to the online Data Supplement Methods section for details.

AAA Quantitation

Mice were treated with AngII (1000 ng/kg per minute) or saline via subcutaneously implanted osmotic mini-pumps and euthanized after 28 days for AAA quantification. A >50% increase in external diameter of the abdominal aorta was used to define the occurrence of an AAA. AAA severity was determined using a classification scheme described previously and by measuring the wet weights of the abdominal aortas. The presence of an AAA and the scoring of AAA pathology were determined by an investigator who was blinded to mouse genotype. On determination of the AAA incidence and classification, another investigator matched the scored AAAs to the genotypes of the mice.

Blood Pressure Measurements

Blood pressure was measured in conscious, unrestrained, male apoE−/−βarr2−/− and apoE−/−βarr2− mice by radiotelemetry, before and after treatment with AngII (1000 ng/kg per minute, osmotic mini-pumps), using methods similar to those described previously. For more details, see the online Data Supplement Methods section.

Inhibition of ERK1/2 Activation

AngII-treated apoE−/−βarr2− mice were treated with the MAPK kinase 1 inhibitor, CI1040, as previously described.
Histology and Immunohistochemistry
Mice were euthanized at the designated time points (7 or 28 days), and abdominal aortic sections were stained with hematoxylin and eosin or Verhoeff–Van Geison (elastin) stain for histological analysis or with antibodies against COX-2, macrophage marker protein Mac-3, or p-ERK1/2 for immunohistochemical analysis. Quantification of immunohistochemistry was performed by determining the ratio of the number of COX-2-, p-ERK1/2-, or Mac-3–positive cells to the total number of hematoxylin-positive nuclei per field (at ×400 magnification). For more details, please refer to the online Data Supplement Methods section.

Quantitation of mRNA Expression
Real-time quantitative polymerase chain reaction analysis for COX-2, CD68, MCP-1, MMP1α, MMP2, and MMP9 was performed using TaqMan gene expression assays and the ΔΔCt method with hypoxanthine phosphoribosyl transferase as the endogenous control. For more details, see the online Data Supplement Methods section.

Statistics
Data are shown as the mean±SEM of independent experiments. The Fisher exact test was used to compare AAA incidence among different groups. Two-way ANOVA was used to examine changes in blood pressure between genotypes. One-way ANOVA, followed by Bonferroni multiple-comparison tests, was used to determine the statistical significance of the data in all other experiments. Values of P≤0.05 were considered statistically significant.

Results
βarr2 Deficiency Attenuates the Incidence and Severity of AngII-Induced AAAs
The effect of βarr2 deficiency on AAA development in hyperlipidemic mice was determined by crossing βarr2+/+ mice with hyperlipidemic apoE−/− mice. AngII infusion for 28 days induced a 61.8% incidence (21 of 34 mice) of AAAs in apoE−/−/βarr2+/+ mice, whereas the AAA incidence in apoE−/−/βarr2−/− mice was significantly reduced to 9.5% (2 of 21 mice) (Figure 1A). As expected, AAAs were not observed in the saline-infused apoE−/−/βarr2−/− or apoE−/−/βarr2+/+ mice (Figure 1A). The deficiency of βarr2 also attenuated the severity of AngII-induced AAAs, as determined by a classification scheme based on the external diameter of the abdominal aortas (Figure 1B) and by measuring the wet weights of the abdominal aortas (Figure 1C). Histological examination of cross sections of the abdominal aortas from apoE−/−/βarr2+/+ mice showed severe thickening and prominent remodeling with thrombi present in the vessel wall (Figure 1D). In contrast, the abdominal aortas from AngII-treated apoE−/−/βarr2−/− mice showed minimal thickening and remodeling (Figure 1E) and 8-month-old, normolipidemic C57BL/6 mice. AngII infusion resulted in a 29.2% incidence (7 of 24 mice) of AAAs in the normolipidemic C57BL/6 (βarr2+/+ mice (Figure 1G). In contrast, none of the normolipidemic C57BL/6 (βarr2−/− mice (0 of 15 mice) displayed any pathology (Figure 1G). Of the 7 C57BL/6 (βarr2−/− mice that developed AAAs, 2 mice displayed a type 2 aneurysm, 3 mice had a type 3 aneurysm, and 2 mice displayed aneurysmal rupture. Furthermore, similar to previous studies,38 the AAAs in the normolipidemic C57BL/6 (βarr2+/+ mice were grossly similar to those that developed in the hyperlipidemic apoE−/− mice after AngII infusion. Thus, the deficiency of βarr2 attenuates AngII-induced AAA incidence in both hyperlipidemic and normolipidemic mouse strains. Because the AngII-induced AAA incidence in the C57BL/6 (βarr2−/− mice on the normolipidemic background is markedly lower than that observed in the hyperlipidemic apoE−/−/βarr2+/+ mice (29.2% versus 61.8%), the mechanistic studies described below were performed in the apoE−/−/βarr2−/− and apoE−/−/βarr2+/+ mice.

βarr2 Deficiency Does Not Alter AngII-Induced Increases in Blood Pressure
Previous studies have demonstrated that AngII infusion rapidly increases systolic blood pressure in mice.39–41 Therefore, to determine whether βarr2 deficiency affected AngII-mediated increases in blood pressure, we measured the systolic blood pressure in apoE−/−/βarr2+/+ and apoE−/−/βarr2−/− mice. As shown in the Table, AngII treatment significantly increased the mean systolic blood pressure in both apoE−/−/βarr2+/+ and apoE−/−/βarr2−/− mice compared with basal blood pressure. However, there was no significant difference in the systolic blood pressure between apoE−/−/βarr2−/− and apoE−/−/βarr2+/+ mice at baseline or with AngII treatment (Table). These results indicate that the reduction in the AngII-induced AAA incidence in βarr2-deficient mice is not dependent on alterations in blood pressure.

AngII-Induced COX-2 Expression Is Attenuated in Aortas From βarr2-Deficient Mice
AngII is known to be a potent inducer of COX-2 expression,30,31,42 and our previous studies have indicated that COX-2 contributes to AngII-induced AAA formation.8,27 Therefore, to determine whether βarr2 played a role in AngII-induced COX-2 expression, apoE−/−/βarr2+/+ and apoE−/−/βarr2−/− mice were treated with saline or AngII for 7 or 28 days and analyzed for COX-2 expression. AngII infusion significantly increased the levels of COX-2 mRNA in the aortas of apoE−/−/βarr2+/+ mice at experimental days 7 (Figure 2A) and 28 (Figure 2B) compared with saline infusion. In contrast, there was a significant reduction in AngII-induced COX-2 expression in the aortas of βarr2-deficient mice at both time points. In addition, numerous COX-2 expressing cells were detected in the medial and adventitial layers of the abdominal aorta from apoE−/−/βarr2+/+ mice after 7 days (Figure 2C) and throughout the aneurysmal tissue after 28 days of AngII infusion (Figure 2D). In contrast, significantly fewer COX-2–positive cells were observed in the abdominal aortas from apoE−/−/βarr2−/− mice at both time points (Figure 2E–2G). Thus, βarr2 plays a key role in the AngII-induced COX-2 expression during AAA development.
βarr2 Contributes to ERK1/2 Activation in AngII-Induced AAAs, and p-ERK1/2 Contributes to COX-2 Induction

ERK1/2 signaling is an extensively studied pathway activated by the AT1a-βarr2 complex, and p-ERK1/2 is also known to contribute to COX-2 induction in several cell types. As shown in Figure 3A, immunohistochemical analysis indicated the presence of p-ERK1/2 in the medial layer of aortas from apoE−/−/βarr2−/+ mice after 7 days of AngII infusion. When analyzed at 28 days after AngII infusion, numerous p-ERK1/2–containing cells were observed throughout the aneurysmal aortas from apoE−/−/βarr2−/+ mice (Figure 3B). In contrast, in the abdominal aortas from apoE−/−/βarr2−/− mice, significantly reduced p-ERK1/2 was observed at both time points (Figure 3C–3E).

To determine whether ERK1/2 activation was involved in the AngII-induced COX-2 expression, we used the MAPK kinase 1 inhibitor, CI1040, which has previously been shown to inhibit ERK1/2 phosphorylation and to attenuate AngII-induced AAA formation in mice. In the absence of CI1040, AngII-induced COX-2 expression was significantly increased in apoE−/−/βarr2+/+ mice compared to apoE−/−/βarr2−/− mice. When CI1040 was administered, the increase in COX-2 expression was significantly attenuated, indicating that ERK1/2 activation is required for AngII-induced COX-2 expression. The results suggest that ERK1/2 signaling plays a crucial role in the pathogenesis of AngII-induced AAAs.
treatment, AngII infusion for 7 days resulted in a significant induction in COX-2 mRNA in the aortas of apoE−/−/βarr2+/− mice (Figure 3F). However, in mice treated with CI1040 plus AngII, the increase in COX-2 expression was significantly reduced compared with AngII treatment alone. Furthermore, COX-2 mRNA levels after CI1040 plus AngII treatment were not statistically different from those observed in AngII-treated apoE−/−/βarr2−/− mice (Figure 3F). Thus, the data indicate that βarr2 is important in AngII-induced ERK1/2 activation, which may subsequently increase COX-2 expression.

**βarr2 Deficiency Attenuates AngII-Induced Macrophage Infiltration Into the Abdominal Aorta**

Macrophage infiltration is an important early event during AAA formation. Therefore, we examined the role of βarr2 in macrophage infiltration during AngII-induced AAA formation. Immunohistochemical staining for the macrophage marker Mac-3 in the abdominal aortas from AngII-treated apoE−/−/βarr2+/− mice indicated an abundant infiltration of macrophages into the media and adventitia by day 7 (Figure 4A) that continued through the 28-day AngII infusion (Figure 4B). However, Mac-3 staining was significantly reduced in the abdominal aortas of apoE−/−/βarr2−/− mice at both time points, indicating decreased macrophage infiltration (Figure 4C–4E). In addition, we observed a robust increase in the mRNA expression for the macrophage marker, CD68, in the aortas of apoE−/−/βarr2+/− mice after AngII infusion (Figure 4F). In contrast, AngII infusion in apoE−/−/βarr2−/− mice did not significantly increase CD68 mRNA expression compared with saline controls (Figure 4F).

AngII has been shown to stimulate the secretion of inflammatory chemokines such as MCP-1 and MIP1α, which are known to increase macrophage infiltration. Therefore, the expression of MCP-1 and MIP1α was examined in the
aortas from apoE−/−/βarr2+/+ and apoE−/−/βarr2−/− mice during the initial stage of AAA formation. AngII infusion for 7 days significantly increased the mRNA expression of both MCP-1 (Figure 4G) and MIP1α (Figure 4H) in the apoE−/−/βarr2+/+ aortas compared with saline infusion. However, the increases in MCP-1 and MIP1α expression in response to AngII were significantly lower in the aortas of apoE−/−/βarr2−/− mice (Figure 4G and 4H). Therefore, the data suggest that attenuated chemokine production may be responsible for reduced macrophage infiltration and diminished AAA formation in apoE−/−/βarr2−/− mice.

βarr2 Contributes to Increased MMP2 and MMP9 Expression During AAA Formation

MMPs have been mechanistically implicated in the pathogenesis of AAAs, and MMP2 and MMP9, in particular, are known to have a concerted role in AAA initiation and progression.48,49 As shown in Figure 5A and 5B, AngII treatment significantly increased MMP2 mRNA expression at days 7 and 28 in apoE−/−/βarr2+/+ mice. However, in apoE−/−/βarr2−/− mice, the increase in MMP2 expression was significantly lower when analyzed at both time points after AngII infusion (Figure 5A and 5B). In contrast to MMP2 expression, AngII treatment resulted in only a modest increase in MMP9 mRNA expression at 7 days in apoE−/−/βarr2+/+ mice, and βarr2 deficiency did not seem to significantly alter MMP9 mRNA expression at this time point (Figure 5C). However, after 28 days of AngII infusion, MMP9 expression was significantly increased in apoE−/−/βarr2+/+ mice, and βarr2 deficiency attenuated this increase (Figure 5D). Increased MMP expression has been associated with the proteolytic degradation and elastin breakage that occur during aneurysmal expansion. Verhoeff–Van Gieson staining of abdominal aortic segments from apoE−/−/βarr2+/+ mice after 28 days of AngII infusion showed regions of breakage and discontinuity of the medial elastin layer (Figure 5E). In contrast, the elastin fibers in the aortas of AngII-treated apoE−/−/βarr2−/− mice appeared intact (Figure 5F), similar to the aortas of saline-treated apoE−/−/βarr2−/− mice (Figure 5G). Aortas from saline-treated apoE−/−/βarr2−/− mice were histologically indistinguishable from aortas from saline-treated apoE−/−/βarr2−/− mice (data not shown).

Discussion

Several studies have demonstrated that AngII infusion leads to the formation of AAAs in mice.12,13,50 AngII exerts its diverse bioactive effects primarily by activating the AT1a receptor in mice, which plays a critical role in AngII-induced AAA development.17 In addition to mediating traditional...
G-protein–dependent signaling, the AT1a receptor is involved in G-protein–independent signaling by forming a complex with the multifunctional scaffolding protein βarr2.19,24 In the present study, we investigated a role for βarr2 in AngII-induced AAA formation and found that βarr2 deficiency significantly attenuates AAA formation in mice both on a hyperlipidemic apoE background and on a normolipidemic C57BL/6 background (Figure 1). These studies suggest that G-protein–independent, βarr2-dependent signaling for the AT1a receptor plays a major role in AngII-induced AAA formation.

Although our present studies showed that βarr2 deficiency attenuated AngII-induced AAA formation in mice on the hyperlipidemic apoE−/− background, it was not clear whether hyperlipidemia was required for this observed phenotype. Therefore, we examined the effect of βarr2 deficiency on AngII-induced AAA formation in mice on a normolipidemic C57BL/6 background. We have previously reported that 8- to 10-week-old, normolipidemic C57BL/6 mice develop only a 5% incidence of AngII-induced AAAs; however, 2 recent reports have used aged (7- to 11-month-old) C57BL/6 mice and have shown that these mice develop an ≈ 40% incidence of AAAs in response to AngII.37,38 Therefore, we performed experiments using 8-month-old, normolipidemic βarr2+/+ and βarr2−/− mice on a C57BL/6 background and found that similar to the effect in apoE−/− mice, the deficiency of βarr2 also significantly attenuated AngII-induced AAA incidence and severity.8 Therefore, we observed only a low AAA incidence (29.2%) in the C57BL/6 βarr2+/+ strain, the mechanistic studies in our present report were performed in mice on the apoE−/− background.

Our previous studies have indicated an important role for COX-2 in AAA formation because genetic deficiency of COX-2 or treatment of mice with the COX-2 selective inhibitor celecoxib significantly attenuated AngII-induced AAA incidence and severity.8,27 Because our present study
shows that βarr2 deficiency also attenuates AngII-induced AAA formation, we investigated a possible link between COX-2 and βarr2 in this pathology. Although previous studies have shown that AngII-mediated COX-2 induction can occur via G-protein–dependent AT1a receptor signaling,30–32 the results in the present study show that the deficiency of βarr2 attenuates AngII-mediated COX-2 induction. This suggests the involvement of a βarr2-dependent, G-protein–independent mechanism for AngII-mediated COX-2 induction. Our findings are supported by a recent study that showed that treatment of rat vascular smooth muscle cells with a biased agonist for the AT1a receptor, which activates G-protein–independent, βarr2-dependent signaling,53 increased COX-2 expression.52 From these studies, together with the results from our present study, we conclude that AngII-mediated COX-2 induction can indeed occur via a G-protein–independent pathway involving βarr2.

AngII-induced COX-2 expression can occur via activation of components of the -MAPK pathway such as ERK1/2,30–32 and ERK1/2 activation is known to be involved in AngII-induced AAA formation.33 Our data show that βarr2 deficiency prevented the AngII-mediated ERK1/2 activation in apoE−/−/βarr2+/+ mice compared with apoE−/−/βarr2−/− mice when examined at either the incipient (7 days) or advanced (28 days) stage of AAA development. Furthermore, similar to the deficiency of βarr2, inhibition of ERK1/2 activation significantly abrogated the AngII-mediated increase in COX-2 expression. Thus, AngII–AT1a–βarr2–mediated COX-2 induction seems to occur, in part, by a mechanism involving activated ERK1/2.

A hallmark of AAA pathology is macrophage infiltration into the aorta, which is an early cellular event after AngII infusion that continues throughout the development of the disease.13 Our previous studies using the COX-2–deficient mice and more recent studies using a prostaglandin E2 receptor 4-selective antagonist have suggested that COX-2–derived PGE2 stimulates the production of inflammatory chemokines such as MCP-1 and MIP1α, which contribute to macrophage infiltration into the aorta.36,37 This is consistent with our current findings, where the deficiency of βarr2 or inhibition of ERK1/2 activation abrogated the AngII-mediated increase in COX-2 expression and subsequent mast cell infiltration into the aorta.36,37 Therefore, these results suggest that AngII–AT1a–βarr2–mediated COX-2 induction can occur, in part, via a mechanism involving activated ERK1/2.
infiltration during AAA development. Because βarr2 has been shown to contribute to proinflammatory gene expression in other models of inflammation, we examined the role of βarr2 in the inflammatory response that occurs during AAA formation. The observations that βarr2 deficiency attenuated the expression of COX-2 and the inflammatory chemokines, MCP-1 and MIP1α, together with reducing macrophage infiltration, suggest that βarr2 positively regulates inflammation in AngII-induced AAAs through the induction of COX-2 expression.

Proteolytic degradation within the vessel wall mediated largely by MMPs is a common feature of AAAs, wherein elastin fragmentation in the medial and adventitial layers is believed to contribute to the initial dilation, and increased collagenase activity may be responsible for aneurysmal rupture. A preponderance of evidence in experimental models and in humans supports a role for MMPs, particularly MMP2 and MMP9, in AAA initiation and progression. Our studies show that the deficiency of βarr2 attenuated the increase in MMP2 when analyzed at 7 and 28 days after AngII infusion. However, the effect of βarr2 deficiency on MMP9 expression was prominent only at the late stages of aneurysm development (Figure 5D). These results may be explained by previous studies suggesting an important role for MMP2 during the formative stage of AAAs involving macrophage infiltration and a dominant role for MMP9 during the progressive stage of AAAs.

AngII is known to be a potent inducer of hypertension in mice. However, it has also been shown that administration of hydralazine to reduce AngII-induced hypertension does not affect the formation of AAAs, indicating that AngII-induced AAA formation is independent of AngII-induced hypertension. Our studies show that βarr2 deficiency had no effect on the hypertensive response to AngII (Table). Thus, these results suggest that our observed effect of βarr2 deficiency on reducing AAA formation is independent of alterations in blood pressure.

In summary, these studies demonstrate that βarr2 plays a crucial role in the development of AngII-induced AAAs in mice via the induction of COX-2 expression. On the basis of our present data and previous studies, we propose the following mechanism for βarr2-dependent AAA formation: Activation of AT1a by AngII leads to βarr2 recruitment and AT1a–βarr2 complex formation, which results in the activation of ERK1/2 and COX-2 induction. The AT1a–βarr2-dependent increase in COX-2 expression contributes to AAA initiation via the induction of inflammatory chemokines and resultant recruitment of macrophages, and this, combined with increased MMP expression, exacerbates AAA pathology. Thus, our studies identify βarr2 as a novel target for the design of pharmacotherapies for AAAs. The fact that βarr2-dependent and G-protein–dependent signaling pathways are pharmacologically distinguishable has given rise to the concept of biased agonism, whereby a ligand may selectively trigger one or the other pathway. Based on this emerging concept, future studies using biased ligands to target βarr2-mediated signaling may provide further mechanistic insight into the contribution of βarr2 to AAA formation.

Acknowledgments
We thank Natasha Clayton, BS, HT, and Pamela Owvigho, BS, of the Histology Core at the National Institute of Environmental Health Sciences (NIEHS) for their assistance with the hematoxylin and eosin- and Verhoeff–Van Geison staining techniques, and Lois Wyrick, BFA, of the NIEHS Arts and Graphics Core for her assistance in the preparation of the digital images.

Sources of Funding
This work was supported by the Division of Intramural Research of the National Institute of Environmental Health Sciences at the National Institutes of Health. C.D.L. is supported by the National Institute of Health (HL083122).

Disclosures
None.

References
Circulation Research  April 2013


51. Manning MW, Cassis LA, Daugherty A. Differential effects of doxycycline, a broad-spectrum matrix metalloproteinase inhibitor, on

**Novelty and Significance**

**What Is Known?**
- Angiotensin II (AngII) infusion results in the formation of abdominal aortic aneurysms (AAAs) in mice by activating the AngII type 1a (AT1a) receptor and inducing an inflammatory response.
- Inflammatory mediators produced by cyclooxygenase-2 are key contributors to AngII-induced AAA pathology.
- β-Arrestin (βarr) activates extracellular signal-regulated kinase 1/2 signaling by coupling with AT1a, and extracellular signal-regulated kinase 1/2 activation has been shown independently to be important in AAA development.

**What New Information Does This Article Contribute?**
- βarr2 is critical for the development of AngII-induced AAAs in mice.
- βarr2 mediates AngII-induced AAA formation by inducing cyclooxygenase-2 expression via the extracellular signal-regulated kinase 1/2 pathway and by increasing inflammation.
β-Arrestin-2 Deficiency Attenuates Abdominal Aortic Aneurysm Formation in Mice
Darshini B. Trivedi, Charles D. Loftin, James Clark, Page Myers, Laura M. DeGraff, Jennifer Cheng, Darryl C. Zeldin and Robert Langenbach

Circ Res. 2013;112;1219-1229; originally published online March 22, 2013;
doi: 10.1161/CIRCRESAHA.112.280399

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2013 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/112/9/1219

Data Supplement (unedited) at:
http://circres.ahajournals.org/content/suppl/2013/03/22/CIRCRESAHA.112.280399.DC1

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/
Supplemental Material

Mice
βarr2+/+ and βarr2−/− mice1 on a C57BL/6 background were generously provided by Dr. Robert Lefkowitz (Duke university, Durham, NC). βarr2−/− mice were crossed with hyperlipidemic ApoE−/− mice (stock #002052, Jackson laboratories, Bar Harbor, ME) and the resulting mice (ApoE+/−/βarr2+/−) were crossed to generate ApoE+/−/βarr2−/− mice and their littermate controls (ApoE−/−/βarr2−/−). Male, hyperlipidemic ApoE+/−/βarr2−/+ and ApoE−/−/βarr2−/− mice at 8-10 weeks of age were use for measuring AngII-induced AAA incidence and severity and for mechanistic experiments. AngII-induced AAA incidence was also examined in 8-month old, male, normolipidemic βarr2+/+ and βarr2−/− mice on a C57BL/6 background. All mice were housed under barrier conditions at the NIEHS animal husbandry facility and food and water were provided ad libitum. All studies were performed with the approval of the NIEHS Institutional Animal Care and Use Committee.

AAA quantitation
Mice were anesthetized by isoflurane inhalation and AngII (1000ng/kg/min; Sigma, St. Louis, MO) or saline was administered via subcutaneously implanted osmotic mini-pumps (Model 1004, Durect, Cupertino, CA) as described previously.2,3 Mice were euthanized after 28 days of AngII infusion and the aortas were perfused with ice-cold PBS followed by 10% formalin. The abdominal aortas were dissected out and immediately placed in PBS and cleaned of adventitial fat. The maximal abdominal aortic diameter was measured using a caliper under a dissecting microscope while the aortas were in PBS without physical stretching. A >50% increase in external diameter of the abdominal aorta was used to define the occurrence of an AAA. AAA severity was classified visually using a classification scheme similar to the one described previously,3 where Type 1 represents a simple dilation of the abdominal aorta with an external diameter from 1.5-2 mm, Type 2 represents a remodeled AAA with the external diameter from 2-3 mm and Type 3 represents a pronounced bulbous containing a thrombus and an external aortic diameter of >3 mm. Mice in the Type 4 AAA category were those that died due to aneurysmal rupture and resultant bleeding in the peritoneal cavity. The presence of an AAA as well as the scoring of AAA pathology was determined by an investigator who was blinded to the mouse genotypes. Upon determination of the AAA incidence and classification, another investigator matched the scored AAAs to the genotypes of the mice. AAA severity was also determined by measuring the wet weights of the abdominal aortas.

Blood Pressure Measurements
Male ApoE+/−/βarr2+/− and ApoE+/−/βarr2−/− mice were used for the blood pressure measurements and were fed a normal chow diet with free access to water. Systolic blood pressure was measured in conscious, unrestrained mice by radio-telemetry using an indwelling transducer-tipped catheter (TA11PA-C20; Data Sciences International, St. Paul, MN, USA) that was surgically inserted into the right carotid artery.4,5 Mice were anesthetized with 2.5% isoflurane with a continuous flow of 100% O2 and given 0.01 mg/kg Buprenorphine Hcl for analgesia, during the surgical insertion of the catheter. Mice were allowed to recover for 1 week following the surgery and baseline measurements were obtained continuously for 2 hours each morning, and averaged to yield a daily value. Ten days of baseline measurements were recorded. Mice were then implanted with osmotic mini-pumps containing AngII (1000ng/kg/min; Sigma, St. Louis, MO) and measurements were obtained for an additional 10 days. Daily values were averaged for statistical comparisons between genotypes.

Inhibition of ERK1/2 activation
The MAPK kinase 1 (MEK1) inhibitor, CI1040 was used to examine the effects of inhibition of ERK1/2 activation. AngII-treated ApoE^{-/-}/βarr2^{+/+} mice were injected subcutaneously with 100mg/kg/day CI1040 (Selleckchem, Houston, TX) or vehicle, 1 day prior to mini-pump implantation, and the injections were continued for 7 days simultaneously with the AngII infusion. CI1040 was suspended in an 8:1:1 PBS: ethanol: cremophore solution.

**Histology and Immunohistochemistry**

ApoE^{-/-}/βarr2^{+/+} and ApoE^{-/-}/βarr2^{-/-} mice were euthanized using CO₂ inhalation at the designated time-points (7 or 28 days) and the aortas were perfused with ice-cold PBS followed by 10% formalin solution. The abdominal aortas were dissected, cleaned of adventitial fat and fixed in 10% formalin solution overnight followed by processing and paraffin embedding. Serial sections (0.006 mm thickness) of the abdominal aortas were stained with hematoxylin and eosin (H&E) or Verhoeff van Geisen (VVG, elastin) for histological analysis. Sections were also subject to immunohistochemical analysis for COX-2 (Vector labs, Burlingame, CA), Mac-3 (BD Biosciences, San Jose, CA), or p-ERK1/2 (Cell Signaling Technology, Danvers, MA) expression. Antibody binding was detected using the Vectastain Elite ABC kit and di-amino benzidine (DAB) staining using manufacturer’s instructions (Vector labs, Burlingame, CA). Quantitation of immuno-positive cells was performed by determining the ratio of the number of positive cells (COX-2, p-ERK1/2 or Mac-3) to the total number of hematoxylin positive cells in a defined field (at 400X magnification) on multiple slides (a minimum of 5 slides per mouse per genotype and treatment).

**Quantitation of mRNA expression**

Abdominal aortic tissue from ApoE^{-/-}/βarr2^{+/+} and ApoE^{-/-}/βarr2^{-/-} mice was dissected as described above and stored immediately in RNAlater solution (Ambion, Austin, TX) at 4°C. Total RNA was extracted from individual abdominal aortic segments using the Qiagen RNeasy fibrous mini kit (Qiagen, Alameda, CA) followed by reverse transcription using the Superscript III First-Strand Synthesis Supermix (Life Technologies, Grand Island, NY). Real time quantitative PCR analysis was performed for COX-2, CD68, MCP-1, MIP1α, MMP2 or MMP9, using Taqman gene expression assays (Applied Biosystems/Life Technologies, Carlsbad, CA). Fold differences in gene expression were calculated using the ΔΔCt method using hypoxanthine phosphoribosyl transferase (HPRT) as the endogenous control.

**Statistics**

Data are shown as the mean ± SEM of independent experiments. Fisher’s exact test was used to compare AAA incidence among different groups. Two-way ANOVA was used to examine changes in blood pressure between genotypes. One-way ANOVA followed by Bonferroni’s multiple comparison tests were used to determine the statistical significance of the data in all other experiments. Values with $P<0.05$ were considered statistically significant.
References


