Angiotensin AT$_1$ Receptor Stimulates Heat Shock Protein 27 Phosphorylation In Vitro and In Vivo

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Abstract—The angiotensin type 1 receptor (AT$_1$) exerts a variety of its signaling and cellular actions through its effects on protein phosphorylation. Phosphoproteomic analysis of angiotensin (Ang) II–stimulated aortic smooth muscle cells revealed that heat shock protein 27 (HSP27) represents a major protein phosphorylation target of the AT$_1$ signaling pathway. Stimulation of cells with Ang II resulted in 1.7-fold ($P<0.05$) and 5.5-fold ($P<0.001$) increases in HSP27 phosphoisoforms at pl 5.7 and pl 5.4, respectively. This was accompanied by a 54% ($P<0.01$) decrease in the nonphosphorylated HSP27 isoform, located at pl 6.4. Treatment of samples with alkaline phosphatase reversed this redistribution of HSP27 phosphoisoforms. Ang II–stimulated HSP27 phosphorylation was completely blocked by pretreatment of cells with the AT$_1$ antagonist CV11974. Phosphoamino acid analysis demonstrated that Ang II–induced phosphorylation of both HSP27 phosphoisoforms occurred exclusively on serine. Protein kinase C inhibition completely blocked phorbol ester–induced HSP27 phosphorylation but did not impair Ang II–stimulated phosphorylation of HSP27, suggesting that AT$_1$ increased HSP27 phosphorylation by a protein kinase C–independent pathway. Intragjugular infusion of Ang II in rats increased HSP27 in aorta by 1.7-fold ($P<0.02$), and this response was inhibited by CV11974. These results suggest that Ang II–induced HSP27 phosphorylation is a physiologically relevant AT$_1$ signaling event. Because serine phosphorylation of HSP27 blocks its ability to cap F-actin, Ang II/AT$_1$–induced HSP27 phosphorylation may play a key role in actin filament remodeling required for smooth muscle cell migration and contraction. (Hypertension. 2001; 38:1260-1265.)

Key Words: angiotensin II ▪ aorta ▪ heat shock proteins ▪ phosphorylation ▪ protein kinases ▪ receptors, angiotensin II

Substantial experimental and clinical evidence suggests that the activation of the renin-angiotensin system contributes to macrovascular disease in part by promoting atherogenesis and vascular smooth muscle cell (VSMC) remodeling.¹⁻³ Angiotensin (Ang) II, the main effector peptide of the renin-angiotensin system, exerts a variety of effects on VSMCs, including stimulation of cellular contraction, migration, growth, and gene expression.⁴ The majority of these Ang II actions are mediated by the angiotensin type 1 (AT$_1$) receptor, which is coupled to the activation of a number of serine/threonine kinases including protein kinase C, S6 kinase, rho-associated kinase, and enzymes that mediate signaling through the mitogen-activated protein kinase (MAPK) pathways.⁵⁻⁶ Ang II also rapidly increases tyrosine phosphorylation by transactivation of the epidermal growth factor receptor⁷ and by activating a number of cytosolic tyrosine kinases such as calcium-dependent tyrosine kinase, PYK2, pp60(c-src) kinase, janus kinases (JAK2 and TYK2), and focal adhesion kinase.⁸ Activation of the Ang II/AT$_1$ signaling pathway has been shown to phosphorylate a limited number of effector and structural proteins including adapter and scaffolding proteins,⁹¹⁰ intermediate filament proteins,¹¹ and transcription factors.¹²

Although an array of Ang II–stimulated phosphoproteins have been identified, little is known regarding which proteins represent major phosphorylation targets of the AT$_1$ receptor signaling pathway(s). Although recent advances in proteomics may create new opportunities to characterization of Ang II signaling pathways and cardiovascular disease,¹³ the AT$_1$-stimulated phosphorylation targets detectable by this approach have not yet been identified. A two-dimensional gel electrophoresis (2-DE)–based proteomic analysis of total proteins from rat aortic smooth muscle cells (RASMCs) revealed that heat shock protein 27 (HSP27) represents the major low-molecular-weight phosphorylation target of the Ang II/AT$_1$ pathway. This finding suggests that kinase cascades that lead to HSP27 phosphorylation represent a major conduit of AT$_1$ receptor signaling. Ang II also increases HSP27 phosphorylation in aorta in vivo, suggesting that this response may have physiological significance. Because phosphorylation of HSP27 modulates actin filament assembly, migration, and contraction,¹⁴⁻¹⁶ HSP27 phosphorylation may provide an important link between AT$_1$ receptor activation and vascular remodeling.

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Methods

Cell Culture and Metabolic Labeling With Ortho $^{32}$P

RASMCs were harvested and cultured as described previously.\textsuperscript{10} Cells were incubated in phosphate-free minimum essential medium/0.1% (wt/vol) BSA containing 0.5 mCi/mL of $^{32}$P-orthophosphate (DuPont-New England Nuclear) for 3 hours at 37°C. Cells were stimulated with Ang II (Sigma) as indicated and harvested in Tris-urea lysis buffer containing 8 mmol/L urea, 4% 3-(3-cholamidopropyl)dimethylammonio]-1-propanesulfonate, 1 μmol/L aprotinin, 1 mmol/L sodium orthovanadate, and 50 mmol/L dithiothreitol.

Sample Preparation

Samples were lysed for 1 hour at 22°C followed by protein precipitation in 20% (vol/vol) trichloroacetic acid (TCA) on ice for 30 minutes. Protein pellets were washed with ethanol and redissolved in a Tris-free urea-lysis sample buffer. Total protein amount was determined with the use of Protein Assay Kit (Bio-Rad).

Protein Dephosphorylation

A subset of samples were precipitated with TCA, washed with ethanol, and resuspended in a buffer with 60 mmol/L Tris-HCl, pH 7.5, 1 mmol/L DTT, 1 μmol/L aprotinin, and 100 mmol/L NaCl. Samples were treated with 100 U of alkaline phosphatase (New England Biolabs) for 120 minutes at 30°C.

Two-Dimensional Gel Electrophoresis

First-dimension protein separation was performed by isoelectric focusing of 100 μg protein on immobilized pH gradient gel strips (pH 3 to 10, nonlinear; Amershams Pharmacia). Strips were equilibrated in 6 mol/L urea; 50 mmol/L Tris-HCl, pH 8.8; 30% (vol/vol) glycerol; 2% SDS; and 10 mg/mL DTT followed by separation in the second dimension by SDS–polyacrylamide gel electrophoresis on 12% C gels. Samples were then transferred to polyvinylidene fluoride (PVDF) or nitrocellulose membrane (Novex).

Immunoblotting and Image Analysis

HSP27 isoforms were separated by 2-DE and detected by immunoblot analysis. Membranes were incubated with polyclonal HSP-27 antibody (Santa Cruz Biotechnology) followed by visualisation with peroxidase-conjugated anti-goat immunoglobulins and enhanced chemiluminescence (Amersham Pharmacia). Detection and quantification of the immunoblot and $^{32}$P-orthophosphate signal of the labeled blotting membrane was determined with use of a PhosphorImager and the Imagequant software (Molecular Dynamics). Ang II–stimulated phosphorylation of proteins from $^{32}$P-labeled cells was analyzed by 2-DE. To disrupt macromolecular interactions that may contribute to selective protein loss, cell lysates were subjected to denaturing conditions of 8 mol/L urea and 20% TCA under reducing conditions before 2-DE analysis. This method revealed an array of phosphoproteins from control and Ang II–stimulated RASMCs (Figure 1, top panels). Among proteins <50 kDa, 2 highly expressed Ang II–stimulated phosphoproteins were identified with mobilities of ~27 kDa and isoelectric points at pI 5.7 and pI 5.4. Ang II stimulation increased incorporation of $^{32}$P by these phosphoproteins by 3-fold and 8-fold, respectively.

On the basis of the molecular weight and isoelectric points, a candidate immunoblot approach was used to determine if these phosphoproteins colocalized with HSP27. Lysates from $^{32}$P-labeled cells were separated by 2-DE, transferred to PVDF membranes, and immunoblotted with anti-HSP27 antibody. Visualization of HSP27 immunoreactivity by enhanced chemiluminescence revealed 4 isoforms, separated according to their pI (Figure 1, bottom panels). The 2 most acidic of these HSP27 isoforms, labeled phosphoprotein-1 (PP1) and PP2, colocalized with the $^{32}$P-labeled phosphoproteins visualized by autoradiography. The Ang II–induced increases in these HSP27 isoforms at pI 5.4 and pI 5.7 by immunoblots were comparable with the increased $^{32}$P-incorporation into these spots. Two additional HSP27 isoforms at pI 6.4 and 5.8, which did not colocalize with $^{32}$P phosphoproteins, were labeled as nonphosphoprotein-1 (NP1) and NP2, respectively.

Ang II Induces Phosphorylation of HSP27 in an Ang II Type 1 Receptor–Dependent Manner

To examine the role of the AT$_1$ receptor in Ang II–induced HSP27 phosphorylation, cells were stimulated with Ang II in the absence or presence of the AT$_1$ receptor antagonist candesartan (CV11974, kindly provided by Dr Peter Morsing, Astra Hassle AB, Sweden). Stimulation of cells with Ang II (100 nmol/L) for 15 minutes decreased NP1 and NP2 levels by 55% and 31%, respectively ($P<0.01$ and $<0.05$, ANOVA; Figure 2). This Ang II response was associated with an increase in the relative amount of PP1 by 68% ($P<0.05$) and PP2 by 5-fold ($P<0.001$). Pretreatment of cells with 1 μmol/L candesartan completely blocked both Ang II–stimulated decreases in NP1 and NP2 levels and increased PP1 and PP2 levels (Figure 2). This Ang II–stimulated shift in HSP27 immunoreactivity was sustained at 30 minutes and occurred with an ED$_{50}$ of 10 nmol/L Ang II (not shown). Treatment of lysates from Ang II–stimulated cells with alkaline phosphatase eliminated immunoreactivity of HSP27 at pI 5.4 and reduced immunoreactivity of HSP27 at pI 5.7 to control levels.

Statistics

Statistical significance using SigmaStat 2.03 was determined by 1-way ANOVA. Differences were designated to be significant at $P<0.05$.
levels (Figure 2), demonstrating that phosphorylation is required for Ang II–induced acidic shift of HSP27 immuno-reactivity. These results support the identification of the 32P-labeled proteins at pI 5.7 and 5.4 as phosphoisoforms of HSP27 and show that Ang II induces the redistribution of HSP27 from nonphosphorylated to phosphorylated isoforms.

Phosphoamino Acid Analysis of Ang II–Induced HSP27 Phosphorylation
Phosphoamino acid analysis was performed on PP1 and PP2 isoforms isolated from ortho 32P-labeled RASMCs, as shown in Figure 1. This analysis revealed that Ang II stimulation increased phosphoserine incorporation into both of these HSP27 isoforms (Figure 3). Phosphorylation of HSP27 on threonine and tyrosine was not detected under basal or Ang II–stimulated conditions.

Effect of Protein Kinase C Inhibition on Ang II–Stimulated and Phorbol Ester–Stimulated HSP27 Phosphorylation
Because Ang II activates protein kinase C (PKC) in VSMCs and direct activation of PKC has been shown to increase the phosphorylation of small heat shock proteins, the role of PKC in Ang II–stimulated phosphorylation was examined.

Figure 1. 2-DE separation of proteins from 32P-labeled RASMCs. Cells were metabolically labeled with 32P-orthophosphate and treated with 100 nmol/L Ang II for 15 minutes as indicated. Cell lysates were separated by 2-DE followed by transfer to PVDF membranes. Lower panels, HSP27 immunoblot analysis visualized by enhanced chemiluminescence; upper panels, 32P-protein labeling detected by autoradiography. Representative results from 3 different experiments are shown.

Figure 2. Immunoblot analysis of HSP27 isoform levels after Ang II stimulation and AT1 antagonism. Cell were stimulated with Ang II (All, 100 nmol/L, 15 minutes) in absence or presence of 1 μmol/L candesartan (Cand) and compared with unstimulated controls (C). Cell lysates were separated by 2-DE and immunoblotted for HSP27. Nonphosphorylated and phosphorylated proteins of HSP27 isoforms were visualized by enhanced chemiluminescence and quantified by densitometric analysis. AP indicates alkaline phosphatase–treated HSP27 from Ang II–stimulated cell lysate. Bar graph shows levels of each isoform relative to total HSP27 immunoreactivity. Representative blots and bar graph quantification from 4 experiments are shown. Significant differences are indicated as *P<0.05, **P<0.01, and #P<0.001.
Cells were pretreated with the PKC inhibitor GF 109203X (GFX, 5 μmol/L) for 15 minutes followed by stimulation with either Ang II or phorbol 12-myristate 13-acetate (PMA) for 15 minutes. Levels of HSP27 phosphoisoform PP2 normalized to total HSP27 content were quantified by immunoblotting, as described in Figure 2. GFX did not affect baseline HSP27 phosphorylation and appeared to enhance Ang II–stimulated HSP27 phosphorylation (Figure 4). Direct activation of PKC by treatment of cells with phorbol ester (PMA) also increased HSP27 phosphorylation, and this response was completely blocked by GFX, confirming the efficacy of this inhibitor.

Effect of Ang II on Aortic HSP27 Phosphorylation In Vivo

To determine whether Ang II affects vascular HSP27 phosphorylation in vivo, the distribution of HSP27 isoforms was examined in aortic tissue isolated from Sprague-Dawley rats. Anesthetized rats received an intrajugular 500-μL bolus injection of saline in the absence or presence of 40 μmol/L Ang II or 200 μmol/L candesartan. Fifteen minutes after injection, aortic tissue was harvested and 2-DE as described in Figure 1. 32P-labeled PP1 and PP2 spots were excised and subjected to phosphaamino acid analysis. Locations of P-Ser, P-Thr, and P-Tyr standard stained with ninhydrin are indicated.

Figure 3. Phosphoamino acid analysis of HSP27 isoforms PP1 and PP2. Cells were labeled with 32P and stimulated with Ang II (100 nmol/L, 15 minutes). Cells were then lysed and separated by 2-DE as described in Figure 1. 32P-labeled PP1 and PP2 spots were excised and subjected to phosphoamino acid analysis. Locations of P-Ser, P-Thr, and P-Tyr standard stained with ninhydrin are indicated.

Figure 4. Effect of PKC inhibition on Ang II–stimulated and PMA-stimulated HSP27 phosphorylation. Cells were pretreated for 15 minutes with either 5 mmol/L GFX as indicated or DMSO and stimulated with 100 nmol/L Ang II or PMA. HSP27 isoforms were quantified by immunoblotting, as shown in Figure 2. Bar graph represents levels of HSP27 phosphoisoform PP2 normalized to total HSP27. *Statistically significant differences (P<0.05).

Discussion

This report provides the first evidence that HSP27 represents a major low-molecular-weight phosphorylation target of the Ang II/AT1 receptor pathway in RASMCs and that its phosphorylation also occurs in aorta in vivo. Analysis of 32P-labeled cellular phosphoproteins from RASMCs by 2-DE identified 2 separate isoforms of HSP27, located at pl 5.4 and pl 5.7, as the major phosphoproteins in Ang II–stimulated cells. The Ang II–stimulated phosphorylation of HSP27 occurred with an ED50 of 10 nmol/L and was completely blocked by candesartan, showing that this response occurs at physiologically relevant Ang II concentrations and is mediated by the AT1 receptor subtype. Treatment of lysates from Ang II–stimulated cells with alkaline phosphatase reduced immunoreactivity of HSP27 isoforms at pl 5.4 and pl 5.7 to control levels, demonstrating that phosphorylation is required for Ang II–induced acidic shift of HSP27 immunoreactivity.

Previous reports have shown that the p38 MAPK pathway, through the activation of downstream kinases MAPKAP activated protein (MAPKAP) and p38-regulated/activated protein kinase, mediates the phosphorylation of HSP27.15,16,19 Recently, it has been shown that a reactive oxygen species–induced stimulation of p38 MAPK in response to Ang II resulted in an activation of MAPKAP kinase-2 and an increase in immunoprecipitable phosphorylated HSP27.20 The latter, however, has neither been quantified nor normalized and was limited to cultured cells. Because HSP27 exists both in monomeric and polymeric forms21,22 and associates with actin filaments,23 which may affect its solubility and antigen accessibility, it is important to quantify the effects of Ang II on HSP27 phosphorylation relative to total HSP27 protein. The quantification of HSP27 isoforms according to isoelectric focusing has been described previously.15,16 2-DE analysis demonstrated that Ang II not only increases levels of highly phosphorylated HSP27, which migrate with an acidic pl 5.4, but also decreases levels of the nonphosphorylated HSP27 isoform NP1. This nonphosphorylated form of HSP27 is the biologically active isoform that binds to F-actin.24

Activation of phorbol ester–sensitive PKC isoforms (α, β, γ, δ, ε, θ, η) increased HSP27 phosphorylation, and this response was blocked with GFX, which inhibits the common...
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tative blots and bar graph quantification (n=4 to 7 per group) are shown. Significant differences, *P<0.05 and **P<0.02.

Figure 5. Effect of Ang II and candesartan on HSP27 phosphorylation in aorta in vivo. Rats were given bolus intrajugular injection of 500 μL saline containing Ang II (40 μmol/L) or candesartan (200 μmol/L) as indicated. After 15 minutes, the aorta was harvested, TCA-precipitated protein fraction was separated by 2-DE, and HSP27 isoform distribution was visualized by immunoblot analysis. Representative blots and bar graph quantification (n=4 to 7 per group) are shown. Significant differences, *P<0.05 and **P<0.02.

(α, β, γ) and novel (δ, ε) PKC isoforms. Our previous results have shown that GFX also inhibits phorbol ester–induced activation of p38 in RASMCs,24 which can mediate to PKC–induced HSP27 phosphorylation. Although Ang II activates PKC in VSMCs, the absence of an inhibition by GFX suggests that this pathway does not significantly contribute to Ang II–stimulated HSP27 phosphorylation. Similarly, GFX does not inhibit AT₁-mediated phosphorylation of p38 MAPK in RASMCs.25 Thus, AT₁ signaling to the p38 MAPK and HSP27 pathway does not require PKC activity.

Because the 2 previously identified phosphorylation sites on human HSP27 and murine HSP25 are conserved at Ser15 and Ser86 in rat HSP27,26,27 it is likely that the Ang II–stimulated serine phosphorylation of HSP27 occurs at these sites. Based on the phosphorylation-dependent acidic shift of HSP27, the presence of 2 phosphoisoforms would be consistent with the monophosphorylation of HSP27, at either Ser15 or Ser86, in the isoform located at pI 5.7 and diphosphorylation of these sites on the isoform at pI 5.4, as described in References 15 and 16. Although Ang II increases phosphorylation of isoforms at both pI 5.7 and 5.4 in cultured RASMCs, Ang II selectively increased levels of the pI 5.4 isoform in vivo. These results suggest that the physiologically significant Ang II effects on HSP27 are reduced levels of the nonphosphorylated HSP27 isoform at pI 5.4 and the increased phosphorylation of the (diphosphorylated) PP2 isoform.

Phosphorylation of HSP27 plays an important role in modulating its structure and functions. Nonphosphorylated monomeric HSP27 binds to F-actin as a capping protein and thereby blocks actin polymerization, whereas phosphorylated HSP27 does not affect actin polymerization.23 Thus, the Ang II–induced decrease in levels of the nonphosphorylated isoform of HSP27, observed both in vitro and in vivo, would be expected to increase the dynamics of actin assembly, which is necessary for VSMC migration.16

Phosphorylation of HSP27 also affects its multimerization, which is required for its chaperone activity, which facilitates the refolding of denatured proteins.21 Mutation of Ser90 to negatively charged Glu in hamster HSP27 (which corresponds to Ser86 in rat and Ser82 in human) reduces HSP27 multimeric structure from oligomers to dimers,22 suggesting that a negative charge at this site interferes with the multimerization of HSP27 dimers. The specific role of Ser15 in multimerization is controversial. Although mutation of Ser15 to Glu did not appear to affect HSP27 oligomerization,24 another report showed that reduction of high-molecular-weight multimers required negative charges at both Ser15 and Ser82 in human HSP27.23 Thus Ang II–induced phosphorylation of HSP27 would be expected to reduce its chaperone activity, which protects cells from a variety of stresses, including oxidation.21

In summary, HSP27 was identified as the major low-molecular-weight target of Ang II/AT₁, stimulated phosphorylation in RASMCs by a proteomic approach. In vivo studies demonstrated that Ang II phosphorylates HSP27 in aorta. The Ang II–induced redistribution of HSP27 phosphoisoforms would be expected to enhance actin remodeling, which is essential for VSMC migration, and impair the chaperone activity of HSP27, which recovers proteins partially denatured by cellular stress. Thus, HSP27 phosphorylation may contribute to the AT₁ receptor effects on cell migration, contraction, and the recovery of denatured proteins.

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References


