Angiotensin-(1-7) Downregulates the Angiotensin II Type 1 Receptor in Vascular Smooth Muscle Cells

Michelle A. Clark, Debra I. Diz, E. Ann Tallant

Abstract—Angiotensin (Ang)-(1-7) is a biologically active peptide of the renin-angiotensin system that has both vasodilatory and antiproliferative activities that are opposite the constrictive and proliferative effects of angiotensin II (Ang II). We studied the actions of Ang-(1-7) on the Ang II type 1 (AT₁) receptor in cultured rat aortic vascular smooth muscle cells to determine whether the effects of Ang-(1-7) are due to its regulation of the AT₁ receptor. Ang-(1-7) competed poorly for [¹²⁵I]Ang II binding to the AT₁ receptor on vascular smooth muscle cells, with an IC₅₀ of 2.0 μmol/L compared with 1.9 nmol/L for Ang II. The pretreatment of vascular smooth muscle cells with Ang-(1-7) followed by treatment with acidic glycine to remove surface-bound peptide resulted in a significant decrease in [¹²⁵I]Ang II binding; however, reduced Ang II binding was observed only at micromolar concentrations of Ang-(1-7). Scatchard analysis of vascular smooth muscle cells pretreated with 1 μmol/L Ang-(1-7) showed that the reduction in Ang II binding resulted from a loss of the total number of binding sites [B_max 437.7±261.5 fmol/mg protein in Ang-(1-7)–pretreated cells compared with 607.5±301.2 fmol/mg protein in untreated cells, n=5, P<0.05] with no significant effect on the affinity of Ang II for the AT₁ receptor. Pretreatment with the AT₁ receptor antagonist L-158,809 blocked the reduction in [¹²⁵I]Ang II binding by Ang-(1-7) or Ang II. Pretreatment of vascular smooth muscle cells with increasing concentrations of Ang-(1-7) reduced Ang II–stimulated phospholipase C activity; however, the decrease was significant (81.2±6.4%, P<0.01, n=5) only at 1 μmol/L Ang-(1-7). These results demonstrate that pharmacological concentrations of Ang-(1-7) in the micromolar range cause a modest downregulation of the AT₁ receptor on vascular cells and a reduction in Ang II–stimulated phospholipase C activity. Because the antiproliferative and vasodilatory effects of Ang-(1-7) are observed at nanomolar concentrations of the heptapeptide, these responses to Ang-(1-7) cannot be explained by competition of Ang-(1-7) at the AT₁ receptor or Ang-(1-7)–mediated downregulation of the vascular AT₁ receptor. (Hypertension. 2001;37:1141-1146.)

Key Words: angiotensin II ■ muscle, smooth, vascular ■ receptors, angiotensin-(1-7)

Angiotensin (Ang)-(1-7), the amino-terminal angiotensin heptapeptide, is an important biologically active peptide of the renin-angiotensin system (RAS).<sup>1</sup> Ang-(1-7) plays a role in vascular regulation that is distinct and often opposite that of angiotensin II (Ang II). Furthermore, these opposing effects of Ang II and Ang-(1-7) occur at similar concentrations of the 2 angiotensin peptides. For example, in contrast to the mitogenic effects of nanomolar Ang II, Ang-(1-7) inhibits vascular smooth muscle cell (VSMC) growth with an IC₅₀ value in the nanomolar range.<sup>2</sup> Ang-(1-7) reduces neointimal formation after vascular injury and increases urinary prostaglandin release at concentrations of the heptapeptide 2- to 3-fold higher than the endogenous circulating concentration of Ang-(1-7) or Ang II.<sup>3,4</sup> Nanomolar concentrations of Ang-(1-7) increased arachidonic acid release and prostacyclin production in rabbit VSMCs, with maximal effects observed at 100 nmol/L Ang-(1-7).<sup>5</sup> Ang-(1-7) stimulated prostaglandin (PG)E₂ and prostacyclin release from both porcine and rat VSMCs with EC₅₀ values in the nanomolar range.<sup>6,7</sup> Finally, Ang-(1-7) caused the vasodilation of rabbit renal afferent arterioles at nanomolar concentrations of the heptapeptide.<sup>8</sup> In addition, the actions of endogenous Ang-(1-7) unmasked after converting enzyme inhibition<sup>9</sup> or a low-salt diet<sup>10</sup> appear to occur at submicromolar concentrations of the heptapeptide. These results indicate that Ang-(1-7) has both vasodilatory and antiproliferative effects that are observed at subpharmacological concentrations of the heptapeptide.

In contrast, various effects of Ang-(1-7) were reported at pharmacological doses of the heptapeptide. We observed a rapid transient increase in pressure preceding a prolonged depressor response when high doses of Ang-(1-7) were injected into pithed rats.<sup>11</sup> The pressor, but not the depressor, component of this response was blocked by the AT₁ receptor antagonist losartan, suggesting that high concentrations of Ang-(1-7) may stimulate the AT₁ receptor to increase blood pressure. Mahon et al<sup>12</sup> reported that micromolar concentrations of Ang-(1-7) caused a rightward shift in the dose-contractile response to Ang II in rabbit aortic rings.
and a concentration-dependent decrease in the maximal response, with a pA2 of 5.5, and suggested that Ang-(1-7) was an antagonist at the AT1 receptor at micromolar concentrations of the heptapeptide. Roks et al13 also demonstrated that Ang-(1-7) at a concentration of 10 μmol/L reduced Ang I- and Ang II–induced contraction of human internal mammary arteries, suggesting that micromolar Ang-(1-7) was an antagonist at the AT1 receptor. Because Ang-(1-7) competes for binding to the vascular AT1 receptor at micromolar concentrations,7 pharmacological concentrations of Ang-(1-7) may oppose or counteract the actions of Ang II through competitive antagonism. Alternatively, Ang-(1-7) could oppose the vasoconstrictive and proliferative effects of Ang II through downregulation or desensitization of the AT1 receptor. This study was designed to determine whether Ang-(1-7) causes a downregulation of the AT1 receptor or desensitizes responses to Ang II by direct actions at the AT1 receptor.

Methods

Materials

[125I]Sodium iodide was obtained from Amersham Pharmacia, and myo-[125I]Hinositol was obtained from American Radiolabeled Chemicals, Inc. DMEM/Ham's F-12 (DMEM/F12), inositol-free DMEM, FBS, penicillin, streptomycin, and trypsin/EDTA were obtained from GIBCO. Ang II and Ang-(1-7) were purchased from Bachem, and Ang II was removed with 0.3 nmol/L [125I]Ang II. Surface-bound Ang-(1-7) was removed with acidic glycine, and acid-stripped cells were incubated with increasing concentrations of [125I]Ang II (0.075 to 2.4 nmol/L) for 1 hour at room temperature.

Measurement of Phosphoinositide-Specific Phospholipase C

Phospholipase C (PLC) activity was assayed by the production of H-labeled inositol phosphates in VSMCs prelabeled with myo-[3H]-inositol, as previously described.16 Confluent monolayers of VSMCs in 6-well culture plates were labeled for 72 hours with myo-[3H]-inositol (2 μCi/well) in inositol-free DMEM that contained 0.5% FBS. The radiolabeled VSMCs were preincubated with increasing concentrations of Ang-(1-7) (0.1 to 10 μmol/L) in HEPES-buffered Krebs-Ringer solution (125 mmol/L NaCl, 5 mmol/L KCl, 1.2 mmol/L MgSO4, 6 mmol/L glucose, 1 mmol/L CaCl2, and 25 mmol/L HEPES, pH 7.4) and 10 mmol/L LiCl, for 30 minutes at 37°C. The cells were then treated with 10 nmol/L Ang II, and the reaction was continued for 30 minutes at 37°C. Inositol phosphates were extracted with ice-cold perchloric acid, separated through ion exchange chromatography, and quantified with liquid scintillation spectroscopy as previously described.16

Statistics

All data are expressed as the mean±SEM of ≥3 experiments. Competition binding data were analyzed by nonlinear regression with the computer program Prism (GraphPad). Saturation isotherms were analyzed with the EBDA/LIGAND computer program (Elsevier-BIOSOFT). Repeated measures 1-way ANOVA or ANOVA with Dunnett’s post hoc test were used to compare treatment groups. The criterion for statistical significance was P<0.05.

Results

Competition for the AT1 Receptor by Ang-(1-7)

VSMCs were incubated with increasing concentrations of Ang II and Ang-(1-7) to determine whether Ang-(1-7) competed for [125I]Ang II binding to VSMCs. As shown in Figure 1, Ang-(1-7) competed poorly for binding to the AT1 receptor on VSMCs isolated from the thoracic aorta of Sprague-Dawley rats with an IC50 value of 2.0 μmol/L compared with an IC50 value of 1.9 nmol/L for Ang II. The [125I]Ang II binding to VSMCs was characterized as AT1 based on ≥95% competition of specific binding by either 10 μmol/L concentration of the AT1 receptor antagonist losartan or EXP 3174 and no competition by 10 μmol/L PD 123319, an AT2 receptor antagonist (Figure 1).

Regulation of the AT1 Receptor by Ang-(1-7)

Ang II binds to AT1 receptors on VSMCs and induces a rapid internalization of the Ang II-AT1 receptor complex. Because we observed that Ang-(1-7) binds to the vascular AT1 receptor, albeit at a 1000-fold higher concentration than Ang II, Ang-(1-7) binding to the AT1 receptor could reduce subsequent responses to Ang II by causing internalization and

Cell Culture Procedures

Aortic VSMCs were isolated from 10- to 12-week-old male Hanover Sprague-Dawley rats bred and raised at the ALACC-accredited animal facility of Wake Forest University School of Medicine. Primary cultures of VSMCs were obtained from aortic explants as previously described.2 The cells were cultured in DMEM/F12 supplemented with 10% FBS, penicillin, streptomycin, and maintained at 37°C in a humidified CO2 incubator (5% CO2, 95% air). Confluent monolayers of VSMCs from passages 4 to 9 were used in all experiments.

Measurement of [125I]Ang II Binding

Ang II wasiodine dated according to a modified chloramine T procedure, and the moniodinated form was purified through HPLC according to previously established procedures.14 [125I]Ang II binding was measured by incubating confluent monolayers of VSMCs in binding buffer (PBS: 50 mmol/L NaHPO4, 0.15 mol/L NaCl, pH 7.4, with 0.2% fatty acid-free BSA, 2.5 mmol/L EGTA, and 5 mmol/L MgCl2) containing [125I]Ang II. Nonspecific binding was determined in the presence of 10 μmol/L unlabeled Ang II. After a 1-hour incubation at room temperature, binding reactions were terminated by aspirating the binding buffer from individual wells and washing each well with ice-cold PBS (2 mL/wash). Cellular proteins were solubilized in 2N NaOH, and cell-associated radioactivity was quantified with γ-spectroscopy. Protein was measured according to the Lowry method15 with BSA used as the standard.

Various types of binding studies were conducted to determine competition by peptides and antagonists, the effect of pretreatment with angiotensin peptides on subsequent Ang II binding, and saturation isotherms to calculate binding constants, as described here.

First, competition studies were performed by incubating VSMCs with increasing concentrations (from 10-10 to 10-5 mol/L) of each peptide or with 10 μmol/L losartan, EXP 3174, or PD 123319 in the presence of 0.3 nmol/L [125I]Ang II.

Second, the effect of pretreatment with Ang-(1-7) or Ang II on subsequent binding of [125I]Ang II to VSMCs was determined through preincubation with increasing concentrations of peptide in Hanks' balanced salt solution for 30 minutes at room temperature. After this preincubation, surface-bound Ang-(1-7) or Ang II was removed with a 5-minute treatment with ice-cold 50 mmol/L glycine/50 mmol/L HCl, pH 3.0, before the measurement of [125I]Ang II binding.

Third, saturation isotherms were constructed after treatment (30 minutes at room temperature) of VSMCs with vehicle or 1 μmol/L Ang-(1-7). Surface-bound Ang-(1-7) was removed with acidic glycine, and acid-stripped cells were incubated with increasing concentrations of [125I]Ang II (0.075 to 2.4 nmol/L) for 1 hour at room temperature.

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All data are expressed as the mean±SEM of ≥3 experiments. Competition binding data were analyzed by nonlinear regression with the computer program Prism (GraphPad). Saturation isotherms were analyzed with the EBDA/LIGAND computer program (Elsevier-BIOSOFT). Repeated measures 1-way ANOVA or ANOVA with Dunnett’s post hoc test were used to compare treatment groups. The criterion for statistical significance was P<0.05.

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subsequent loss of membrane AT_1 receptors. To test this hypothesis, VSMCs were pretreated with increasing concentrations of Ang-(1-7) before the measurement of [125I]Ang II binding to determine whether treatment with Ang-(1-7) downregulates the AT_1 receptor. As a control, cells were also pretreated with Ang II. After a 30-minute pretreatment with either Ang-(1-7) or Ang II, surface-bound peptide was removed through treatment with acidic glycine and [125I]Ang II binding was measured. Ang II caused a dose-dependent reduction in total binding, with a significant reduction of 51.4±10.5% (P<0.05) of total binding at 10 nmol/L (Figure 2). Ang-(1-7) also caused a similar reduction in Ang II binding, with significant inhibition of 36.1±7.8% of [125I]Ang II binding at 1 μmol/L Ang-(1-7). A higher concentration of Ang-(1-7), up to 10 μmol/L, caused no further reduction in [125I]Ang II binding.

To determine whether Ang-(1-7) reduced binding to the vascular AT_1 receptor by increasing receptor affinity or by reducing the total number of AT_1 receptors, VSMCs were pretreated with 1 μmol/L Ang-(1-7) for 30 minutes. The cells were subsequently treated with acidic glycine to remove surface-bound Ang-(1-7) and incubated with increasing concentrations of [125I]Ang II to saturate the receptor. Specific [125I]Ang II binding was measured and receptor density and affinity were determined through Scatchard analysis. Pretreatment with Ang-(1-7) had no significant effect on the affinity of Ang II for the AT_1 receptor (Table). In contrast, pretreatment with 1 μmol/L Ang-(1-7) for 30 minutes caused a significant 66±8% decrease in the B_max of Ang II receptors on VSMCs.

**Effect of AT_1 Receptor Antagonism on AT_1 Receptor Downregulation**

The AT_1 receptor antagonist L-158,809 was used to further demonstrate that the reduction in [125I]Ang II binding by Ang-(1-7) was due to a direct interaction of the heptapeptide with the AT_1 receptor. VSMCs were treated with 10 nmol/L L-158,809 before the addition of 1 μmol/L Ang-(1-7) or 100 nmol/L Ang II. After 30 minutes at room temperature, the cells were treated with acidic glycine to remove surface-bound peptide and antagonist, and the amount of [125I]Ang II binding was measured. Pretreatment with 1 μmol/L Ang-(1-7) reduced Ang II binding to the AT_1 receptor to 84.3±2.2% of total binding. The inclusion of 10 nmol/L L-158,809 prevented the Ang-(1-7)–induced reduction in [125I]Ang II binding (Figure 3). Pretreatment with 100 nmol/L Ang II also reduced subsequent binding to the AT_1 receptor to 74.2±7.0% of total binding, which was prevented by the inclusion of the AT_1 receptor antagonist L-158,809. Pretreatment with the antagonist alone followed by treatment with acidic glycine had no significant effect on [125I]Ang II binding to the AT_1 receptor, as would be expected with this antagonist.

**Effect of Ang-(1-7) on Ang II–Induced PLC Activity**

Ang II significantly stimulated inositol phosphate release from VSMCs, measured as the release of total inositol phosphates from cells prelabeled with myo-[3H]inositol. A 30-minute incubation of VSMCs with Ang II (10 nmol/L) increased phosphoinositide-specific PLC activity by 102.6±19.6% above basal levels (P<0.05, n=5). A similar incubation with 1 μmol/L Ang-(1-7) had no effect on inositol
phosphate release (85.8±8.7% of basal level, n=5). However, a 30-minute pretreatment with concentrations of Ang-(1-7) of 0.1 to 10 μmol/L, followed by a 30-minute incubation with 10 nmol/L Ang II, resulted in a dose-dependent decrease in Ang II–stimulated PLC activity, with a significant decrease to 81.2±6.4% above basal levels (P<0.01, n=5) at 1 μmol/L Ang-(1-7) and to 38.4±7.0% above basal levels (P<0.01, n=5) at 10 μmol/L Ang-(1-7) as shown in Figure 4.

Discussion

The pretreatment of VSMCs with Ang-(1-7) followed by treatment with acidic glycine to remove surface-bound peptide reduced subsequent binding of Ang II to the AT1 receptor. However, the decrease in Ang II binding was detected only at micromolar concentrations of the heptapeptide, which is in agreement with the micromolar affinity of Ang-(1-7) for the AT1 receptor. The reduction in Ang II binding by Ang-(1-7) resulted from a decrease in the number of receptors available for subsequent binding with no significant effect on receptor affinity. The downregulation of the Ang II receptor by Ang-(1-7) was blocked by pretreatment with the AT1 receptor antagonist L-158,809, demonstrating that micromolar concentrations of Ang-(1-7) have direct effects at the AT1 receptor to reduce the number of receptors available for subsequent binding. Finally, Ang-(1-7), at a concentration of 1 μmol/L, significantly attenuated the Ang II–mediated stimulation of PLC to reduce the production of inositol phosphates. These results clearly demonstrate that the short-term treatment of VSMCs with pharmacological concentrations of Ang-(1-7) downregulates the vascular AT1 receptor.

Although 1 μmol/L Ang-(1-7) alone did not activate PLC in VSMCs, it did reduce subsequent binding of Ang II to the AT1 receptor and attenuated activation of AT1-coupled cellular responses by Ang II. The AT1 receptor on VSMCs is rapidly internalized on stimulation by Ang II, a phenomenon accompanied by a reduction in subsequent responses. This suggests that Ang-(1-7), at micromolar concentrations, binds to the AT1 receptor to induce receptor internalization without activating subsequent cellular responses. Previous work with substance P and serotonin receptors clearly indicates that receptor internalization can occur independent of changes in functional responsiveness.17–19 Studies by several investigators suggest that different motifs in the structure of the AT1 receptor are required for receptor internalization compared with intracellular signal generation by Ang II.20–22 The truncation of a section of the carboxyl terminus of the AT1A receptor prevented receptor internalization without affecting coupling to PLC.20,21 A point mutation in the AT1 receptor that eliminates Ang II coupling to PLC (Asp32→Asn) did not block receptor internalization.22 In addition, the potent antagonist [Sar1,Ile8]Ang II, a sarcosine analog of Ang II, was internalized but did not activate PLC in Chinese hamster ovary cells transfected with the AT1 receptor, as well as in adrenal medullary cells.22,24 This suggests that Ang-(1-7), as well as sarcosine analogs of Ang II, bind to and activate the AT1 receptor to produce receptor internalization without coupling to G proteins to activate PLC. In contrast, the nonpeptide antagonist L-158,809 did not cause internalization in our study. Thus, it is possible that high concentrations of Ang-(1-7) and the peptide antagonists produce receptor internalization through weak agonist properties. This would also be consistent with our observation of a weak pressor response to high doses of Ang-(1-7) in the pithed rat, an effect that was mediated by an AT1 receptor.11

Mahon et al12 suggested that Ang-(1-7) is a noncompetitive antagonist at AT1 receptors in rabbit aortic rings, causing a rightward shift in the dose-response contraction curve to Ang II administered 60 minutes after Ang-(1-7). However, the concentrations of Ang-(1-7) used in their study ranged from 1 to 30 μmol/L. Roks et al13 also suggested that 10 μmol/L Ang-(1-7) was antagonistic at the AT1 receptor in human VSMCs. This would be consistent with our observation that Ang-(1-7) had an IC50 value of 2 μmol/L at the AT1 receptor in VSMCs. Our evidence suggests that short-term exposure of cells to micromolar levels of Ang-(1-7) downregulates the AT1 receptor over a time frame consistent with receptor...
internalization. Thus, when Ang II is given after a prior exposure to Ang-(1-7) (as we did in our study) or in the presence of a large excess of Ang-(1-7) (as in studies described by Roks et al\textsuperscript{13} and Mahon et al\textsuperscript{12}), one might expect antagonist actions of Ang-(1-7). However, endogenous circulating levels of Ang-(1-7), as well as tissue concentrations of the peptide, are in the picomolar range.\textsuperscript{25–27} Although treatment with ACE inhibitors increased circulating levels of Ang-(1-7) from 9- to 25-fold,\textsuperscript{25,28} there is no evidence showing an increase in endogenous Ang-(1-7) levels to the micromolar range. In addition, the majority of the in vivo and in vitro actions of Ang-(1-7) occur at doses lower than 1 to 30 \textmu\text{mol/L}. Because Ang-(1-7) downregulated Ang II binding and receptor activation only at micromolar concentrations, the vasodilatory and antiproliferative responses that occur at nanomolar concentrations of the heptapeptide cannot be explained by antagonist effects of Ang-(1-7) at the AT\textsubscript{1} receptor. Ueda et al\textsuperscript{29} recently reported that the infusion of Ang-(1-7) antagonized the Ang II–mediated vasoconstriction of human forearm resistance vessels, suggesting that Ang-(1-7) is an endogenous antagonist of the human AT\textsubscript{1} receptor. However, the authors reported that Ang-(1-7) significantly reduced the response to Ang II at a dose of 10 \textmu\text{mol/L}, a concentration significantly lower than the IC\textsubscript{50} value for the AT\textsubscript{1} receptor (>1 \textmu\text{mol/L}). In light of our observations, the responsiveness to Ang-(1-7) in the study by Ueda et al\textsuperscript{29} may be due to activation of a non-AT\textsubscript{1} receptor by Ang-(1-7) and the release of a compensatory vasodilator such as NO or prostaglandins.

In addition, evidence from several studies clearly shows that the actions of Ang-(1-7) are independent of AT\textsubscript{1} receptor activation. The vasodilation of canine or porcine coronary arteries induced by Ang-(1-7) was prevented by removal of the endothelium or by blockade of NO release,\textsuperscript{30,31} suggesting that Ang-(1-7) stimulated NO production to counter the vasoconstrictor effects of Ang II. These effects were not blocked by AT\textsubscript{1} or AT\textsubscript{2} receptor antagonists. Muthalif et al\textsuperscript{3} showed that Ang-(1-7) stimulated arachidonic acid release from rabbit VSMCs, an effect that was partially prevented by [D-Ala\textsubscript{7}]Ang-(1-7), the selective Ang-(1-7) receptor antagonist, or by the AT\textsubscript{2} antagonist PD 123319 but not by an AT\textsubscript{1} receptor antagonist. Ang-(1-7) caused the vasodilation of renal afferent arterioles, an effect blocked by [D-Ala\textsubscript{7}]Ang-(1-7).\textsuperscript{8} Further, Ang-(1-7) blocked mitogen–stimulated growth of rat VSMCs, responses that were not reversed by an AT\textsubscript{1} or AT\textsubscript{2} receptor antagonist\textsuperscript{3} but were prevented by the selective Ang-(1-7) receptor antagonist [D-Ala\textsubscript{7}]Ang-(1-7).\textsuperscript{32} suggesting that Ang-(1-7) activates a unique receptor on VSMCs to counteract the mitogenic response to Ang II. These in vitro studies are further supported by observations in combined ACE inhibitor/losartan–treated rats where a monoclonal antibody to Ang-(1-7)\textsuperscript{39} or [D-Ala\textsubscript{7}]Ang-(1-7)\textsuperscript{35} unmasked a role for endogenous Ang-(1-7), working in part through prostaglandins, in the blood pressure–lowering effects.\textsuperscript{34} Furthermore, there is evidence for a [D-Ala\textsubscript{7}]Ang-(1-7)–sensitive, non-AT\textsubscript{1}, non-AT\textsubscript{2} receptor in the aorta\textsuperscript{32} and mesentery\textsuperscript{34} of the animals treated with ACE inhibitors and losartan. Thus, Ang-(1-7) has unique effects in the vasculature that are coupled to a non-AT\textsubscript{1} receptor and do not result from antagonism of the AT\textsubscript{1} receptor.

In the present study, we showed that prior treatment of VSMCs with Ang-(1-7) attenuated \textsuperscript{34} [\textsuperscript{3}H]Ang II binding to the AT\textsubscript{1} receptor and reduced Ang II–stimulated PLC activation. However, significant downregulation of Ang II binding and Ang II–mediated responsiveness occurred only at micromolar concentrations of Ang-(1-7), in agreement with its IC\textsubscript{50} value for competition at the AT\textsubscript{1} receptor. These results suggest that at micromolar concentrations, Ang-(1-7) acts as a weak agonist at the AT\textsubscript{1} receptor to downregulate the receptor and to reduce subsequent cellular responses to Ang II.

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References


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