Recent Progress in Angiotensin II Type 2 Receptor Research in the Cardiovascular System

Masatsugu Horiuchi, Masahiro Akishita, Victor J. Dzau

Abstract—Angiotensin II (Ang II) plays an important role in regulating cardiovascular hemodynamics and structure. Multiple lines of evidence have suggested the existence of Ang II receptor subtypes, and at least 2 distinct receptor subtypes have been defined on the basis of their differential pharmacological and biochemical properties and designated as type 1 (AT_1) and type 2 (AT_2) receptors. To date, most of the known effects of Ang II in adult tissues are attributable to the AT_1 receptor. Recent cloning of the AT_2 receptor contributes to revealing its physiological functions, but many functions of the AT_2 receptor are still an enigma. AT_1 and AT_2 receptors belong to the 7-transmembrane, G protein–coupled receptor family. However, accumulating evidence demonstrates that the function and signaling mechanisms of these receptor subtypes are quite different, and these receptors may exert opposite effects in terms of cell growth and blood pressure regulation. We will review the role of the AT_2 receptor in the cardiovascular system and the molecular and cellular mechanisms of AT_2 receptor action. (Hypertension. 1999;33:613-621.)

Key Words: angiotensin II ▪ apoptosis ▪ blood vessels ▪ cell growth ▪ heart ▪ receptors ▪ signaling

Angiotensin II (Ang II) has significant influence on the heart and blood vessels through its effects on systemic hemodynamics and blood volume. Ang II also exerts long-term structural effects through its direct hypertrophic and proliferative growth actions.1,2 Multiple lines of evidence have suggested the existence of Ang II receptor subtypes, but it was only recently that at least 2 distinct receptor subtypes were defined on the basis of their differential pharmacological and biochemical properties and designated as type 1 (AT_1) and type 2 (AT_2) receptors.3-4 Subsequent cloning of these 2 receptors5-8 fostered renewed interest in the biochemical, pharmacology, and physiology of Ang II receptors. To date, extensive pharmacological evidence indicates that most of the known effects of Ang II in adult cardiovascular tissues are attributable to the AT_1 receptor, but less is known about the AT_2 receptor. As shown in the Table, accumulating evidence revealed that this receptor acts as an antagonistic receptor against AT_1 receptor, ie, AT_2 receptor exerts antithrombotic, antihypertrophic, and proapoptotic effects.

Vascular Effect

Vascular Development

It has been shown that rat and mouse vascular AT_2 receptor mRNA is expressed at very low levels in the aorta during early embryonic development (up to embryonic day 15) but at high levels during the later stages of development (embryonic days 16 to 21) and in the neonate,9,10 whereas the AT_1 receptor in aorta is expressed at relatively constant levels from the first point tested (embryonic day 10) throughout development and the neonatal period and into the adult stage. After birth, AT_2 receptor levels decline rapidly. Shanmugam et al11 confirmed this observation using in situ hybridization. The high level of AT_2 receptor mRNA expression in the outer medial-adventitial region persisted after birth in the neonate, but AT_1 receptor mRNA expression was absent in the tunica media and was decreased in the tunica adventitia 10 days after birth and had almost completely disappeared at 22 days after birth.

To further elucidate the physiological significance of the effects mediated by the AT_2 receptor in fetal vasculature, we examined the effects of angiotensin receptor blockade on the rates of DNA synthesis in the developing aorta when AT_2 receptor is expressed. The physiological role of the AT_2 receptor in the developing fetal aorta was examined by PD123319 infusion in utero (embryonic days 15 to 21).9 At embryonic day 15, when the AT_2 receptor is not expressed and aortic DNA synthesis rates are at or near maximum, before the developmentally regulated decrease in DNA synthesis, PD123319 has no effect on DNA synthesis. However, when the growth rates in the fetal aorta are declining and the AT_2 receptor is expressed (embryonic days 16 to 21), PD123319 attenuates the reduction in aortic DNA synthesis. These results suggest strongly that the AT_2 receptor mediates an antigrowth effect on the aorta in vivo. The opposing effects of the AT_1 and AT_2 receptor subtypes suggest an antagonistic interaction between these receptors in their effect on vascular structure (Figure 1). On the basis of these data, one might conclude that the AT_2 receptor modulates the...
growth of the vessel, perhaps by controlling the growth-stimulatory effects of developmentally regulated growth factors or by other mechanisms such as apoptosis.

To examine further the role of the AT2 receptor, we have generated the AT2 receptor knockout mouse using homolo-
gous recombination. The structural consequences of vascu-
lar AT2 receptor expression in vascular development in the knock-
out mouse still await detailed analysis. Recent studies using 
neuronal cells suggest that AT2 receptor activation may en-

hance differentiation in PC12W cells (a rat pheochromo-
cytoma cell line) and in NG108-15 cells. Accordingly, we 
examined, in the AT2 receptor knockout mouse, vascular 
differentiation that drives the alteration in expression of 
numerous proteins, notably the constituents of the contractile 
apparatus. One of the hallmarks of development and differ-
entiation of the vessel wall is the regulation of the synthesis 
of smooth muscle-specific proteins. We have demonstrated 
that the expression of h-caldesmon and calponin is delayed in 
the aorta of the AT2 receptor knockout mouse, which suggests 
that the AT2 receptor enhances the differentiation of vascular 
smooth muscle cells (VSMCs). To date, a careful morpho-
lcal examination of the relationship between the expres-
sion of AT2 receptor in the vessel wall and apoptosis, 
differentiation, and fibrosis, for example, has not been com-
pleted. Furthermore, a detailed morphometric analysis of 
vascular structure, including thickness of the vessel layers 
and internal and external diameters of large, medium, and 
small arteries and arterioles, is required. In summary, current 
data suggest that the AT2 receptor plays a role in VSMC 
growth inhibition and differentiation during late gestation, 
thereby influencing the structure and function of the blood 
vessels (Figure 1).

Vascular Remodeling

Growth

In adults with certain pathological conditions such as vascular 
balloon “injury” or inflammation induced by cuff placement, 
the AT2 receptor is reexpressed (Figure 1). Our group 
examined further the function of the AT2 receptor using a 
gain-of-function approach. Adult rat aortic VSMCs ex-
pressing very low levels of endogenous AT2 receptors were 
transfected with the AT2 receptor expression vector, and its 
effect on cell growth was examined. Ang II significantly 
increased the cell number in the control vector–transfected 
VSMCs. This increase was abolished with the AT1 receptor 
antagonist DuP753, thereby demonstrating that AT1 receptor 
activation enhances VSMC growth. On the other hand, in the 
cells coexpressing the AT2 receptor, Ang II treatment had 
little or no effect on cell number. Treatment of these VSMCs 
with the AT2 receptor antagonist PD123319 unmasked the 
growth effect of Ang II exerted through the AT1 receptor. 
Consistent with our results, Stoll et al also observed an 
antiproliferative influence of the AT2 receptor on cultured 
coronary endothelial cells. Goto et al reported that the 
cultured mesangial cells prepared from stroke-prone sponta-
neously hypertensive rats (SHR) showed lower expression of 
AT2 receptor and higher proliferation activity than those of 
normotensive Wistar-Kyoto rats, suggesting that AT2 receptor
may exert antiproliferative effect in mesangial cells. Moreover, antiproliferative effects of AT₂ receptor were also shown in mouse fibroblast R3T3 cells and in PC12W cells (rat pheochromocytoma cell line). In contrast, Otsuka et al. observed very recently that mRNA expression for both AT₁ and AT₂ receptors was enhanced in the aorta of SHR and demonstrated that treatment with PD123319 reduced the media cross-sectional area of the aorta, whereas losartan reduced the arterial systolic blood pressure and the collagen concentration. They suggest that AT₁ receptor, but not AT₂ receptor, plays a crucial role in the remodeling of matrix tissue, while AT₂ receptor plays a role in the development of hypertrophy of smooth muscle in aorta in SHR.

Our group examined the effects of the expression of the transfecting AT₂ receptor expression vector on adult VSMCs in vivo using the rat carotid injury model. The AT₂ receptor vector or control vector was transfected into the balloon-injured rat carotid artery by the hemagglutinating virus of Japan–liposome method at the time of surgery. The neointimal area (expressed as a ratio of medial area) of the vessels transfected with and expressing the AT₂ receptor transgene was significantly smaller (70% decrease) than that of the untransfected or the control vector–transfected vessels. This inhibitory effect on the development of the neointimal lesion could be blocked with the AT₂ receptor antagonist PD123319.

To define the role of the endogenous AT₂ receptor in vascular disease, we applied the mouse model of vascular disease induced by polyethylene cuff placement. Our experiments using this model of cuff-wrapped mouse femoral artery revealed that the upregulation of the AT₂ receptor was preceded by an increase in inflammatory cytokines and that both AT₂ receptor knockout mice and wild-type mice developed neointima in the femoral artery, but the lesion was twice as large in the knockout mice as in the wild-type mice. On the other hand, Levy et al. reported that chronic blockade of AT₁ receptor by losartan in rats receiving Ang II resulted in normal arterial pressure, but it induced significant aortic hypertrophy and fibrosis, and that chronic blockade of AT₂ receptor by PD123319 in Ang II–induced hypertensive rats had no effect on arterial pressure but antagonized the effect of Ang II on arterial hypertrophy and fibrosis, suggesting that in vivo vasotrophic effects of Ang II are at least partially mediated by AT₂ subtype receptors. These apparent differences in functions of AT₂ receptor are partly due to the difference in the species and/or experimental models, and these issues must be addressed in the near future.

**Apoptosis**

Because of evidence that apoptosis is critical for cardiovascular remodeling, we examined the effect of Ang II on apoptosis in VSMCs. After serum growth factor depletion, cultured VSMCs showed morphological changes typical of apoptosis and internucleosomal DNA fragmentation, and Ang II inhibited the onset of apoptosis through the AT₁ receptor. In contrast, as we demonstrated using AT₂ receptor–transfected VSMCs, selective AT₂ receptor stimulation enhanced apoptosis after serum starvation. In addition, we have demonstrated that AT₂ receptor exerts a proapoptotic effect in neonatal cardiomyocytes, PC12W cells, and R3T3 mouse fibroblasts. Recently, Dimmeler et al. reported that Ang II induces apoptosis of human umbilical venous endothelial cells by activation of the caspase cascade and that simultaneous blockade of both AT₁ and AT₂ receptors prevents Ang II–induced apoptosis, whereas selective agonistic stimulation of the AT₂ receptor alone induces apoptosis. Moreover, Li et al. demonstrated that Ang II induces apoptosis in the skin fibroblasts of the mouse embryo but not in those prepared from AT₂ receptor knockout mice.

**Blood Pressure**

Ichiki et al. recently reported that mice lacking the gene encoding the AT₂ receptor have higher blood pressure than the wild-type control, while Munzenmaier and Greene reported that AT₂ receptor blockade augments the pressor effect of Ang II in the rat. Consistent with these results, we observed that the AT₂ receptor knockout mouse exhibits an enhanced acute blood pressure response to low-dose Ang II infusion. These findings suggest that the AT₂ receptor mediates vasodilation. Neither the target vasculature nor the underlying mechanism, however, is well understood. Since the vascular AT₂ receptor was minimally expressed in the vasculature when the blood pressure and Ang II infusion studies were performed (3- to 5-month-old mice), the data suggest that transient and developmentally regulated AT₂ receptor expression exerts a long-term effect on blood pressure, possibly through its influence on vascular structure (Figure 1).

Moreover, Arima et al. directly examined the AT₂ receptor–mediated effect of Ang II on renal arterioles. They isolated and microperfused the rabbit glomerular afferent arteriole, which is a vascular segment crucial to the control of glomerular hemodynamics, and examined whether the AT₂ receptor is involved in the vasodilation and, if so, by what mechanism. They showed that the AT₂ receptor mediates vasodilation and that dilation was abolished by either disrupting the endothelium or inhibiting the cytochrome P-450 pathway, which suggests that afferent arteriole activation of the AT₂ receptor causes endothelium-dependent vasodilation via a cytochrome P-450 pathway, possibly by epoxyeicosa trienoic acids. In contrast, it has been reported that stimulation of renal AT₂ receptors in anesthetized rats has no effect on total renal blood flow but blunts the pressure natriuresis. Siragy and Carey have demonstrated that activation of the renin-angiotensin system during sodium depletion increases renal nitric oxide (NO) production through stimulation by Ang II at the AT₂ receptor and renal production of cGMP and that AT₂ receptor blockade potentiates AT₁ receptor–induced prostaglandin E₂ production. NO release by AT₂ receptor stimulation was also reported in dog coronary microvessels and large coronary arteries. Consistent with these results, Gohlke and colleagues demonstrated that AT₂ receptor–mediated cGMP production in hypertensive rat aorta is mediated by bradykinin and NO.

In addition, AT₂ receptors may be involved in salt conservation. Madrid et al. examined the effect of an Ang II AT₂ or AT₂ receptor antagonist on the impairment of the pressure diuresis and natriuresis response produced by NO synthesis blockade by Nω-nitro-L-arginine methyl ester (L-NAME).
They observed that, in rats given L-NAME, valsartan elevated baseline excretory values at all renal perfusion pressure, but it had no effect on the sensitivity of the pressure diuresis and natriuresis response. However, the administration of PD-123319 to L-NAME–pretreated rats shifted the slopes of the pressure diuresis and natriuresis responses toward control values, indicating that the impairment produced by NO synthesis blockade on pressure diuresis is dependent on the activation of AT2 angiotensin receptors. Ozono et al. demonstrated that Ang II mediates jejunal sodium and water absorption by an action at the AT2 receptor involving cGMP production, while Ang II inhibits absorption through the AT1 receptor. They also showed that dietary sodium depletion increased the AT2 receptor expression in mature adult rat kidneys.

**Myocardial Effect**

**Cellular Effects**

The function of the AT1 receptor in the myocardium has not been well defined. In recent studies, AT2 receptor stimulation in cultured rat neonatal cardiomyocytes and fibroblasts inhibited AT1 receptor–dependent growth. Consistent with this observation, in our preliminary experiments the AT1 receptor blocked apoptosis and the AT2 receptor enhanced apoptosis in cultured neonatal rat cardiomyocytes, suggesting that Ang II exerts simultaneous opposing effects on cell growth through 2 different receptor subtypes. In contrast, Kajstura and colleagues reported that Ang II induced apoptosis in cultured rat neonatal ventricular myocytes through a protein kinase C–mediated mechanism, an effect that was blocked by losartan. Moreover, having found that p53 increased angiotensinogen and AT1 receptor expression in cultured adult rat ventricular myocytes, they postulated that p53 induced myocyte apoptosis through activation of the myocyte angiotensin system and that stretch-mediated release of Ang II in adult myocytes is coupled with apoptosis and the activation of p53, which may be responsible for the prolonged upregulation of the local renin-angiotensin system and the increased susceptibility of myocytes to undergo apoptosis. The basis for the discrepancy in our observation on AT1 versus AT2 receptor effect on myocyte apoptosis is unclear. It may be partially dependent on the cell characteristics and the conditions of the cell culture experiment. Further investigation to clarify this issue and its physiological relevance is clearly warranted.

**AT2 Receptor in Cardiac Diseases**

If AT1 and AT2 receptors exert antagonistic action on myocardial biology, especially growth, then the relative expression of these receptors and their ratios under different cardiac pathological conditions may be important in determining myocardial function and structure. Cardiac expression of AT1 and AT2 receptor subtypes is species dependent, and changes in their relative proportion may influence myocardial hypertrophy and fibrosis. The density of the myocardial AT2 receptor was shown to be increased in experimental myocardial infarction 1 day after infarction in the infarcted portion, and AT2 receptor expression was further upregulated 7 days after infarction in both the infarcted and the noninfarcted portions. In the hypertrophied rat heart, the ratio of AT2 to AT1 receptor densities is increased. In failing Bio14.6 cardiomyopathic hamster hearts, AT2 receptor expression has been reported to increase in cardiac fibroblasts in fibrous regions, in turn exerting an anti-AT1 receptor effect on the progression of interstitial fibrosis during cardiac remodeling by inhibiting both fibrillar collagen metabolism and growth of cardiac fibroblasts. In contrast, AT1 receptor expression increased in the hypertrophy stage and then decreased to the control level during heart failure. Moreover, changes in AT2 receptor expression in human cardiac diseases have been reported. In failing human heart, the relative ratio of AT2 receptor expression to AT1 receptor has been reported to be higher than in the normal heart. Wharton et al. carefully examined the expression and localization of the AT2 receptor in human diseased hearts and reported that endocardial, interstitial, perivascular, and infarcted regions in the ventricles of patients with end-stage ischemic heart disease or dilated cardiomyopathy exhibited a significantly greater density of high-affinity AT2 binding sites than adjacent noninfarcted myocardium. Regions displaying the relative increase in AT2 binding sites corresponded to areas of fibroblast proliferation and collagen deposition. The border zone between infarcted and noninfarcted myocardium characteristically contained numerous microvessels exhibiting perivascular AT2 receptors. In contrast, AT1 binding sites were localized to nerves, occurred at relatively low density in coronary vessels, and represented only 23% to 29% of myocardial Ang II binding sites. Taken together, these results suggest that the AT2 receptor plays some role in cardiovascular remodeling in humans.

**Cardiac Function**

Given these associations, if we postulate that the AT2 receptor contributes to the pathogenesis of cardiac diseases and the subsequent remodeling process, then treatment with the selective AT2 receptor antagonist may have interesting cardiac remodeling effects that have not heretofore been appreciated. Using a model of heart failure induced by myocardial infarction in rats, Liu and colleagues demonstrated that a significant increase in left ventricular end-diastolic and endsystolic volume and a decrease in ejection fraction, interstitial collagen deposition, and cardiomyocyte size were all improved by AT2 receptor antagonist and that these effects were blocked by the AT1 receptor antagonist. They speculate that in heart failure, blockade of AT1 receptors increases both renin and angiotensin; this angiotensin stimulates the AT2 receptor, which in turn is part of the therapeutic effect of the AT1 receptor antagonist.

Using an α-myosin heavy chain promoter, Masaki and colleagues developed a mouse model that shows cardiac-specific overexpression of the AT2 receptor gene, which resulted in decreased sensitivity to AT1-receptor mediated pressor and chronotropic actions. They saw no obvious morphological change in the myocardium and no significant difference in cardiac development or ratio of heart to body weight between wild-type and transgenic mice.
Signaling Mechanism of AT$_2$ Receptor

The signaling mechanism of AT$_2$ receptor action has not been well defined compared with that of the AT$_1$ receptor. As shown in Figure 2, growth-inhibitory effects of the AT$_2$ receptor are reported to be at least partly mediated by the activation of protein tyrosine phosphatase (PTPase), which results in the inactivation of AT$_1$ receptor– and/or growth factor–activated mitogen-activated protein (MAP) kinase (p42 and p44 MAP kinases are known as extracellular signal–regulated kinase [ERK]).

Serine/threonine phosphatase 2A (PP2A) activation and consequent ERK inactivation through AT$_2$ receptor have also been reported in neuronal cells cultured from neonatal rat hypothalamus and brainstem. We also observed a decrease in ERK activity in the heart of AT$_2$ receptor transgenic mice, which suggests that the ERK inactivation by the AT$_2$ receptor has a physiological role in vivo.

Specific phosphatases that couple with AT$_2$ receptor have not been identified. An immediate early gene product known as 3CH134 was identified recently as a phosphatase specific for MAP kinase and named MAP kinase phosphatase-1 (MKP-1). A reduction of MKP-1 has been reported in rat VSMC after vascular injury and in the rat aorta in acute hypertension elicited by stress or vasoactive substances, thus suggesting the important role of this enzyme in vascular remodeling and hypertension. Our finding in PC12W cells that pretreatment with antisense oligonucleotide of MKP-1 inhibited the proapoptotic effect of the AT$_2$ receptor suggests that MKP-1 is an AT$_2$ receptor–activated phosphatase. In NIE-115 neuroblastoma cells and in Chinese hamster ovary cells expressing recombinant human AT$_2$ receptor, Ang II rapidly stimulates the catalytic activity of SH-PTP1, a soluble PTPase that has been implicated in termination of signaling by cytokine and growth factor receptors; SH-PTP1 activation resulted in ERK inactivation. It is intriguing to find other target substrates in addition to ERK, which are regulated by AT$_2$ receptor–activated phosphatases.

Apoptosis is controlled in part by a family of cytoplasmic proteins, the Bcl-2 protein family. Phosphorylation/dephosphorylation of Bcl-2 family proteins such as Bcl-2 and Bad is reported as a mechanism of posttranscriptional regulation of their function. Consistent with these reports, we demonstrated in PC12W cells that nerve growth factor (NGF) activated Bcl-2 by ERK-dependent phosphorylation and that AT$_2$ receptor inhibits NGF-mediated Bcl-2 phosphorylation by inhibiting ERK activity, thereby resulting in the induction of apoptosis. We also observed that serum depletion in PC12W cells increased the Bax mRNA expression, while NGF decreased Bax expression and AT$_2$ receptor stimulation increased it. Moreover, we found that AT$_2$ receptor stimulation increased de novo ceramide production through PTPase activation.

Pertussis toxin treatment attenuated AT$_2$ receptor–mediated ERK inactivation and resulted in the inhibition of the growth-inhibitory and proapoptotic effects of this receptor. Using coimmunoprecipitation studies with antibodies specific for various G protein $\alpha$ subunits, Zhang and Pratt found that only antibodies specific for G$\alpha$ were able to coimmunoprecipitate AT$_2$ receptor binding sites in the membrane prepared from rat fetus. Moreover, we demonstrated that transfection of the synthetic intracellular third loop peptide of the AT$_2$ receptor into rat adult aortic VSMCs resulted in ERK inactivation and growth inhibition and that the $^{125}$I-labeled third loop peptide of AT$_2$ receptor was immunoprecipitated with anti-G$\alpha$ antibody. Taken together, these results suggest that the AT$_2$ receptor is a G protein–coupled receptor and that the intracellular third loop domain of the AT$_2$ receptor is closely linked with the cellular signaling pathways in which G$_i$ is involved, and this interaction results in the ERK inactivation. Consistent with these observations, Kang and colleagues reported that the AT$_2$ receptor stimulates potassium current in neurons cultured from rat hypothalamus and brainstem via a G$_i$-protein coupling mechanism through the intracellular third loop of this receptor. Moreover, Buisson et al demonstrated that in nondifferentiated NG108-15 cells, AT$_2$ receptor stimulation decreased the T-type calcium current amplitude, an effect that was reversed with GDP$_\beta$S and mimicked with GTP$_\gamma$S, and that the inhibitory effect of the AT$_2$ receptor on the T-type calcium current involves PTPase activity, thus supporting the notion that G protein–coupled PTPase activation is involved in AT$_2$ receptor signaling.

While both AT$_1$ and AT$_2$ receptors belong to the 7-transmembrane, G protein–coupled receptor family, recent evidence reveals that the functions of AT$_1$ and AT$_2$ receptors are mutually antagonistic. The AT$_1$ receptor promotes cell growth, whereas the AT$_2$ receptor mediates growth inhibition. Growth-inhibitory effects of AT$_2$ receptor are unique in that this is a 7-transmembrane, G protein–coupled receptor that counteracts the growth action of other 7-transmembrane, G protein–coupled receptors as well as that of other classes of growth factor receptors.

Transcriptional Regulation of AT$_2$ Receptor Expression

To understand the molecular mechanism of the developmental and growth regulation of AT$_2$ receptor expression,
we cloned the mouse AT$_2$ receptor gene, analyzed its structure, and examined its promoter activity.$^{20}$ We used R3T3 cells, a mouse fibroblast cell line, in our model since these cells express only AT$_2$ subtype binding sites and the expression of AT$_2$ receptor sites in these cells is modulated by the growth state of the cells, ie, AT$_2$ receptor expression is low in the growing state and becomes high in the confluent state.$^{71,72}$ Promoter/luciferase reporter deletion analysis of the AT$_2$ receptor in R3T3 cells showed a putative negative regulatory region located between positions −453 and −225 that plays an important role in the transcriptional control of AT$_2$ receptor gene expression along with the cell growth. The expression of AT$_2$ receptor in R3T3 cells is transcriptionally regulated by the competitive binding of interferon regulatory factor (IRF)-1 and IRF-2, ie, IRF-1 increases growth-dependent AT$_2$ receptor expression in mouse fibroblast R3T3 cells, whereas IRF-2 inhibits it.$^{70}$ Moreover, upregulation of IRF-1 in apoptotic R3T3 cells results in the increased expression of AT$_2$ receptor, thereby exerting proapoptotic effects.$^{26}$ Thus, it is intriguing to note that the same transcriptional factor, IRF-1, activates the expression of inducible nitric oxide synthase$^{73}$ and interleukin (IL)-1β-converting enzyme,$^{74,75}$ both of which are involved with apoptosis (Figure 3).

Ichiki and colleagues$^{76}$ also examined the effects of several growth factors on the expression of AT$_2$ receptor mRNA in R3T3 cells and observed that serum (10%), fibroblast growth factor, phorbol ester, and lysophosphatidic acid reduced AT$_2$ receptor expression, whereas IL-1β and insulin enhanced it, thus suggesting that AT$_2$ receptor expression is modulated by multiple growth factors in both positive and negative directions. They also proposed the presence of potential cis DNA elements that respond to IL-1β (CCAAT enhancer binding protein site), insulin [insulin response sequence of phospho(enol)pyruvate carboxykinase gene], and phorbol ester (AP-1 site) in the promoter region of the mouse AT$_2$ receptor gene. Moreover, it has been reported that Ang II enhances the number of AT$_2$ receptor in R3T3 cells.$^{72,77}$

In contrast, the mechanism of AT$_2$ receptor expression in VSMCs and cardiomyocytes is poorly understood. Expression of the AT$_2$ receptor in the fetal aorta is substantial, while that in the adult aorta and cultured VSMCs is very low or even absent. Kambayashi and colleagues$^{78}$ reported that prolonged serum depletion (6 to 8 days) with a supplement of insulin induced expression of AT$_2$ receptor mRNA in cultured VSMCs from Wistar-Kyoto rats, but receptor expression could not be induced in VSMCs prepared from SHR.$^{79}$ They also reported that insulin-like growth factor upregulates AT$_2$ receptor expression in cultured VSMCs. Moreover, vasoactive substances with the protein kinase C–calcium pathway, such as norepinephrine and Ang II, have been reported to downregulate the AT$_2$ mRNA level in cultured rat neonatal myocytes.$^{80}$

**Summary**

Angiotensin-converting enzyme (ACE) inhibitor has been widely used for the treatment of hypertension.$^{81–83}$ It has been well established that ACE inhibitors improve cardiac function and remodeling and prolong survival in patients with heart failure. AT$_1$ receptor antagonists constitute an exciting and important new class of antihypertensive drug and are already used in antihypertension treatment. The effect of AT$_1$ receptor antagonist may not be entirely due to blockade of the AT$_1$ receptor.$^{84}$ When AT$_2$ receptor is blocked, plasma renin and angiotensins increase,$^{85}$ and therefore increased angiotensins may act preferably on AT$_2$ receptor (Figure 3). If the AT$_2$ receptor contributes to the pathogenesis and consequent remodeling of cardiovascular diseases in humans, AT$_1$ receptor antagonist may have some specific effects in the treatment of cardiovascular diseases. Indeed, cardioprotective effects and improved cardiac functions by AT$_1$ receptor antagonist have been reported in heart failure in experimental animal models.$^{86–89}$ Liu and colleagues,$^{52}$ using a model of heart failure induced by myocardial infarction in rats, demonstrated that AT$_1$ receptor antagonist improved cardiac functions and decreased interstitial collagen deposition and cardiomyocyte size and that these effects were blocked by...
the AT₂ receptor antagonist, suggesting that the part of the effect of AT₁ receptor antagonist was due to the stimulation of AT₂ receptor. However, there are no reports demonstrating the clear differences between the long-term effects of AT₁ receptor antagonists and ACE inhibitors in the treatment of hypertension and cardiovascular diseases. One of the reasons is due to the fact that the cardioprotective effect of ACE inhibitor may be due to the renin-angiotensin system and/or inhibition of kinin destruction. Moreover, detailed localization and time course of AT₂ receptor expression in cardiovascular diseases as well as the factors regulating AT₂ receptor in vivo including receptor ligands must be elucidated. In summary, it is now conceivable that AT₂ receptor plays some roles in the pathogenesis and the remodeling of cardiovascular diseases, and further understanding of AT₂ receptor may contribute to new therapeutic strategies for cardiovascular diseases and hypertension.

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References

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