Activation of Local Chorionic Villi Angiotensin II Levels But Not Angiotensin (1-7) in Preeclampsia

Lauren Anton, David C. Merrill, Liomar A.A. Neves, Kathryn Stovall, Patricia E. Gallagher, Debra I. Diz, Cheryl Moorefield, Courtney Gruver, Carlos M. Ferrario, K. Bridget Brosnihan

Abstract—The chorionic villi in the placenta are responsible for the regulation of fetal oxygen and nutrient transport. Although the peripheral renin-angiotensin system is activated during normal pregnancy, the regulation of the local chorionic villi renin-angiotensin system remains unknown. Therefore, placental chorionic villous tissue was collected from nulliparous third-trimester normotensive or preeclamptic subjects and was analyzed for angiotensin peptide content, angiotensinogen, renin, angiotensin-converting enzyme (ACE), ACE2, nephrilysin, angiotensin II type I (AT$_1$), angiotensin II type 2, Mas receptor mRNAs, and angiotensin receptor density and subtype. Angiotensin II in chorionic villi was significantly higher in preeclamptic subjects, whereas angiotensin (1-7) was not different. Angiotensinogen and AT$_1$ receptor gene expression was significantly higher in preeclamptic subjects. No differences were observed in renin, ACE, ACE2, or nephrilysin gene expression. Mas receptor mRNA in preeclamptic subjects was decreased. The AT$_1$ receptor was the predominant receptor subtype in normal and preeclamptic chorionic villi. There was no difference in the density of the AT$_1$, angiotensin II type 2, and angiotensin (1-7) receptors. These results indicate that enhanced chorionic villous expression of angiotensin II may result from increased angiotensinogen. Elevated angiotensin II, acting through the AT$_1$ receptor, may favor vasoconstriction in placent chorionic villi and contribute to impaired fetal blood flow and decreased fetal nutrition observed during preeclampsia. (Hypertension. 2008;51:1066-1072.)

Key Words: preeclampsia ■ renin angiotensin system ■ pregnancy ■ placenta ■ angiotensin receptors ■ Mas receptor ■ angiotensin (1-7)

Preeclampsia, a hypertensive disorder of pregnancy, is clinically defined as maternal hypertension, proteinuria, and generalized edema occurring after the 20th week of gestation. Preeclampsia is the second leading cause of maternal mortality in the United States, affecting 7% to 10% of all pregnancies and contributing significantly to stillbirths and neonatal morbidity and mortality. Thus, the prevention of preeclampsia would have a significant impact on maternal and neonatal outcome. Nevertheless, the pathophysiology of preeclampsia remains poorly understood. Although preeclampsia is often considered a multisystem disorder, one of the postulated pathological features of this disease is an impaired maternal uterine spiral artery remodeling. In preeclampsia, there is a decrease of embryonic trophoblast cell invasion of the uterine spiral arteries, which, in turn, prevents the diameter of these arteries from expanding and consequently leads to a reduction of blood flow into the placenta. Without the remodeling of the uterine vasculature, the placenta becomes hypoxic as gestation advances, resulting in an oxygen deficiency within the tissue. The hypoxic placenta can then release factors into the maternal circulation that result in generalized endothelial dysfunction, vascular inflammation, and proteinuria. Although several factors, including soluble fms-like tyrosine kinase 1 and soluble endoglin, were discovered recently to play a role in the pathogenesis of preeclampsia, there are still many unanswered questions in the development of this disease.

The renin-angiotensin system (RAS) is an important regulator of blood pressure, sodium, and fluid homeostasis and has been shown previously to play a role in preeclampsia. In normal pregnancy, estrogen causes an overexpression of the RAS by increasing both tissue and circulating levels of angiotensinogen and renin. Consequently, plasma angiotensin (Ang) II is increased in association with the rise of angiotensinogen and plasma renin activity during gestation. Normal pregnant women are resistant to the pressor effects of Ang II and they remain normotensive despite a 2-fold increase in Ang II. We showed that human plasma and urinary levels of Ang-(1-7) are increased in normal pregnant subjects. The physiological consequences of the activated RAS during normal pregnancy are unknown; even less understood is how this system may be altered in women with preeclampsia. Our previously published study showed that many of the components of the circulating RAS in
women with preeclampsia are downregulated, including plasma Ang I, Ang II, Ang-(1-7), and plasma renin activity, when compared with normal pregnant women. In addition, we showed previously that Ang-(1-7) and its generating enzyme, angiotensin-converting enzyme (ACE)2, are colocaled within different cell types in the placenta, including primarily the chorionic villous syncytiotrophoblast and cytotrophoblasts, of normal and preeclamptic women. This study suggested that the RAS may play an important role within the chorionic villi, an essential component of the placenta that is responsible for maternal-fetal blood flow and, thus, the transport of oxygen and nutrients to the growing fetus. Several studies investigated the local tissue-specific RAS in the placenta; however, none have characterized the entire RAS in the chorionic villi specifically. In this study, we investigated angiotensin peptides, RAS component mRNAs, and angiotensin receptor binding in chorionic villi from normal and preeclamptic subjects.

Materials and Methods

Human Subjects

These experiments were conducted using human placental tissue collected from women with both normal pregnancy and preeclampsia. Placental tissue was collected from women who had either cesarean section or vaginal deliveries. Two separate groups of subjects were included. Group 1 (n = 25) consisted of normotensive pregnant subjects who have remained normotensive throughout pregnancy (BP < 140/90 mm Hg), have no history of chronic blood pressure elevation, and have an absence of proteinuria. Group 2 (n = 21) consisted of preeclamptic subjects who developed new-onset hypertension (BP > 140/90 mm Hg) and proteinuria (1+ = 30 mg/dL, ≥ 300 mg in a 24-hour urine sample) after the 20th week of gestation. Blood pressure readings are reported as the highest blood pressure measured in the labor and delivery suite before delivery. Subjects in the 2 groups were matched according to gestational age and parity (all nulliparous). Patients with evidence of chorioamnionitis were excluded. Women in both groups were over age 18 years and less than age 50 years and were free of other known cardiovascular, renal, or connective tissue diseases; diabetes; cancer; or hyperplasia.

The study was approved by the institutional review boards at both Wake Forest University School of Medicine and Forsyth Medical Center. The procedures followed were in accordance with institutional guidelines. After signed, informed consent was obtained and the baby and placenta were delivered, placental samples were taken.

Experimental Procedures

For both normal pregnant and preeclamptic patients, immediately after delivery, the whole placenta was collected on ice, and tissue sections were taken from the center of the placenta, near the umbilical cord attachment site. The total amount of time from delivery of the placenta until the samples were collected did not exceed 15 minutes. For each tissue section, the maternal basal plate and fetal membranes were removed so that only the fetal villous tissue was present. When taking tissue sections from the placenta, areas of necrosis or tissue damage were avoided. Tissue sections were immediately snap frozen in liquid nitrogen and stored at −80°C for analysis of angiotensin peptides [Ang I, Ang II, and Ang-(1-7)] by radioimmunoassay or for quantification of angiotensinogen, renin, ACE, ACE2, nephrilysin (NEP), and Ang II type 1 (AT1), Ang II type 2 (AT2), and Mas receptor mRNAs by reverse transcription, real-time PCR. In addition, tissue sections were frozen in OCT freezing medium for AT1, AT2, and Ang II type 1-7 (AT1-7) receptor density measurements by receptor autoradiography, as described below.

Tissue Concentration of Angiotensin Peptides

Frozen tissues were rapidly weighed and homogenized, as described previously.20 Tissue homogenates were extracted using Sep-Pak columns, as described previously.25-27 The elute was divided for 3 radioimmunoassays [Ang I, Ang II, and Ang-(1-7)], and the solvent was evaporated. Ang I was measured using a modification of a commercially available Peninsula radioimmunoassay kit. Ang II was measured using an Alpco Diagnostic kit. Ang-(1-7) was measured using an antibody produced in our laboratory.28 The minimum detectable levels of the assays were 1.0 fmol/mL for Ang I, 0.8 fmol/mL for Ang II, and 2.8 fmol/mL for Ang-(1-7). The intra-assay and interassay coefficients of variation for Ang I radioimmunoassay are 18% and 22%, for Ang II are 12% and 22%, and for Ang-(1-7) are 8% and 20%, respectively.

RNA Isolation and Reverse Transcription/ Real-Time PCR

RNA was isolated from human chorionic villi from normal and preeclamptic women using TRIzol reagent (GIBCO Invitrogen) and reverse transcribed using avian myeloblastosis virus reverse transcriptase. The resultant cDNA was added to TaqMan Universal PCR Master Mix (Applied Biosystems) with gene-specific primer/probe sets, and amplification was performed on an ABI 7000 Sequence Detection System. Human primer/probe sets were purchased from Applied Biosystems except for ACE2, which was our design (forward primer 5'-CCCAGAGAACAGTGGACCAAAA-3'; reverse primer 5'-GCTCCACCACCAACGAT-3'; and probe 5'-FAM-CTCCCGCTTCATCTCC-3'). All of the reactions were performed in triplicate, and 18S ribosomal RNA, amplified using the TaqMan Ribosomal RNA Control kit (Applied Biosystems), served as an internal control. The results were quantified as Ct values, where Ct was defined as the threshold cycle of PCR at which product amount was first detected and expressed as relative gene expression (the ratio of target to control).

Autoradiography

Chorionic villous tissues frozen in OCT were sectioned at 14 μm, and receptor autoradiography was performed using 125I-[sarcosine1, threonine1]-Ang II at 0.6 nM to determine the apparent maximal density of receptors.25,28 A lower concentration of 125I-[sarcosine1, threonine1]-Ang II (0.2 nM) was used in the presence or absence of 3 μM Cs of losartan, PD 123319, or D-Ala3-Ang-(1-7) (A779 or D-Ala) to determine the percentage of each receptor subtype present. Sections were exposed to film and films were analyzed using a computerized densitometry system (MCID) as reported previously.29,30 Data for binding density are expressed as the amount of total binding attributed to each receptor subtype as determined by the competition study.

Statistics and Data Analysis

Data were analyzed with a standard 1-way ANOVA followed by the Newman-Keul’s posthoc test for multiple comparisons. The Student t test for unpaired observations was used for comparing 2 groups (GraphPad Software). A P value of <0.05 was considered statistically different. All of the arithmetic means are presented ± SEMs.

Results

Clinical Profile of Normal and Preeclamptic Patients

The Table shows the clinical profile of the study population. A total of 25 placental chorionic villous samples were collected from normal pregnant women, and 21 chorionic villous placental samples were collected from preeclamptic women. The preeclamptic subjects had significant hypertension as shown by increases in systolic (143 ± 4 versus 173 ± 3 mm Hg; P < 0.0001), diastolic (80 ± 2 versus

Anton et al Chorionic Villi RAS and Preeclampsia 1067

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Angiotensin peptide levels in normal pregnant and preeclamptic chorionic villi. Angiotensin peptide levels were measured by radioimmunoassay of Ang I (A), Ang II (B), and Ang-(1-7) (C) in normal and preeclamptic placental chorionic villi. There was a significant increase in Ang II (P<0.001) and 8-fold higher than Ang-(1-7) levels (28.5±6.2 versus 3.4±0.3 fmol/mg of protein; P<0.001) in the preeclamptic chorionic villi. Analysis of Ang II expression levels between preeclamptic women undergoing cesarean (n=10) versus vaginal (n=11) delivery revealed no significant differences (data not shown). There was no significant difference in chorionic villi Ang I or Ang-(1-7) levels between normal and preeclamptic subjects (Figure 1A and 1C).

RAS Gene Expression in Normal and Preeclamptic Chorionic Villi
Gene expression of RAS components, including renin, angiotensinogen, NEP, ACE, ACE2, AT1 receptors, AT2 receptors, and Mas receptors, was measured as shown in Figure 2. Preeclamptic chorionic villi were found to have 2.5-fold higher angiotensinogen mRNA when compared with normal chorionic villi (1.0±0.1 versus 2.4±0.4 U; P<0.01). No significant differences were found in angiotensinogen mRNA levels in preeclamptic women undergoing cesarean versus vaginal delivery. In addition, there was a trend for a higher renin mRNA in preeclamptic chorionic villi versus normal; however, statistical significance was not reached (Figure 2A). In addition, there were no significant differences in NEP, ACE, or ACE2 mRNAs in preeclamptic chorionic villi when compared with normal controls (Figure 2B). However, in the preeclamptic chorionic villi, AT1 receptor mRNA levels were significantly higher than the concentrations found in tissue from normal pregnant subjects (1.0±0.1 versus 3.0±0.7 U; P<0.01; Figure 2C). In addition, AT1 receptor mRNA levels were significantly higher in preeclamptic women undergoing a cesarean section versus those who had a normal vaginal delivery (4.7±1.5 versus 1.6±0.2; P<0.05). An analysis of the correlation between AT1 receptor mRNA and Ang II peptide levels revealed no correlation (r=0.21; P>0.05). Mas receptor mRNA was low but present in both the normal and preeclamptic villi. Mas receptor mRNA levels were lower in preeclamptic chorionic villi when compared with normal (1.5±0.40 versus 0.3±0.06 U; P=0.01; Figure 2D). AT2 receptor mRNA levels were below detectable limits in both the normal and preeclamptic chorionic villi.

Angiotensin Receptor Binding in Normal and Preeclamptic Chorionic Villi
Chorionic villous tissue from both normal and preeclamptic subjects was also analyzed by in vitro receptor autoradiography.
phy to determine the maximal density of binding and the percentage of each receptor subtype, AT₁, AT₂, and AT₁-7 (Figure 3). AT₁ receptors were the predominant receptor subtype in both the normal and preeclamptic chorionic villi (P<0.001), with AT₂ and AT₁-7 receptors making up <15% of the total RAS receptor binding. There was no statistical difference in AT₁ receptor density, defined by losartan competition, between normal and preeclamptic chorionic villi (412 ± 17 versus 380 ± 19 fmol/mg of protein). There was no difference in either AT₂, defined by PD12339 competition (412 ± 26 versus 61 ± 24 fmol/mg of protein), or AT₁-7, defined by A779 competition (412 ± 20 versus 55 ± 21 fmol/mg of protein), receptor binding density between normal and preeclamptic chorionic villi.

**Discussion**

This study is the first to demonstrate that all 3 of the key RAS peptides, Ang I, Ang II, and Ang-(1-7), are found in the chorionic villi of both normal and preeclamptic subjects. In addition, we found the presence of angiotensinogen, renin, ACE, ACE2, NEP, AT₁, and Mas receptors. Ang II, a potent vasoconstrictor of the RAS, is by far the most predominant peptide in the chorionic villi. Ang II was also twice as high in preeclamptic chorionic villi when compared with normal tissue. This indicates that the local placental RAS may play an important role in the regulation of the maternal-fetal interface in the chorionic villi. No changes were seen in either Ang I or Ang-(1-7) levels between normal and preeclamptic chorionic villi. In addition to increased Ang II peptide levels, we also observed an increase in angiotensinogen and AT₁ receptor mRNAs in the preeclamptic chorionic villi. The observation of no significant changes in renin, NEP, ACE, or ACE2 mRNA in preeclamptic chorionic villi indicates that the highly increased activation of the vasoconstrictor arm of the RAS in the preeclamptic chorionic villi arises at the level of the angiotensinogen substrate and AT₁ receptors of the system. Although there were no significant changes in Ang I and Ang-(1-7) peptide levels and renin, NEP, ACE, and ACE2 mRNA, the presence of these RAS components in the chorionic villi indicates that they may be playing a role in both normal and preeclamptic pregnancies.

Angiotensinogen mRNA was found in our study to be present in normal and preeclamptic chorionic villi, which is consistent with earlier reports showing the presence of angiotensinogen in the human placenta, amnion, and chorion.31,32 Previous studies also show that angiotensinogen mRNA is present in the whole placenta throughout normal pregnancy.
starting at 6 weeks of gestation²³,³³ and in decidual spiral arteries in the first and second trimesters of normal pregnancy.³⁴ Angiotensinogen mRNA was higher in the chorionic villi obtained from preeclamptic subjects in our study. On the contrary, Herse et al²² found no significant difference in angiotensinogen mRNA levels in the placenta of normal versus preeclamptic pregnancies. The conflicting results of our study versus Herse et al²² may result from the fact that we investigated angiotensinogen expression exclusively in the chorionic villi, whereas the previous study used the whole placenta, including the amnion and chorion, possibly diluting the contribution of the chorionic villi. The upregulation of angiotensinogen in the chorionic villi of the preeclamptic placenta is consistent with an activation of the RAS in these tissues and may be the primary rate-limiting protein of the RAS in the chorionic villi.

Renin gene expression in the placenta of normal and preeclamptic pregnancies was previously studied by Shah et al,³⁵ where the placenta was microdissected into chorionic villous tissue, decidua basalis, and decidua vera. Our studies are in agreement with the results of Shah et al³⁵ in that we also found no significant difference in renin expression between normal and preeclamptic chorionic villous tissue. However, whereas there was a trend for higher renin mRNA in the preeclamptic chorionic villi, this did not reach statistical significance. Herse et al²² also found a trend for elevated renin expression in preeclamptic placental tissue. Measurements of total renin concentration and active renin were significantly higher in preeclamptic placentas,³⁶ which corroborates our data showing a possible trend for increased renin mRNA in the preeclamptic chorionic villi.

Ang II was significantly higher in preeclamptic when compared with normal pregnant chorionic villi and is consistent with the elevated angiotensinogen mRNA. Kalenga et al²⁴ found no difference in Ang II levels between normal and preeclamptic placentas, but differences in placenta dissection and experimental methodologies may contribute to the results observed. Interestingly, circulating Ang II is significantly downregulated in women with preeclampsia,¹⁹ suggesting a difference in circulating versus local chorionic villous RAS regulation in normal and preeclamptic women. The actions of elevated Ang II in the chorionic villi may contribute to vasoconstriction of the fetal blood vessels resulting in a decrease of maternal-fetal transport and, thus, contributing to the pathophysiology of preeclampsia.

There was no significant difference in Ang-(1-7) peptide levels in normal versus preeclamptic chorionic villi. A previous study done by our laboratory investigated the expression and localization of Ang-(1-7) and its generating enzyme, ACE2, by immunohistochemistry and found that both Ang-(1-7) and ACE2 were present in the cells of normal and preeclamptic chorionic villi, including the syncytiotrophoblast and cytotrophoblasts.²¹ Similar to the present study, we found no significant difference in the amount of Ang-(1-7) or ACE2 staining in normal versus preeclamptic chorionic villous syncytiotrophoblasts in the third trimester. Ang-(1-7) was decreased in the circulation of normal and preeclamptic women,¹⁹ again highlighting differences in local tissue versus circulating RAS. The fact that Ang-(1-7) did not change in the chorionic villi of preeclamptic women, whereas Ang II was increased suggests that the balance of these 2 biologically active peptides may be skewed toward the Ang II vasoconstrictor arm of the RAS.

The gene expression of the enzymes of the RAS, including ACE, ACE2, and NEP, were similar in normal and preeclamptic chorionic villi. Previous studies using quantitative reverse transcription, real-time PCR and radioenzymatic assay indicate that ACE expression does not differ between normal and preeclamptic placentas.²²,²⁴ However, a study by Ito et al³⁷ measured ACE in uncomplicated and preeclamptic villous tissue and found significant increases in ACE protein and mRNA in the preeclamptic placenta. Reasons behind the differences in the results are unclear. No change in ACE enzyme levels with a significant increase in angiotensinogen and Ang II suggests that the system is being driven by the increased substrate, although an increase in ACE activity cannot be ruled out. Consideration should also be given to other enzymes involved in the production of Ang II, such as chymase.

ACE2, an Ang-(1-7) generating enzyme, has been shown to be present in the chorionic villi of the human placenta by immunohistochemistry.²¹ We show for the first time the expression of ACE2 mRNA in the human placenta. Although no differences in ACE2 mRNA were observed between normal and preeclamptic tissues, its presence in the chorionic villi of the placenta indicates that it may play a role in the generation of Ang-(1-7). Studies investigating ACE2 activity are required to understand whether this enzyme participates in the increased level of Ang II in the presence of no change in Ang-(1-7). NEP, another enzyme with the potential to convert Ang I or Ang-(1-9) to Ang-(1-7), was not different in preeclamptic chorionic villi. A previous study showed that NEP is present in the placenta, including the trophoblast cells of normal and preeclamptic women as assessed by immunohistochemistry. The authors also observed a qualitative increase in NEP staining in the preeclamptic villous trophoblasts.³⁸ The presence and expression of NEP in normal placental villous tissue with no differences in preeclamptic women are consistent with the lack of change in either Ang I or Ang-(1-7) peptide levels in preeclamptic chorionic villi.

Although a number of studies have measured AT₁ receptors in the placenta of women with normal and preeclamptic pregnancies few have focused specifically on the chorionic villi. Moreover, there are conflicting reports in preeclamptic pregnancies few have focused specifically on the chorionic villi. In addition, there is a tight association of autoantibodies with the receptor, they may block the radioactive Ang II ligand from binding to the AT₁ receptors present in the tissue. If this
were the case, then the AT1 receptor density in the preeclamptic chorionic villi would appear to be lower than it actually is. However, more studies are needed to confirm this hypothesis. Regardless of whether there is an upregulation of AT1 receptors, the increase in Ang II content in preeclamptic chorionic villi strongly suggests that the downstream actions of Ang II may be playing a major role in the pathophysiology of preeclampsia.

AT2 receptor mRNA was below the detectable limits in the placental tissue, and results from receptor autoradiography show that the AT2 receptor levels were low in the chorionic villi. There was no difference in AT2 receptor density between normal and preeclamptic tissues consistent with several previously studies,22,41,44 In addition, mRNA levels of the Mas receptor, a reported Ang-(1-7) receptor,45 were lower in preeclamptic than normal chorionic villi. Low levels of the Mas receptor were also observed with the measurement of AT1 receptor density by autoradiography; however, there was no difference in the density between normal and preeclamptic chorionic villi. Taken together with the observed higher Ang II levels in preeclamptic placentae, the modest downregulation in Mas receptors and normal Ang-(1-7) peptide levels would shift the balance toward the vasoconstrictor arm of the RAS.

**Perspectives**

This study provides evidence for the presence and regulation of a local tissue-specific RAS in the chorionic villi of normal and preeclamptic women. Our results show that the chorionic villous RAS is dysregulated in preeclamptic women with a significant increase in Ang II, associated with the upregulation of angiotensinogen and AT1 receptor mRNAs. With no increase in Ang-(1-7) and a modest decrease in the Mas receptor, the balance of the 2 active peptides of the RAS is tilted toward Ang II in the preeclamptic chorionic villi, the components of the placenta that contain the fetal vessels and make up the cell barrier between maternal and fetal blood. Our results indicate that the major actions of Ang II, including vasoconstriction, will predominate and may be contributing to the pathophysiology of preeclampsia by decreasing the maternal-fetal exchange of vital oxygen and nutrients. In addition, this study, along with our previous findings, demonstrates that differential regulation exists between circulating and local chorionic villous RAS. Although ACE inhibitors are contraindicated during pregnancy, clinical strategies aimed at RAS regulation in preeclamptic women might be beneficial. However, therapeutic agents that do not cross the placental barrier should be used to target the local chorionic villous RAS rather than the systemic RAS as a whole.

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