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Regulatory T Cells Ameliorate Intrauterine Growth Retardation in a Transgenic Rat Model for Preeclampsia

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Abstract

Preeclampsia is a multisystemic syndrome during pregnancy that is often associated with intrauterine growth retardation. Immunologic dysregulation, involving T cells, is implicated in the pathogenesis. The aim of this study was to evaluate the effect of upregulating regulatory T cells in an established transgenic rat model for preeclampsia. Application of superagonistic monoclonal antibody for CD28 has been shown to effectively upregulate regulatory T cells. In the first protocol (treatment protocol), we applied 1 mg of CD28 superagonist or control antibody on days 11 and 15 of pregnancy. In the second protocol (prevention protocol), the superagonist or control antibody was applied on days 1, 5, and 9. Superagonist increased regulatory T cells in circulation and placenta from $8.49 \pm 2.09\%$ of CD4-positive T cells to $23.50 \pm 3.05\%$ and from $3.85 \pm 1.45\%$ to $23.27 \pm 7.64\%$, respectively. Blood pressure and albuminuria (30.6 ± 15.1 versus 14.6 ± 5.5 mg/d) were similar in the superagonist or control antibody-treated preeclamptic group for both protocols. Rats treated with CD28 superagonist showed increased pup weights in the prevention protocol (2.66 ± 0.03 versus 2.37 ± 0.05 g) and in the treatment protocol (3.04 ± 0.04 versus 2.54 ± 0.1 g). Intrauterine growth retardation, calculated by brain:liver weight ratio, was also decreased by the superagonist in both protocols. Further analysis of brain development revealed a 20% increase in brain volume by the superagonist. Induction of regulatory T cells in the circulation and the

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Disclosures

None.

uteroplacental unit in an established preeclamptic rat model had no influence on maternal hypertension and proteinuria. However, it substantially improved fetal outcome by ameliorating intrauterine growth retardation.

Keywords

fetal growth retardation; preeclampsia; pregnancy; T-lymphocytes; regulatory

Preeclampsia is characterized by new onset of maternal hypertension after 20th week of gestation and proteinuria or in association with thrombocytopenia, impaired liver function, the new development of renal insufficiency, pulmonary edema, or new-onset cerebral or visual disturbances.¹ It is a leading cause of maternal and perinatal morbidity and mortality worldwide, with a global incidence of 3% to 5% of all pregnancies. Preeclampsia originates in the placenta, but the underlying cause is complex and probably heterogeneous in origin.² Preeclampsia causes variable maternal and fetal problems, and intrauterine growth retardation (IUGR) is a common sequel of preeclampsia.^{1,2} Newborns with IUGR have structural and metabolic abnormalities that compromise their immediate development and also adversely affect their long-term cardiovascular and metabolic outcomes.³

Recently, dysregulation of immune mechanisms have been implicated in preeclampsia and IUGR, leading to a pathological maternal immune recognition of the trophoblast, resulting in abnormal placentation and an imbalance between factors produced by the placenta and maternal adaptation to them.⁴ A genetically foreign fetus (presented as extravillous trophoblast cells in the maternal uterine wall) challenges the maternal immune system, and both innate and adaptive immune cells are necessary for several important processes during pregnancy for normal maternal physiology leading to a robust fetal development.^{4,5}

One CD4⁺ lymphocyte subset, CD4⁺CD25⁺FoxP3⁺ regulatory T cells (Tregs) play an important role in maintaining immunologic tolerance. They are induced by tolerogenic dendritic cells and home to the uterus before implantation.⁶ Tregs are necessary for implantation and maintenance of early pregnancy. An association between the number of Tregs and implantation failure or recurrent spontaneous miscarriage in humans and mouse models has been demonstrated.^{7,8}

Several authors have proposed that defective control of effector T cells by Tregs leads to an increased T helper 17 (Th17) and increased Th1/Th2 balance, causing maternal hypertension, associated clinical manifestations, and poor placentation with IUGR. Reduced numbers of Tregs in preeclamptic patients have been reported by several groups.^{4,9,10} However, experimental evidence is scarce. In a previous study, adoptive transfer of pregnancy-induced CD4⁺ CD25⁺ Tregs reversed the increase in the abortion rate caused by interleukin 17 in a mouse model.¹¹ We reasoned that Treg upregulation might ameliorate the preeclamptic phenotype in an established animal model of preeclampsia and possibly favorably influence IUGR.

A rodent model for preeclampsia by mating female rats transgenic for human angiotensinogen with rats transgenic for human renin has been established.^{12,13} Dams

exhibit an increase in blood pressure from 100/80 mm Hg to 180/140 mm Hg, develop proteinuria, a pathological trophoblast invasion, and display uteroplacental vascular remodeling.¹⁴ Fetuses develop IUGR with an increased brain:liver ratio compared with normal Sprague-Dawley rats.¹⁵ We have shown previously that Tregs ameliorate angiotensin II-induced target-organ damage¹⁶; CD28 is a costimulatory receptor required for activation of T cells. We used a well-established rat specific monoclonal superagonistic antibody for CD28 (JJ316), which has been shown in various experimental models to expand and upregulate Tregs and their function in vivo.^{17,18} We have tested the hypothesis that application of the superagonistic antibody for CD28 will induce regulatory T cells during pregnancy and ameliorate hypertension and proteinuria, as well as IUGR in our preeclamptic rat model.

Methods

Animals and Protocol

Female rats transgenic for human angiotensinogen were mated with male rats transgenic for human renin. Pregnant dams developed hypertension on day 13 of pregnancy (plug-recognition day is assigned as day 1) and albuminuria.¹⁹ We also used Sprague Dawley rats to compare with pregnant dams. Both transgenic rats are of Sprague Dawley background. Local authorities approved the studies, which were performed according to American Physiological Society guidelines. During telemetry implantation, tail-cuff measurements and termination rats were anaesthetized using isoflurane.

We established 2 protocols, a treatment protocol and a prevention protocol (Figure S1 in the online-only Data Supplement). We have performed all treatments using monoclonal superagonistic antibody specific to rat CD28 (clone JJ316) that has been previously described and can induce Tregs without the involvement of T-cell receptor.²⁰ We used the same isotype monoclonal antibodies (MOPC-21) as control (vehicle).

For the treatment protocol, pregnant rats were transferred to a metabolic cage on days 10 and 17 for 24 hours each. On days 11 and 15, 1 mg of JJ316 was given by intraperitoneal injection. For the prevention protocol, rats were injected on days 1, 5, and 9 with 1 mg of JJ316. To investigate blood pressure, tail-cuff measurements were performed on days 8, 13, 15, and 18 of pregnancy. In selected rats as indicated, radiotelemetry was used to follow blood pressure. Rats were transferred to metabolic cage for 24 hours at days 8 and 17.

All experimental animals were euthanized on day 21. Fetuses were weighted and their brains were removed from the skulls for analysis. Maternal and fetal organs were collected and weighed. Urinary rat albumin was measured with a commercially available ELISA (CellTrend, Germany). Creatinine was determined in serum by an automated clinical method.

Expanded methods are described in the online-only Data Supplement.

Results

Fewer Tregs in Preeclamptic Placentas

We first investigated whether T or B cells are dysregulated in the placenta of our transgenic preeclamptic rat model, compared with controls (Figure 1A). CD4⁺ cells (Figure 1B) and CD8⁺ T cells (Figure 1C) were not significantly different on day 15 of pregnancy between the 2 groups. However, Tregs were markedly reduced in placentas ($25.37 \pm 7.60\%$ versus $3.85 \pm 1.45\%$ of CD4⁺ cells; $P < 0.05$) of preeclamptic rats compared with control rats (Figure 1D). B cells (CD45R⁺) were not different in the placenta from the 2 groups (data not shown).

CD28-Superagonist Treatment Normalizes Placental Tregs

A representative flow cytometry analysis is shown in Figure 2A, gated for FoxP3 and CD25 from a preeclamptic placenta derived from a dam treated with control antibody (vehicle; left) or with CD28 superagonist (JJ316; right). Tregs were increased from $3.85 \pm 1.45\%$ to $23.27 \pm 7.64\%$ of CD4⁺ T cells measured on day 15 and from $8.52 \pm 1.93\%$ to $23.93 \pm 7.88\%$ on day 21 in preeclamptic placenta (Figure 2B). These levels corresponded to Treg frequencies from control pregnant rats, so that JJ316 treatment normalized placental Treg levels during the last trimester of pregnancy. We found a similar upregulation of Tregs in blood (Figure 2C) and spleen (Figure 2D) on days 15 and 21 after JJ316 application, compared with vehicle in preeclamptic rats. We additionally analyzed other subsets of T cells (Figure S3). Memory T cells (CD3⁺CD4⁺CD45R⁻), naive T cells (CD3⁺CD4⁺CD45R⁺), general cytotoxic T cells (CD3⁺CD8⁺CD45R⁻), and their subpopulation suppressor effector T cells (CD3⁺CD8⁺CD45R⁺) were not imbalanced in spleen, blood, and placenta at days 15 and 21 of pregnancy.

No Influence on Hypertension and Proteinuria

To investigate the effect of JJ316 on the preeclamptic phenotype, we used 2 different strategies (Figure S1). In the treatment protocol, we applied JJ316 or vehicle when blood pressure increased at day 11. For the prevention strategy, JJ316 or vehicle was given after mating so that Tregs were upregulated during implantation and placental development. For the treatment strategy (Figure 3A), we observed no effects on blood pressure over the course of pregnancy, as measured by radiotelemetry (Figure 3A, left), no improvement in albuminuria (Figure 3A, right top) or effects on serum creatinine (Figure 3A, right bottom). Maternal organs from treated rats showed similar weights compared with control, except spleen, which was heavier (0.45 ± 0.06 versus 0.66 ± 0.04 g; data not shown) and corresponds to the findings of previous studies and is because of the increase in CD4 T-cell numbers.²⁰ Previous application of JJ316 (Figure 3B) did not alter the results, which we observed with the treatment protocol. Early upregulation of Tregs did not alter blood pressure (Figure 3B, left), albuminuria (Figure 3B, right top), or creatinine (Figure 3B, right bottom) in preeclamptic rats.

Upregulation of Tregs Is Associated With Improved IUGR

We recorded increased fetal weights (2.54 ± 0.10 versus 3.04 ± 0.04 g, $P < 0.005$) in preeclamptic rats treated with JJ316 compared with control antibody-treated preeclamptic rats (Figure 4A). Interestingly, the effect on mean fetal weight was mediated by reducing the numbers of markedly underdeveloped pups (<10th percentile). The effect on fetuses <the 10th percentile (Figure 4B and 4C) showed that Treg upregulation was predominantly successful in the smaller pups.

The IUGR ratio is calculated by dividing the weight of fetal brains by the weight of fetal livers. This ratio (Figure 4D) was improved by 30% in the JJ316-treated group (1.05 ± 0.07 in controls versus 0.72 ± 0.02 ; $P < 0.0001$). Brain is the paramount organ in fetal development. Brain weights (Figure 4E) in the treatment group were heavier (0.14 ± 0.00 in controls versus 0.16 ± 0.00 g; $P < 0.05$). Liver weights (Figure 4F) were substantially increased in the treatment group (0.155 ± 0.01 in controls versus 0.22 ± 0.01 g; $P < 0.0001$), indicating that Treg upregulation could overcome the brain sparing effect of IUGR in our preeclamptic rat model. Similar effects were observed when JJ316 was applied early during placental development (prevention protocol). Fetal weights (Figure 4G) were significantly reduced with a dominant effect on fetuses below the 10th percentile (Figure 4H and 4I). IUGR was significantly reduced (Figure 4J), showing a mild increase in brain weight (Figure 4K) but significant upregulation of liver weight (Figure 4L).

Further analysis of brain development revealed that JJ316 induced a 20% increase in brain volume (23.21 ± 0.66 versus 29.36 ± 2.46 mm³; $P = 0.04$; Figure 5A). Cellular density was determined in 4 regions of interest: cortex, hippocampus, thalamus, and striatum. Representative brain sections are shown in Figure 5B. In all 4 brain regions, treatment with JJ316 induced a higher cellular density compared with controls (Figure 5C). These effects were also present in the late treatment group, however, to a lesser degree (Figure S4). Notably, analysis of the different neural cell types revealed a profound increase of mature neurons (neuronal nuclei positive) in the developing cortex of animals treated with JJ316 (0.87 ± 0.06 versus 1.27 ± 0.05 ; $P = 0.0005$), whereas neither immature neurons (doublecortin positive) nor microglia (ionized calcium-binding adapter molecule 1 positive), and oligodendrocytes (Oligodendrocyte transcription factor positive) showed obvious differences in staining intensities. Furthermore, reactive astrogliosis (glial fibrillary acidic protein positive) was downregulated in cortical (0.77 ± 0.6 versus 0.69 ± 0.03) and hippocampal areas (0.88 ± 0.07 versus 0.67 ± 0.04 ; $P = 0.03$; Figure S6).

Placental Development

We found no influence on angiogenesis profile and trophoblast invasion by upregulation of Tregs in the placenta. We also investigated whether the angiogenesis profile of the placenta (fetal tissue) or mesometrial triangle (maternal tissue with fetal cells invading the area) was altered. However, mRNA expression of placental growth factor and soluble fms-like tyrosine kinase-1 was not altered in the placenta or mesometrial triangle after JJ316 (Figure S5A). We next investigated whether Treg upregulation had an effect on uteroplacental morphology and trophoblast cell invasion. JJ316 treatment did not change placental area (Figure S5B) and did not influence the relationship between labyrinth and trophospongium area (data not

shown). We also found no difference in the area of the mesometrial triangle (Figure S5C) and the area of interstitial trophoblast cell invasion into the mesometrial triangle (Figure S5D).

Autoantibodies Against the Angiotensin II Receptor Type 1 Receptor

Because this preeclampsia model features autoantibodies directed to angiotensin II receptor type 1 autoantibodies (AT1-AA), we next investigated whether Treg upregulation could influence AT1-AA.¹² Both early and late application of JJ316 reduced the presence of AT1-AA (Figure 6A and 6B).

Discussion

We have shown that Tregs are reduced in the uteroplacental unit in our preeclamptic rat model. We were successful in restoring Tregs in preeclamptic placentas of our animals, as well as in maternal circulation and spleen. However, increasing Tregs did not ameliorate the maternal phenotype. Importantly, we improved IUGR, reversed the brain sparing effect, showed improved brain size with an increase in mature neurons, and reduced reactive astrogliosis in the cortex, indicating an improved fetal development. Interestingly, we reduced the number of severely retarded pups (<10th percentile). The improvement of fetal outcome was independent of altering the antiangiogenic balance and of altering trophoblast cell invasion in the uteroplacental unit, although we reduced AT1-AA. We think that the improvement of fetal outcome, independent of reducing hypertension, deserves further attention.

Tregs play an important role in regulating immune tolerance in pregnancy. The invading fetal trophoblast cells are recognized by the maternal immune system, and Tregs suppress reactive cells so that a transient state of tolerance of specific paternal alloantigens is achieved.⁵ Presentation of paternal antigens on invading fetal trophoblasts and their interaction with Tregs besides uterine natural killer cells are responsible not only for suppression of antifetal cytotoxic T cell responses but also for long-term immunologic memory.²¹ Tregs are expanded already before implantation.

In the setting of preeclampsia, little is known about the role of Tregs. Sasaki et al^{4,5,8} reported reduced Tregs in circulation and in placental bed biopsies of preeclamptic patients compared with those in normal pregnancy. These findings suggest that a decreased number of Tregs might break the maternal tolerance to the fetus. However, others found no differences in Treg numbers between healthy and preeclamptic pregnancies.²² The reason why Tregs are reduced in preeclampsia is unknown. Inflammation at the decidua might impair the immunoregulatory function of Tregs.²³ Tregs suppress systemic and mucosal activation to control inflammation. Therefore, decreased Tregs might augment systemic inflammation in preeclampsia, so that a vicious circle is induced.⁸

Tregs are needed for a successful allogeneic pregnancy in mice. These Tregs expand during pregnancy, induced by paternal antigens, and prevent rejection of the fetus. Zenclussen et al²⁴ showed that allogeneic fetuses are rejected when CD4+CD25+ Tregs are absent and adoptive transfer of CD4+CD25+ Tregs improved the phenotype. Treatment with anti-CD25

monoclonal antibodies during implantation period induced implantation failure in allogeneic but not in syngeneic pregnant mice.⁷ Anti-CD25 monoclonal antibodies treatment in the late pregnancy phase reduced the Tregs in a similar manner to treatment during the implantation period, but interestingly, this treatment did not induce preeclampsia symptoms, such as hypertension and proteinuria. Thus, although Tregs seem to be necessary for implantation and the early phase of pregnancy, they may not have a critical role in the maintenance of pregnancy in the late gestation phase. Our data also show a more pronounced effect on brain development by early upregulation of Tregs.

We expanded the effects of preeclampsia on IUGR on investigating the fetal brain around time of delivery (21st embryonic day) in our experimental model. In addition to poor pup somatic growth, the present experiments revealed an obvious abnormality on brain development with reduced cellular density in cortex, hippocampus, thalamus, and striatum. Increasing Tregs by injection of JJ316 restored brain growth by increased number of mature cortical neurons and decreased astrogliosis. Moreover, it increased fetal weight and reduced the number of severely retarded offsprings. In other experimental models of IUGR, induced by unilateral ligation of the uterine artery, significant delays in oligodendrocyte differentiation and myelination that resolved at adult age have been observed.^{25,26} Whether reduction of brain growth shown in our model is a temporary phenomenon needs to be investigated in postnatal studies up to adult age where myelination and synaptic formation can be assessed.

JJ316 causes preferential expansion of Tregs compared with conventional T cells and enhances their suppressive activity.¹⁷ Tregs expand numerically, are functionally hyperactive, and migrate to inflamed tissues in rats after JJ316 treatment.¹⁷ Accordingly, CD28 superagonists have been used effectively in the treatment of rodent models of autoimmunity, such as experimental autoimmune neuritis and encephalitis, arthritis, tumor necrosis factor–induced bone destruction, and unwanted T-cell responses in transplantation of both solid organs and hematopoietic stem cells. CD28 superagonist has also been used in rodent models with cardiovascular endorgan damage, such as cardiac remodeling after myocardial infarction, diabetes mellitus, and glomerulonephritis.^{17,18} We do not know the mechanisms by which increased numbers of Tregs ameliorated IUGR in our model. We observed neither a change in the local angiogenic profile nor an improvement in trophoblast invasion. The rat model itself does not show all key features of human preeclamptic placental pathology, namely the deeper trophoblast invasion. Nevertheless, several other features are in concordance to the human situation. Vessels which had been invaded by endovascular trophoblasts show a higher presence of vascular smooth muscle cells, indicating that the trophoblasts are remodeling the vessels to a lesser extent, although they migrate deeper. In 2 interventional studies, we already could show that the trophoblast function can be altered.^{14,15} However, we observed a reduction in AT1-receptor autoantibodies. Previous studies have shown that increased T cell differentiation into a proinflammatory phenotype leads to an increased number of inflammatory T helper cells and possibly B cell stimulation for AT1-AA production.^{27,28} Adoptive transfer of CD4⁺ T cells from preeclamptic rats (reduced uterine perfusion pressure model) induced a preeclamptic phenotype and generation of AT1-AA.²⁷ Administration of Abatacept, a fusion

molecule of cytotoxic T-lymphocyte-associated protein 4, reduces T cells and hypertension in reduced uterine perfusion pressure rats, as well as AT1-AA production.²⁸

Our data elucidate novel aspects on AT1-AA in preeclampsia. Although we did not aim at elucidating the precise molecular mechanism of Treg-induced improvement of fetal brain development, our data are in line with the concept that Tregs control autoantibody-induced inflammation and antibody production.²⁹ In this study, we have not considered the interaction between Tregs and regulatory B cells induced by the CD28 superagonist. Regulatory B cells restrain excessive inflammatory responses that occur during autoimmune diseases and might be involved in reducing AT1-AA. Tacke et al²⁰ showed that B cells are activated in spleen and lymph nodes after 3 and 7 days in response of superagonist application. The effect is mediated via T-cells because there is no upregulation of B cells in response to superagonist application. We know from human studies that AT1-AA are present in the fetal circulation of preeclamptic women.³⁰ Recently, Cipolla et al³¹ could show that plasma from preeclamptic women induce hyperexcitability in the brain through activation of microglia in the maternal brain. In a follow-up study, they could show that neuroinflammation and activation of microglia are present in reduced uterine perfusion pressure rats, a different rodent model for preeclampsia with established pathophysiological role for AT1-AA.³² Girardi et al³³ could show in a recent study that autoantibodies can be detected in vivo in placenta and fetal brain by a magnetic resonance imaging-based method. They could show that autoantibodies induce IUGR and fetal brain retardation with cortical axonal cytoarchitecture disruption and increased neurodegeneration.

This study does not necessarily question the role of AT1-AA in preeclampsia or vascular pathology. In general, Treg induction led to significantly lower AT1-AA levels; nevertheless, they were still present and above the cut-off. Future studies will have to determine whether a critical cut-off level might be important. In a previous study, we had shown that AT1-AA alone were not capable of inducing hypertension but only pro-teinuria in pregnant rats.³⁴ Although together with a subthreshold angiotensin II level, they induced an increase in blood pressure. Others have shown that passive transfer of AT1-AA induces preeclampsia-like symptoms in mice and rats.^{28,35} We learn that AT1-AA are complex and their mode of action is only poorly understood, a phenomenon which AT1-AA share with many other autoantibodies in rheumatology, nephrology, and endocrinology.

Novel drugs to improve maternal and fetal health in preeclampsia have not been developed in the past decade. Nonspecific interventions, especially antihypertensive therapy, failed to improve the clinical manifestations and prolong pregnancy. A large meta-analysis reported a relationship between treatment-induced reduction of blood pressure and impaired fetal growth.³⁶ Recently, Thadhani et al³⁷ presented preliminary data that extracorporeal apheresis might prolong pregnancy.

The concept of developing effective and safe treatment application that promotes generation of tolerogenic dendritic cells and differentiation and maintenance of Treg phenotype is appealing. One possible dietary approach was introduced by Park et al.³⁸ They showed that short-chain fatty acids, an important microbial metabolite, are able to upregulate effector and Tregs. The authors found that the cytokine milieu and immunologic context were important

for the effect. Tregs were increased by short-chain fatty acids under the steady conditions in vivo, whereas effector T cells, such as Th17, were increased only during active immune responses. Further studies will have to determine whether dietary interventions are able to upregulate Tregs during pregnancy and whether this leads to improved fetal health.³⁹

Perspectives

Other than optimizing nutrition, few strategies are available for ameliorating IUGR. Our findings suggest a role for Tregs. We speculate that CD28 superagonist strategy or alternative approaches to mobilize Tregs might help offspring in which IUGR is anticipated. Importantly, after a dramatic failure in the First-in-human (FIH) trial in 2006, in which a life-threatening cytokine release syndrome (CRS) was observed,⁴⁰ human CD28-SA treatment has re-entered clinical development and effectively activates Tregs if appropriately dosed.⁴¹

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Novelty and Significance

What Is New?

- We demonstrate that regulatory T cells are reduced in the uteroplacental unit in an established transgenic rodent model for preeclampsia. We report the first interventional study of upregulating regulatory T-cells in this model.

What Is Relevant?

- Upregulation of regulatory T cells has no effect on maternal phenotype of preeclampsia (hypertension and proteinuria), but it ameliorates intrauterine growth restriction. Brain development is improved by administration of regulatory T cells. Moreover, the presence of activating autoantibodies against the AT1-receptor is reduced, indicating a beneficial effect on altered autoimmunity.

Summary

This study demonstrates a role for inducing regulatory T-cells in fetal development and outcome in the pathophysiology of preeclampsia.

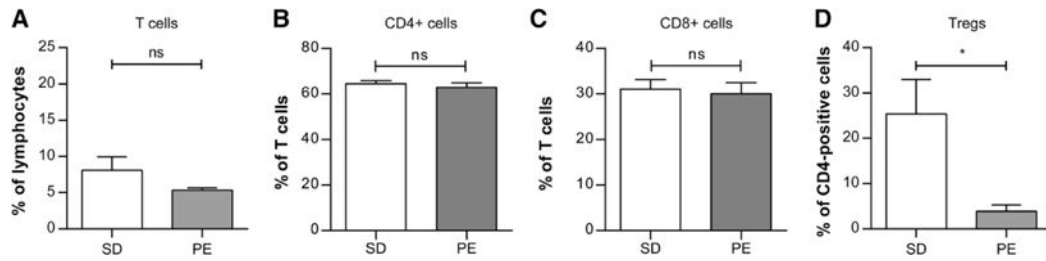


Figure 1.

T-cell repertoire in the placenta of healthy and preeclamptic pregnant rats on day 15. **A**, Frequencies of total CD3⁺ T cells were not different in healthy pregnant rats compared with preeclamptic. **B** and **C**, Levels of CD4⁺ and CD8⁺ cells were presented as percentages of T-cell population and showed no difference in the 2 groups. **D**, Frequencies of double positive (CD25⁺FoxP3⁺) Tregs are presented as percentages of CD4⁺ T cell population and were significantly reduced in preeclamptic placentas. Data are shown as mean±SEM. Mann–Whitney *U* test was used. **P*<0.05. ns indicates nonsignificant; PE, preeclamptic rats; and SD, Sprague Dawley.

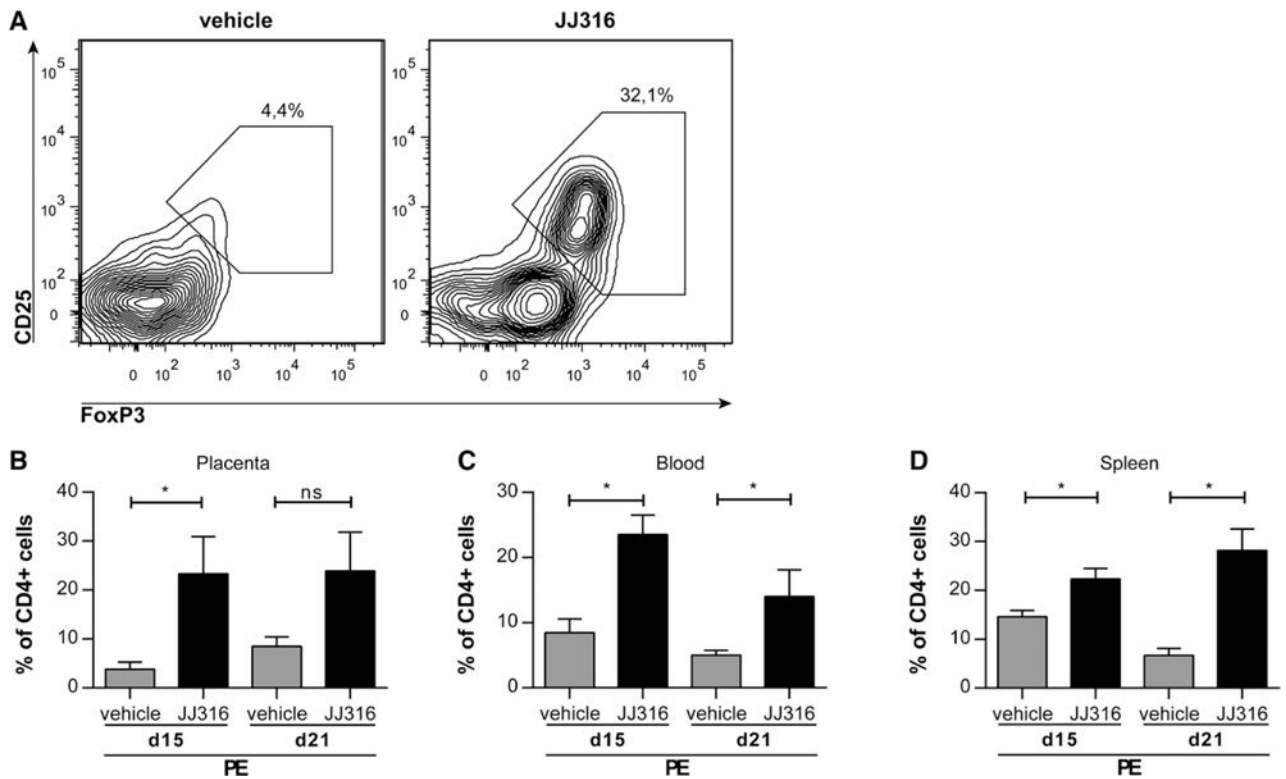


Figure 2.

JJ316 resulted in expansion of Tregs in placenta, circulation, and spleen of preeclamptic rats. Representative flow cytometry analysis for Tregs gate ($CD25^+FoxP3^+$) in placenta of vehicle and JJ316 treated rats (A). Elevated levels of Tregs in placenta (B), blood (C), and spleen (D) after treatment with JJ316 compared with vehicle in preeclamptic rats. Data are shown as mean \pm SEM; n=3 to 5. * P <0.05. ns indicates nonsignificant; and PE, preeclamptic rats.

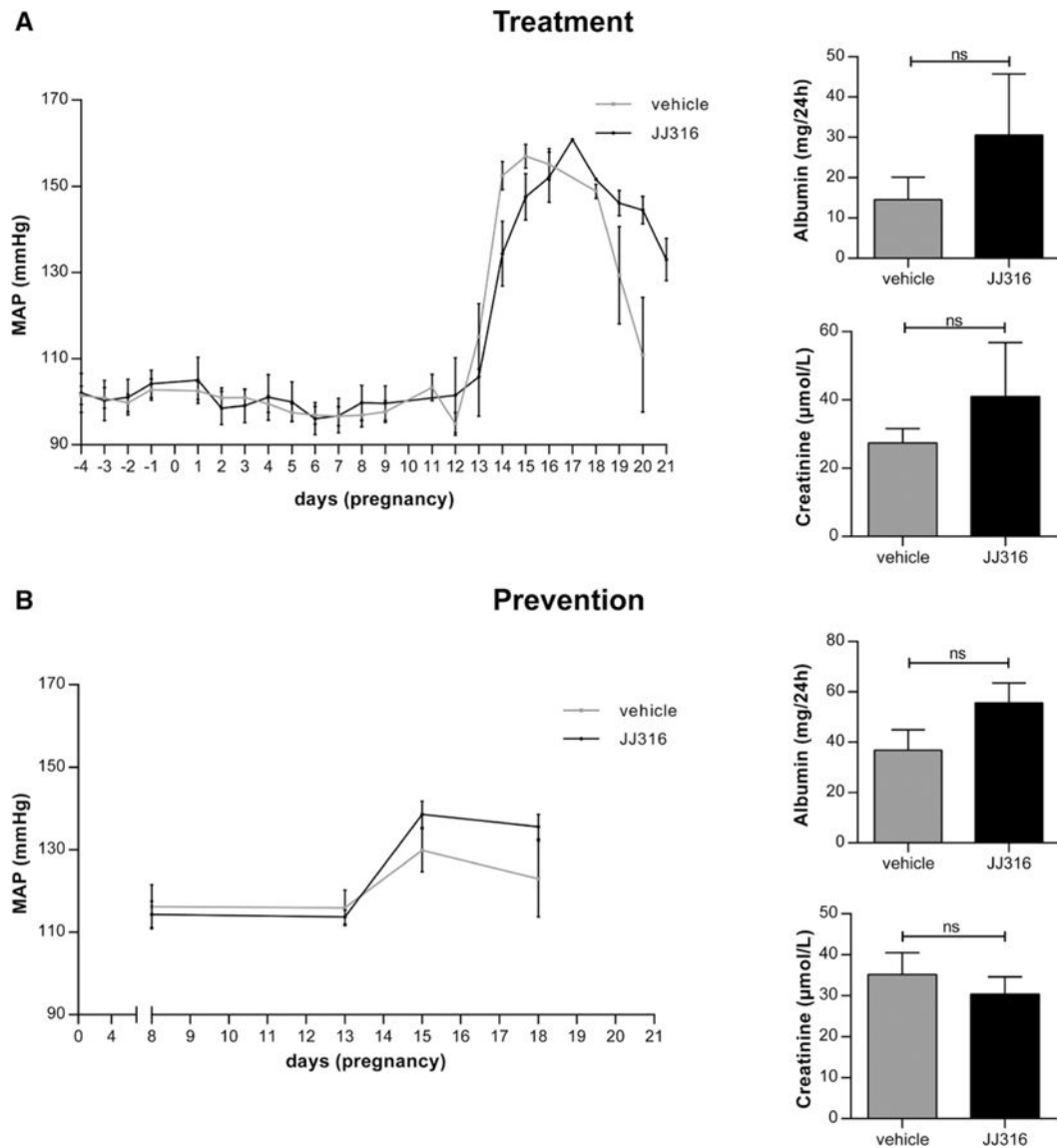
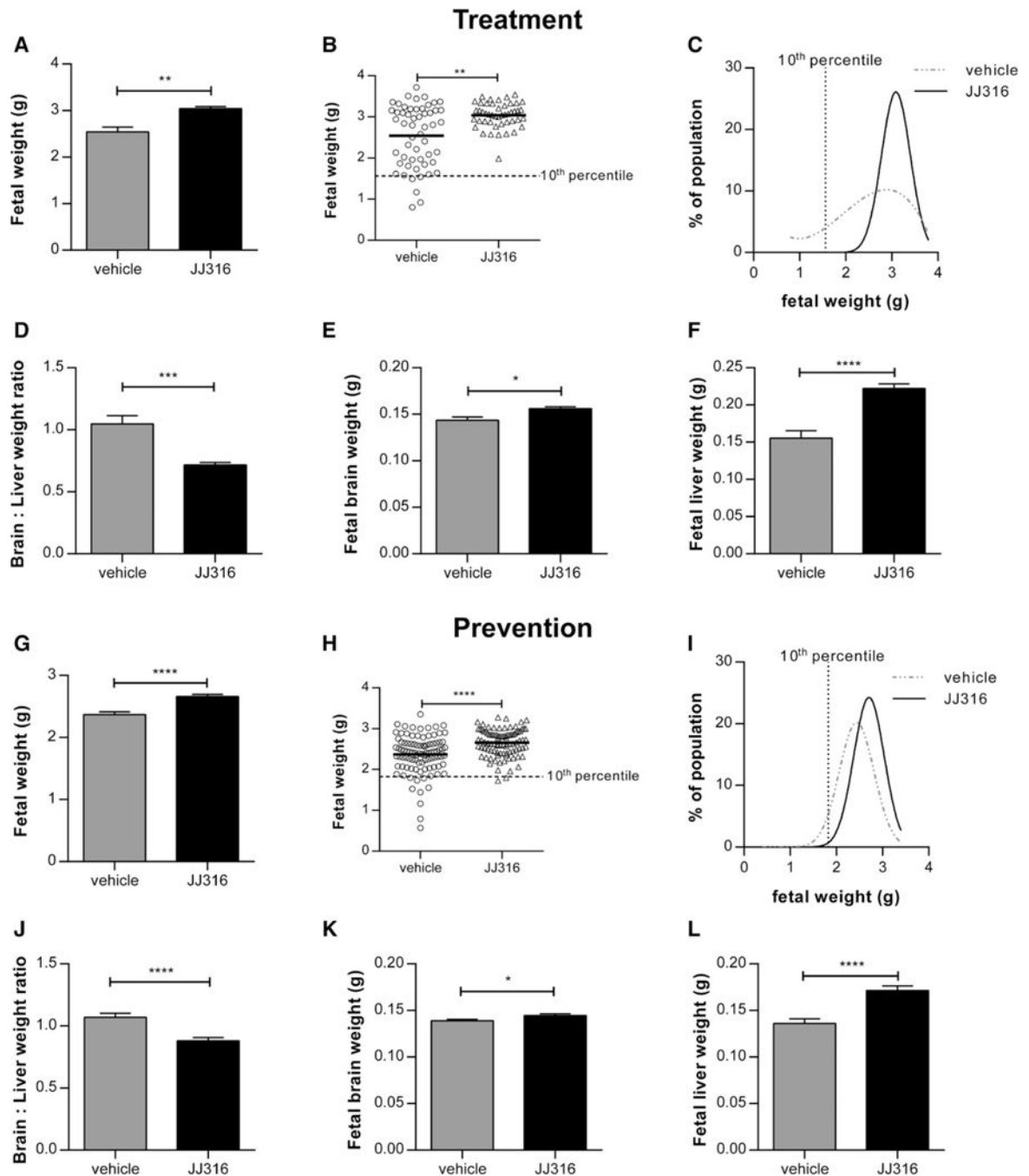


Figure 3.

Treatment with JJ316 does not ameliorate maternal preeclampsia in either treatment (**A**) or prevention protocol (**B**). **A**, Mean arterial blood pressure (MAP) measured by telemetry was not significantly different between groups (**left**). Total albumin secretion in urine gathered during 24 hours in metabolic cage from days 17 to 18 of pregnancy in treatment (**right top**) and creatinine concentration in serum at day 21 of pregnancy (**right bottom**) showed no significant differences. **B**, Blood pressure measured by tail cuff (**left**), proteinuria (**right top**) and serum creatinine (**right bottom**) were similar for both groups when JJ316 was applied early after mating. ns indicates nonsignificant.

**Figure 4.**

Treg upregulation improved fetal outcome reducing intrauterine growth restriction in treatment (A–F) and prevention protocols (G–L). Fetal weights are increased after application of JJ316 in the treatment protocol (A and B; n=54 vs 47) and in the prevention protocol (G and H; n=96 vs 93). A marked reduction of pup weights <10% after JJ316 treatment is achieved (C and I). Intrauterine growth restriction is shown as the ratio fetal brain:liver weights and reduced for both strategies (D and G). Brain weight is slightly increased (E and K), whereas JJ316 markedly increased liver weight (F and L), reducing the

brain sparing influence of intrauterine growth retardation. Data are shown as mean±SEM.
* $P<0.05$, ** $P<0.01$, *** $P<0.001$, **** $P<0.0001$.

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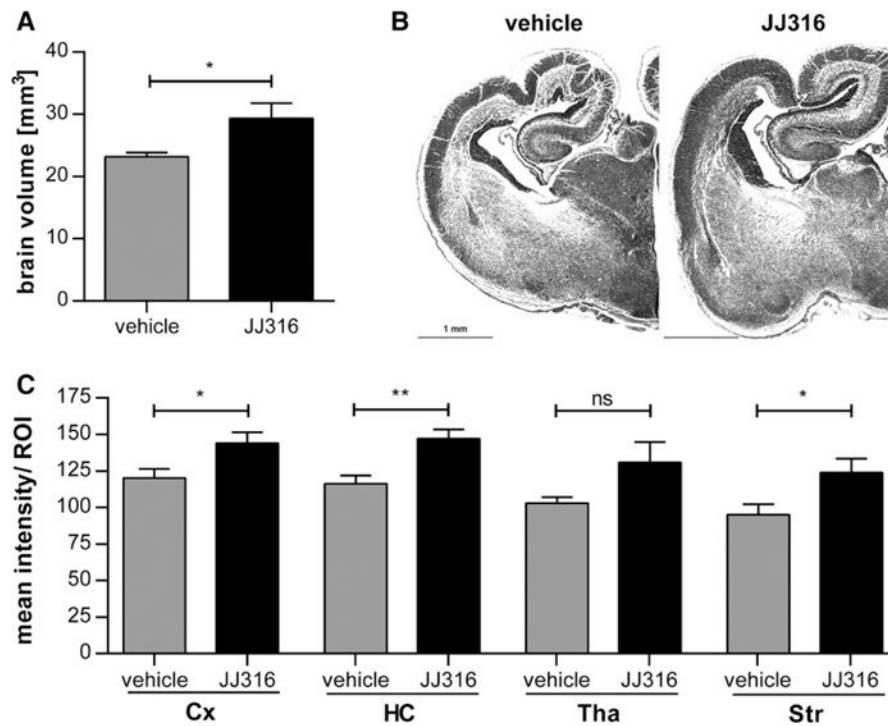


Figure 5. Administration of JJ316 improves brain development of the fetus. Brain volume was increased after early treatment with JJ316 compared with control (A). A representative fetal brain is shown in B. Cell density is measured in 4 regions of interests: cortex (Cx), hippocampus (HC), thalamus (Tha), and striatum (Str) and revealed a significant increase after JJ316 treatment (C). ns indicates nonsignificant; and ROI, region of interest. * $P < 0.05$, ** $P < 0.01$.

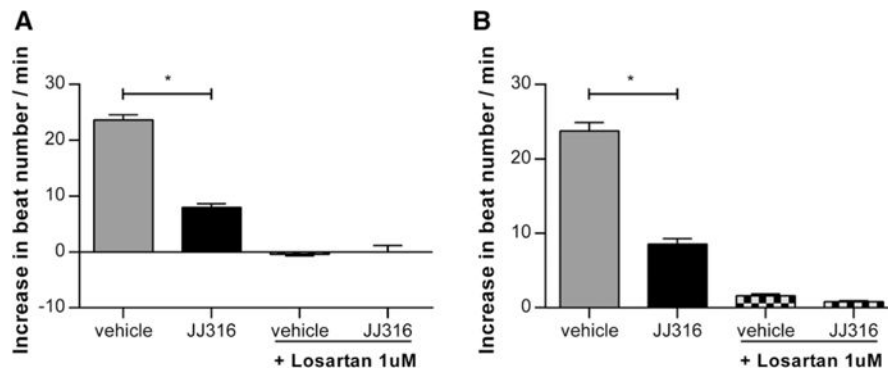


Figure 6.

Treatment with JJ316 decreases the concentration of angiotensin II receptor type 1 autoantibodies (AT1-AA) in serum of pregnant preeclamptic rat model. Isolated rat neonatal cardiomyocytes were treated in vitro with IgG from vehicle or JJ316-treated rats. Data are presented as an increase of beating rate of cardiomyocytes after treatment with IgG from prevention (**A**) and treatment (**B**) protocols compared with baseline. Administration of AT1 receptor blocker (Losartan) was used to show that the effect is mediated via the AT1 receptor. Mean of 6 view fields per treatment was used in analysis. Data are shown as mean \pm SEM. Mann–Whitney *U* test was used. * $P < 0.05$.