Cerebral vascular adaptation to pregnancy and its role in the neurological complications of eclampsia

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Cipolla MJ, Sweet JG, Chan SL. Cerebral vascular adaptation to pregnancy and its role in the neurological complications of eclampsia. J Appl Physiol 110: 329–339, 2011. First published November 11, 2010; doi:10.1152/japplphysiol.01159.2010.—The cerebral circulation has a central role in mediating the neurological complications of eclampsia, yet our understanding of how pregnancy and preeclampsia affect this circulation is severely limited. Here, we show that pregnancy causes outward remodeling of penetrating arterioles and increased capillary density in the brain due to activation of peroxisome proliferator-activated receptor-γ (PPARγ), a transcription factor involved in cerebrovascular remodeling and highly activated in pregnancy. Pregnancy-induced PPARγ activation also significantly affected cerebral hemodynamics, decreasing vascular resistance and increasing cerebral blood flow by ~40% in response to acute hypertension that caused breakthrough of autoregulation. These structural and hemodynamic changes in the brain during pregnancy were associated with substantially increased blood-brain barrier permeability, an effect that could promote passage of damaging proteins into the brain and cause the neurological complications of eclampsia, including seizure.

cerebral blood flow; cerebral vascular resistance; acute hypertension; peroxisome proliferator-activated receptor γ; vascular remodeling

PREECLAMPSIA is a serious complication of pregnancy that becomes life-threatening when neurological symptoms, including severe and persistent headache, cortical blindness, and seizure, accompany hypertension and proteinuria in the last half of pregnancy (14, 32, 40). While it is seizure that distinguishes eclampsia, numerous neurological symptoms can precede the eclamptic convulsion in what is considered severe preeclampsia (32, 40). The primary explanation for the neurological symptoms of severe preeclampsia and eclampsia is that they represent a form of posterior reversible encephalopathy syndrome in which an acute elevation in blood pressure, secondary to the preeclamptic state, causes breakthrough of autoregulation, blood-brain barrier (BBB) disruption, and passage of damaging protein and serum constituents into the brain (14, 23, 40). In addition to BBB disruption, the eclamptic seizure is associated with intracerebral hemorrhage that can further promote neurological complications and threaten the life of the mother and fetus (40).

Although the cerebral circulation has a central role in the pathogenesis of the neurological complications of severe preeclampsia and eclampsia, our understanding of how pregnancy and preeclampsia affect this unique circulation is severely limited. Because women who develop preeclampsia and eclampsia are by definition asymptomatic and normotensive before and for the first half of pregnancy, we have hypothesized that the cerebrovascular adaptation to normal pregnancy predisposes the brain to neurological complications when blood pressure is acutely elevated, as in severe preeclampsia and eclampsia.

Pregnancy is a condition of profound cardiovascular adaptation with major alterations in both local and systemic hemodynamics (13, 15, 29, 30). The pregnant state is characterized by decreased vascular resistance, hyperpermeability, and increased cardiac output, which are necessary to accommodate the considerable expansion of plasma volume and perfuse vital organs such as the uterus and placenta (13, 15, 29, 30). While such changes are considered adaptive for the cardiovascular system in general, similar hemodynamic changes in the brain during pregnancy (including diminished vascular resistance and hyperpermeability) increase the potential for edema formation, elevated intracranial pressure, and other neurological complications. This risk becomes even greater under conditions of severely elevated blood pressure, such as that seen during severe preeclampsia and eclampsia (14, 23, 40).

Here we investigated how normal pregnancy affects the cerebral circulation under normotensive and acutely hypertensive conditions to mimic hydrostatic pressure changes that occur during severe preeclampsia and eclampsia (14, 23, 40). We used in vivo and in vitro models to study the effect of pregnancy, with and without acute hypertension, on BBB permeability and hemodynamic alterations in the brain, including cerebral vascular resistance (CVR), cerebral blood flow (CBF), and capillary density. We found that pregnancy alone increases BBB permeability in response to acute hypertension through an effect that appears to be due to decreased CVR driven by outward remodeling of small penetrating arterioles and increased capillary density in the brain.

Peroxisome proliferator-activated receptor-γ (PPARγ) is a transcription factor that has an important role in pregnancy, including placental development and changes in maternal metabolism (20, 35, 37). The presence of dominant negative mutations of PPARγ in humans produces early-onset hypertension and preeclampsia (2). PPARγ also has prominent effects on the cardiovascular system (34), particularly in the cerebral circulation where it affects both structure and function (3, 9, 21). Thus we also investigated the role of PPARγ as an underlying mechanism by which pregnancy causes outward remodeling, increased capillary density, and decreased vascular resistance in the brain.

MATERIALS AND METHODS

Animal model of pregnancy. All experiments were conducted using virgin nonpregnant (NP) female (280–320 g) or timed-pregnant Sprague-Dawley rats (Charles River). Rats were housed in the Animal

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Pregnancy Facility at the University of Vermont, an Association for Assessment and Accreditation of Laboratory Animal Care-accredited facility. Rats are a useful model of pregnancy because they have similar placenta (hemochorial) and cerebrovascular anatomy as humans and a short gestation period (22 days). Pregnant rats were used for experimentation as late-pregnant (LP; day 19 or day 20) as this is when neurological complications of severe preeclampsia and eclampsia occur most often (14, 40). All animal protocols and procedures were approved by the Institutional Animal Care and Review Board at the University of Vermont.

PPAR\textsubscript{\gamma} inhibition/activation. To investigate the role of PPAR\textsubscript{\gamma} in changes in hemodynamics associated with pregnancy, two groups of animals were used and compared with NP and LP control animals. First, a group of NP animals was treated with the PPAR\textsubscript{\gamma} activator rosiglitazone (20 mg/kg) daily in food for 10 days to mimic the increase in PPAR\textsubscript{\gamma} activation that occurs during pregnancy. Second, a group of pregnant animals was treated with the PPAR\textsubscript{\gamma} inhibitor GW9662 (10 mg/kg) daily in food for 10 days from day 9 or day 10 of pregnancy. We chose to inhibit PPAR\textsubscript{\gamma} after implantation and the establishment of pregnancy because PPAR\textsubscript{\gamma} activation has a significant role in placental development (20, 35), and earlier treatment might have terminated pregnancy.

Acute hypertension. A model of acute hypertension was used to mimic changes in hydrostatic pressure and autoregulatory breakdown that have been shown to occur during severe preeclampsia and eclampsia. Acute hypertension was induced by infusion of phenylephrine (PE) under anesthesia, as previously described (16, 17). Briefly, animals were anesthetized using isoflurane (3\% in oxygen) for placement of the laser-Doppler probe, arterial and venous catheters, and a tracheostomy. Isoflurane anesthesia was discontinued and anesthesia maintained by intravenous infusion of 60 mg·kg\textsuperscript{-1}·h\textsuperscript{-1} phenylephrine. Animals were mechanically ventilated with air and supplemental oxygen to maintain blood gases within the normal range (Table 1). The femoral artery catheter was used to obtain blood samples for blood gas measurements and to measure systemic blood pressure via a pressure transducer (Living Systems Instrumentation, Burlington, VT). Phenylephrine (0.01 g/10 ml lactated Ringer solution, Sigma, St. Louis, MO) was infused intravenously and adjusted as needed to achieve basal cardiovascular parameters. This model of acute hypertension raises blood pressure through a pressor effect on arteries and decreases peripheral vascular resistance, acute hypertension raises blood pressure through a pressor effect on arteries and arterioles, and autoregulatory breakdown, which is described below. This model of acute hypertension was used in conjunction with the in situ carotid perfusion model to determine BBB permeability in response to autoregulatory breakdown and changes in hydrostatic pressure. Arteries and large tracers, respectively. The infusion pump was then stopped, the animal’s chest was opened, and the right atrium was cut to allow for drainage of the tracer and lactated Ringers while the circulation was flushed with 60 ml of lactated Ringers at a rate of 2 ml/min. The animal was then decapitated and the brain removed and processed for measurement of fluorescence intensity in brain as follows. After sectioning the cortex into anterior and posterior regions and weighing, each brain section was homogenized in PBS and trichloroacetic acid, vortexed for 1 min, and centrifuged at 4°C for 10 min at 4,500 rpm. The supernatant was removed and the pellet centrifuged again. The fluorescence of the remaining pellet was determined at excitation and emission wavelengths of 460 and 515 nm for sodium fluorescein and 595 and 614 nm for Texas red dextran. The reference sample was processed similarly and the flux calculated as: \( Q_T = (C_T \times Q_B)/C_R \), where \( Q_T \) and \( Q_B \) are the flux of the brain tissue and reference samples, respectively, and \( C_T \) and \( C_R \) are the fluorescence counts of the brain tissue and reference samples, respectively.

CBF measurement with microspheres. Absolute CBF was determined as previously described, with modifications (10). Briefly, once the appropriate blood pressure was attained (measured from the femoral artery catheter), either during the phenylephrine infusion or at baseline for control animals, a catheter connected to a pressure transducer was placed into the right common carotid artery and advanced into the left ventricle of the heart (appropriate placement was evident as the pressure recording profile dropped from arterial to ventricular). Microspheres labeled with a stable isotope (15 \( \mu \)m; Biopall Spheres, Worcester, MA) were injected into a period of 10–20 s. Microspheres were vortexed and sonicated for several minutes before injection. Arterial reference samples were taken from the femoral artery at a known flow rate (0.85 ml/min), starting 10–15 s before microsphere infusion and continued for 90 s. The animals were then euthanized by decapitation and the brains removed, sectioned, weighed, and dried overnight at 90°C. The dried brain samples were sent to Biopall for reading of isotopes and calculation of CBF and CVR, as previously described (10).

In vitro BBB permeability. Permeability of isolated cerebral arteries from NP and LP animals to Lucifer yellow (LY) in response to intravascular pressure was performed as previously described (11). Isolated posterior cerebral arteries (PCA) were used for these studies because they have BBB properties (5) and can be studied pressurized in their physiological state. This method also allowed for permeability to be assessed in response to changes in hydrostatic pressure. Arteries

<table>
<thead>
<tr>
<th>BW, g</th>
<th>BP\textsubscript{start}, mmHg</th>
<th>BP\textsubscript{max}, mmHg</th>
<th>Arterial P\textsubscript{OCO\textsubscript{2}}, mmHg</th>
<th>Arterial P\textsubscript{O\textsubscript{2}}, mmHg</th>
<th>Arterial pH</th>
<th>Total CBF, ml·100 g\textsuperscript{-1}·min\textsuperscript{-1}</th>
<th>CVR, mmHg·m\textsuperscript{-1}·100 g\textsuperscript{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP CTL (( n = 8 ))</td>
<td>292 ± 6</td>
<td>116 ± 5</td>
<td>129 ± 5</td>
<td>38.2 ± 2.2</td>
<td>141 ± 10</td>
<td>7.38 ± 0.01</td>
<td>92.4 ± 9.3</td>
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<tr>
<td>LP CTL (( n = 8 ))</td>
<td>356 ± 12\textsuperscript{a}</td>
<td>111 ± 4</td>
<td>119 ± 5</td>
<td>41.2 ± 2.5</td>
<td>159 ± 7</td>
<td>7.35 ± 0.02</td>
<td>88.0 ± 6.6</td>
</tr>
<tr>
<td>LP Rosi CTL (( n = 6 ))</td>
<td>327 ± 7\textsuperscript{b}</td>
<td>124 ± 6</td>
<td>128 ± 6</td>
<td>34.2 ± 1.4</td>
<td>162 ± 6</td>
<td>7.38 ± 0.01</td>
<td>94.7 ± 20.5</td>
</tr>
<tr>
<td>LP+GW CTL (( n = 6 ))</td>
<td>375 ± 11\textsuperscript{c}</td>
<td>100 ± 4\textsuperscript{d}</td>
<td>104 ± 4</td>
<td>36.7 ± 2.4</td>
<td>88 ± 6</td>
<td>7.39 ± 0.02</td>
<td>106.7 ± 15.3</td>
</tr>
<tr>
<td>NP NTN (( n = 8 ))</td>
<td>276 ± 6</td>
<td>122 ± 4</td>
<td>205 ± 3\textsuperscript{e}</td>
<td>36.6 ± 1.1</td>
<td>141 ± 9</td>
<td>7.39 ± 0.02</td>
<td>256.6 ± 30.0 \textsuperscript{f}</td>
</tr>
<tr>
<td>LP NTN (( n = 8 ))</td>
<td>353 ± 15\textsuperscript{e}</td>
<td>100 ± 5\textsuperscript{e}</td>
<td>193 ± 3\textsuperscript{f}</td>
<td>40.7 ± 2.0</td>
<td>141 ± 6</td>
<td>7.35 ± 0.03</td>
<td>398.9 ± 45.7 \textsuperscript{g}</td>
</tr>
<tr>
<td>NP Rosi HTN (( n = 8 ))</td>
<td>337 ± 9\textsuperscript{f}</td>
<td>125 ± 2\textsuperscript{f}</td>
<td>192 ± 4\textsuperscript{f}</td>
<td>35.2 ± 0.9</td>
<td>135 ± 8</td>
<td>7.38 ± 0.01</td>
<td>394.8 ± 45.9 \textsuperscript{g}</td>
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<tr>
<td>LP+GW HTN (( n = 8 ))</td>
<td>378 ± 11\textsuperscript{f}</td>
<td>100 ± 6\textsuperscript{f}</td>
<td>179 ± 5\textsuperscript{f}</td>
<td>34.7 ± 2.2</td>
<td>100 ± 10</td>
<td>7.41 ± 0.02</td>
<td>396.1 ± 55.5 \textsuperscript{g}</td>
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</table>

Values are means ± SEM. CBF, cerebral blood flow; CVR, cerebral vascular resistance; NP, nonpregnant; LP, late-pregnant; CTL, control; HTN, hypertension; Rosi, rosiglitazone; GW, GW9662. \textsuperscript{a}P < 0.05 vs. NP CTL; \textsuperscript{b}P < 0.05 vs. LP CTL; \textsuperscript{c}P < 0.05 vs. NP Rosi CTL; \textsuperscript{d}P < 0.05 vs. LP GW CTL; \textsuperscript{e}P < 0.05 vs. NP HTN; \textsuperscript{f}P < 0.05 vs. LP HTN; \textsuperscript{g}P < 0.05 vs. NP Rosi HTN.
were perfused with 0.5 mg/ml Lucifer yellow-CH (LY; Molecular Probes, Eugene, OR) in HEPES buffer for 3 min and the HEPES buffer outside the vessel wall (superfusate) was sampled to measure baseline fluorescence intensity using an ultraviolet-fluorescent spectrophotometer (Photon Technology International, Birmingham, NJ). To obtain pressure vs. permeability curves, the superfusate was sampled after step increases in pressure from 60 to 200 mmHg to determine the change in fluorescence intensity. The concentration of LY was quantified from a linear standard curve plotted from known amounts of LY in HEPES.

PCR analysis of cerebral arteries. Real-time PCR was performed on isolated cerebral arteries from NP and LP rats using standard techniques for real-time quantitative PCR (qPCR) and was performed by the DNA Facility at the University of Vermont. Briefly, cerebral arteries and penetrating arterioles were dissected separately from NP and LP brains and rapidly frozen in RNAlater. The vessels were then placed in an RNase-free microcentrifuge tube, homogenized in the presence of RLT buffer, and total RNA was isolated using an RNeasy Micro Kit animal tissue protocol (Qiagen, Valencia, CA). Samples were not DNase treated. The concentration of total RNA was measured using a NanoDrop ND-1000 Spectrophotometer (Wilmington, DE) and its integrity analyzed by an Agilent 2100 Bioanalyzer (Santa Clara, CA). cDNA was made from total RNA using a SuperScript III Kit (Invitrogen, Carlsbad, CA). The cDNA reaction was done according to standard protocol. All target genes (claudin-1, claudin-5, occludin, ZO-1, PPARγ, and B2m for an endogenous control) were assessed using Assays on Demand from Applied Biosystems (Foster City, CA) that were validated for efficiency and did not amplify genomic DNA. All samples were run in technical duplicates using a 7900HT Sequence Detection System (Applied Biosystems, Foster City, CA). Only Ct duplicate values of <35 were used (if replicates were >1.0 apart, they were rerun). Ct values were averaged and used for comparison using the 2^-ΔΔCt method (26).

Isolated arteriole reactivity and structural measurements. Penetrating brain arterioles were dissected and mounted in an arteriograph chamber, as previously described (17). Lumen diameter and wall thickness were measured by video microscopy under active conditions in HEPES buffer at pressures from 25 to 200 mmHg and again under passive conditions in the presence of papaverine (0.1 mM) and diltiazem (10^-5 M). Circumferential wall tension (T) was calculated by the equation T = pressure × radius. Before T was calculated, pressure in mmHg was converted to dynes per square centimeter (1 mmHg = 1.3332 dyn/cm^2) and radius in micrometers was converted to centimeters. Circumferential wall stress was then calculated by the equation T/√wall thickness.

Capillary density. Capillary density of the anterior and posterior cerebral cortex was determined by immunohistochemical staining for von Willebrand factor (vWF) and morphometric analysis, as previously described (9). Briefly, brain sections were paraffin embedded and processed for immunohistochemistry. A polyclonal rabbit anti-human vWF primary antibody (dilution 1:400, Dako, Glostrup, Denmark) and an Ultravision LP horseradish peroxidase kit (ThermoScientific, Fremont, CA) were used according to specifications. Sections of anterior and posterior cerebral cortex were imaged at ×20 and the images imported into Metamorph for counting of capillaries per area. Counting was done blinded relative to group. Four images from each section and two sections from each animal were counted. Images were counted twice and the results averaged.

Determination of PPARγ activity in brain tissue and vasculature. PPARγ activity was determined in nuclear extracts using a commercially available immunonassay from brains in which the vasculature was separated from the brain tissue and then the vasculature was further separated into pial vessels vs. microvessels. First, cerebral arteries that were on the top of the brain (pial) were dissected and kept on ice in PBS until nuclear extraction. The brain was then homogenized in PBS for separation of brain tissue and microvessels. The homogenate was centrifuged at 3,150 rpm at 4°C for 10 min and the pellet resuspended in 10 ml of PBS, layered over 10 ml of 15% dextran, and centrifuged again at 4,400 rpm for 60 min. The top layer was discarded and the second layer containing the brain tissue was carefully collected using a serological pipette. The third layer containing dextran and microvessels was poured over an 80-μm sieve and microvessels collected in cold PBS. Nuclear extracts of brain tissue, pial arteries, microvessels, and spleen were obtained using a commercially available kit (Caymen Chemicals, Ann Arbor, MI) and stored at −80°C until use in the PPARγ assay. PPARγ activity was determined in nuclear extracts using a PPARγ transcription factor assay kit (Caymen Chemicals, Ann Arbor, MI) following manufacturer’s instructions.

Drugs and solutions. All isolated vessel experiments were performed using HEPES buffered saline solution, the composition of which was (in mM) 142 NaCl, 4.7 KCl, 1.71 MgSO4, 0.50 EDTA, 2.8 CaCl2, 1.0 HEPES, 1.2 KH2PO4, and 5.0 glucose. HEPES, papaverine, and diltiazem were purchased from Sigma (St. Louis, MO).

Data analysis and statistics. Data are presented as means ± standard error of the mean (SE). One-way ANOVA was used for most analysis with a post hoc Tukey’s test for multiple comparisons where appropriate. To determine the effect of pressure or pregnancy on BBB permeability in vitro, two-way repeated-measures ANOVA was used. Statistical significance was considered at P < 0.05.

RESULTS

BBB permeability is increased during pregnancy. Brain edema occurs in patients with severe preeclampsia and eclampsia and is thought to be a primary contributor to the neurological complications of these conditions (14, 23, 25, 40). Because increased permeability of the BBB is a necessary event in the development of vasogenic brain edema (36), we measured BBB permeability to different-sized solutes in nonpregnant (NP) and late-pregnant (LP) rats using a well-established in situ carotid perfusion model after acute hypertension. We found that pregnancy caused a significant increase in BBB permeability to both sodium fluorescein and 70-kDa dextran following acute hypertension (Fig. 1, A and B). Permeability of the BBB was size-selective as the smaller molecule (sodium fluorescein) had considerably greater flux than the larger 70-kDa dextran in both types of animals. However, permeability to both solutes was significantly greater in LP animals compared with NP. Similar to our previous study (16), permeability to the larger dextran tended to be greater in the posterior cortex, but this difference was not statistically significant (Fig. 1B).

The increase in BBB permeability during pregnancy could be due to decreased CVR and subsequent increases in hydrostatic pressure in the microcirculation or to direct changes in barrier properties of cerebral endothelium. To examine the question of whether pregnancy decreases barrier properties independent of hydrostatic pressure, we used an in vitro method that allows measurement of BBB permeability in cerebral arteries from NP and LP rats in response to changes in hydrostatic pressure. Figure 1C shows that BBB permeability was increased in response to pressure in arteries from LP and NP animals, suggesting pressure did increase permeability during pregnancy. In addition, there was an increase in permeability in arteries from LP vs. NP rats. This difference was present over a range of pressures but was only statistically significant at the highest pressure studied. It therefore appears that pregnancy moderately enhances BBB permeability in response to hydrostatic pressure.
We next assessed whether pregnancy affected mRNA levels for key tight junction proteins. Reductions in expression of these proteins at the BBB increases permeability and may explain the increase in permeability seen in situ during pregnancy (27). We used real-time PCR to assess expression of claudin-1, claudin-5, occludin, and ZO-1 in cerebral vessels from LP rats compared with NP and found no change with pregnancy (Fig. 1D).

Cerebral blood flow and vascular resistance during pregnancy. Acute hypertension, similar to what occurs during severe preeclampsia and eclampsia, causes decreased CVR and breakthrough of autoregulation that severely increases hydrostatic pressure at the BBB, causing an increase in permeability and edema formation (16–19, 24). Because pregnancy is known to have significant effects on vascular resistance and blood flow to many organs (13, 15, 25, 30), we hypothesized that pregnancy causes a greater decrease in CVR and that this difference contributes to increased BBB permeability in response to acute hypertension. To test this hypothesis, we measured CBF and determined CVR in NP and LP rats under control conditions and in response to acute hypertension with breakthrough of autoregulation. Pregnancy did not affect CVR or CBF under normotensive conditions whereas acute hypertension significantly reduced CVR and caused considerable hyperperfusion in both NP and LP rats (Fig. 2). Notably, there was a significantly greater decrease in CVR during pregnancy compared with NP animals and a much greater increase in CBF in response to acute hypertension. Changes in CBF during acute hypertension were similar between anterior and posterior cerebral cortex (Fig. 2B).

Pregnancy promotes outward remodeling of penetrating brain arterioles and decreases CVR through activation of PPARγ. To gain insight into how pregnancy causes a decrease in CVR in response to acute hypertension, we measured the lumen diameter of different segments of the cerebral circulation. The cerebral circulation is unique compared with most vascular beds in that the large cerebral (pial) arteries contribute significantly to CVR (18, 22). Because large cerebral arteries...
are key contributors to CVR, these vessels contribute to regulation of CBF and protect downstream vessels during changes in systemic blood pressure (18). Similar to previous studies, we found that the diameter of large cerebral arteries was not different during pregnancy (Fig. 3A). Importantly, penetrating brain arterioles—segments of the vasculature that branch off pial vessels and penetrate into the brain parenchyma—had considerably larger lumen diameters both actively, when myogenic tone was present, and in the presence of papaverine and diltiazem to inactivate smooth muscle contraction (Fig. 3, B and D). The larger lumen diameters of the arterioles during pregnancy were not due to a decrease in myogenic tone. The percent tone at 50 mmHg (calculated as a percent decrease in diameter from fully relaxed) for NP and LP PA was 44.6 ± 2.7 and 44.9 ± 2.7 (P > 0.05). Thus the larger lumen was due to outward remodeling as vessel diameters were significantly larger under passive conditions. Notably, outward remodeling of penetrating arterioles was hypertrophic in nature as wall thickness was significantly decreased (Fig. 3C), but outer diameter was unchanged (data not shown).

PPARγ is highly activated in pregnancy due to increased production of endogenous ligands and has an important role in both the establishment and maintenance of pregnancy (6, 20, 31, 35, 37). PPARγ has also been shown to inhibit inward remodeling of cerebral arterioles under nonpregnant conditions (3, 21). Thus we hypothesized that increased activation of PPARγ during pregnancy contributes to outward remodeling of penetrating arterioles in the brain. To test this hypothesis, we treated NP animals with the PPARγ agonist rosiglitazone for 3 wk to mimic the increase in activation seen in pregnancy. In addition, we treated pregnant animals with the PPARγ inhibitor GW9662 during the last half of pregnancy. Rosiglitazone administration in NP animals caused outward hypotrophic remodeling similar to that seen during pregnancy. In contrast, inhibition of PPARγ during pregnancy prevented outward remodeling altogether (Fig. 3, A–C). These results suggest that outward remodeling of brain arterioles during pregnancy is mediated by PPARγ.

To further assess the effect of pregnancy and PPARγ activation on the structure of brain arterioles, we calculated circumferential wall stress at 75 mmHg, the approximate pressure that these vessels would experience in vivo during acute hypertension (17, 19). During pregnancy, brain arterioles experienced significantly greater wall stress than NP arterioles due to the larger lumen and thinner wall: 0.83 ± 0.08 vs. 1.43 ± 0.1 dyn/cm² (P < 0.01). A similar effect on wall stress was found in NP animals treated with rosiglitazone as arterioles from these animals underwent similar outward hypotrophic remodeling (1.15 ± 0.06 dyn/cm²; P < 0.01 vs. NP). Further, inhibition of PPARγ during pregnancy with GW9662 decreased wall stress. This difference was even greater than that seen in the NP state due to the smaller lumen and thicker vascular wall (0.67 ± 0.04 dyn/cm²; P < 0.01 vs. LP).

To determine if remodeling of downstream arterioles during pregnancy and PPARγ activation was associated with changes in cerebral hemodynamics, we measured CBF under normal conditions and during acute hypertension in NP animals treated with rosiglitazone and pregnant animals treated with GW9662. These hemodynamic parameters were then compared with vehicle-treated NP and LP rats (Table 1). We found that there was no difference in CVR or CBF under normotensive conditions between any of the groups. As expected, CVR was significantly decreased with acute hypertension in all groups compared with normotensive animals and was accompanied by a significant increase in CBF. Compared with normotensive animals, all animals had significantly decreased CVR and substantially increased CBF during acute hypertension, suggesting breakthrough of autoregulation had occurred. PPARγ activation tended to decrease CVR and increase CBF similar to pregnancy, but this did not reach statistical significance (P = 0.07).

**P < 0.01 vs. control. ††P < 0.01 vs. NP.
microcirculation, we measured capillary density in brains from NP and LP animals with and without activation or inhibition of PPARγ, respectively. We assessed capillary number in the anterior vs. posterior cerebral cortex because of the propensity for edema to form in the posterior brain region during eclampsia (14, 23, 40). There was a significant increase in capillary density in the posterior cerebral cortex in all groups compared with anterior, except LP animals treated with GW9662 (Fig. 4, A and B). However, the percent change in capillary density in the posterior brain region was significantly greater in all groups compared with NP (Fig. 4C).

**PPARγ expression and activation in cerebral cortex and brain vasculature during pregnancy.** It was unclear how pregnancy and PPARγ activation could selectively affect penetrating brain arterioles during pregnancy and increase brain capillary density, with no apparent effect on upstream cerebral arteries [a previous study from our laboratory showed that inhibition of PPARγ during pregnancy had no effect on the structure of cerebral arteries (7)]. Because the difference in response to pregnancy and PPARγ in these two vascular segments could be due to differences in expression of PPARγ, we measured mRNA levels of PPARγ in arteries and microvessels pooled from LP pregnant animals. We found that expression of PPARγ was considerably less in microvessels compared with larger upstream arteries (Fig. 5A). Thus there does not appear to be a direct correlation between the level of PPARγ mRNA expression in whole vessels and vascular responsiveness to pharmacological activation of PPARγ. One major difference between cerebral parenchymal microvessels and arteries on the brain surface is the close association with nonvascular cells that express PPARγ (1, 42). To determine if the effect of PPARγ during pregnancy might be affecting the
microvessels through a paracrine effect on the vasculature, we used a commercially available immunoassay to measure PPARγ activation of nuclear extracts of isolated brain tissue (without vasculature), cerebral (pial) arteries, and microvessels from LP animals. We found that baseline PPARγ activity was higher in brain tissue compared with either vascular segment (Fig. 5B). To confirm that pregnancy was associated with an increase in PPARγ activity, we measured PPARγ activity in nuclear extracts from spleen, an organ with high PPARγ expression (4), and found that the activity of PPARγ was significantly increased in LP animals vs. NP. 

DISCUSSION

Increased BBB permeability and subsequent formation of vasogenic brain edema is considered a major contributor to the neurological complications of severe preeclampsia and eclampsia (14, 23, 36, 40). Here, we show that normal pregnancy is associated with an increase in BBB permeability when blood pressure is acutely elevated to mimic the change in hydrostatic pressure that occurs during these conditions (14, 23, 40). The increase in BBB permeability during pregnancy does not appear to be related to changes in expression of tight junction proteins but to an effect on barrier properties and a pregnancy-induced decrease in CVR that increases hydrostatic pressure on the BBB. The cerebral circulation actively increases vascular resistance in the brain in response to increases in cerebral perfusion pressure, providing a protective mechanism that limits transmission of hydrostatic pressure to the microcirculation (18, 19, 22). Thus diminished CVR during pregnancy would be expected to increase CBF and BBB permeability and promote vasogenic brain edema during acute hypertension. These results are in agreement with our previous study that showed significant brain edema formation in LP but not NP animals after acute hypertension (17).

Changes in cerebral hemodynamics during pregnancy in humans have been highly debated and are still largely unknown, mostly because of the difficulties in obtaining accurate quantification of CBF in pregnant women. Our results suggest that pregnancy is associated with decreased resistance in small but not large vessels in the brain during acute hypertension, a hemodynamic change that has been predicted to occur (but not measured previously) in human studies (41). The prominent contribution of large cerebral arteries to vascular resistance is unique to the brain. One advantage of this arrangement is that small arterioles can adjust their diameter or undergo remodeling without an appreciable change in total CVR under normotensive conditions (18, 19, 22). The greater decrease in CVR and hyperperfusion during pregnancy was un-
masked only during acute hypertension that caused break-through of autoregulation when large vessel resistance was also decreased (19).

PPARγ activity is an important determinant of cerebrovascular structure (3, 9, 21). For example, genetic interference with PPARγ produces inward remodeling of cerebral arterioles (3). Consistent with this concept, our results suggest that outward remodeling of cerebral microvessels during pregnancy occurs through a mechanism involving PPARγ. Both pregnancy and PPARγ activation caused outward remodeling of penetrating arterioles that was at the expense of the vascular wall, i.e., hypertrophic remodeling, thus substantially increasing circumferential wall stress. This elevation in wall stress in cerebral arterioles from LP animals may predispose these vessels to increased permeability or rupture, especially under conditions of acute hypertension such as that seen in severe preeclampsia and eclampsia. Increases in capillary density during pregnancy, which were also observed in our studies, may also contribute to reductions in CVR with acute hypertension. Such changes may provide a mechanistic basis for the appearance of edema and hemorrhage during eclampsia (40; Fig. 6).

Pregnancy is a state of tremendous hormonal changes that drive hemodynamic adaptations systemically, including decreased total peripheral vascular resistance (13), increased renal blood flow and glomerular filtration rate (29), and increased uterine blood flow in the uteroplacental vascular bed (30). In addition to changes in multiple hormones, pregnancy is associated with increased activation of PPARγ by endogenous ligands (6, 31, 37). While the effect of PPARγ activation has been studied extensively in the placenta during pregnancy (20, 35), the present study is the first to suggest that PPARγ activation during pregnancy promotes outward remodeling of microvessels within the brain that is associated with changes in cerebral hemodynamics. However, unlike other organs in which there are substantial increases in blood flow over the course of gestation, brain blood flow during normal pregnancy remains relatively constant (28). Maintenance of normal blood flow is not surprising for a vital organ that relies almost exclusively on oxidative metabolism. Thus it appears that the adaptation of the brain or cerebral vasculature to pregnancy includes the ability to maintain stable levels of CBF and oxygen delivery despite marked changes in hormone concentrations and systemic hemodynamics.

Fig. 5. Effect of pregnancy on PPARγ expression and activity in brain tissue vs. cerebral vasculature. A: relative expression of PPARγ in cerebral pial arteries compared with penetrating arterioles (PA) pooled from late-pregnant (LP) rats. Microvessels had considerably less expression of PPARγ compared with upstream arteries. B: selective PPARγ activation in nuclear extracts from LP rat brain microvessels, arteries, and brain tissue (without vasculature) compared with spleen. PPARγ activation was significantly elevated in brain tissue compared with vasculature and spleen: **P < 0.01 vs. both vascular segments and spleen. C: PPARγ activation was significantly increased in spleen from LP vs. nonpregnant (NP) rats: *P < 0.05 vs. NP.
PPARγ has been shown to have an important role in vascular structure and function and promotes outward remodeling in the cerebral microcirculation during pregnancy. The cell type(s) in which PPARγ exerts these effects is not clear. Our results raise the question of whether there are paracrine effects of PPARγ from nonvascular cells, rather than a direct effect of PPARγ on the vasculature, that promotes outward remodeling of cerebral microvessels during pregnancy. This possibility is based on several findings, including that cerebral microvessels, but not arteries, were highly responsive to pregnancy and activation of PPARγ yet they expressed considerably lower levels PPARγ than upstream arteries—vessels that did not respond to pregnancy (shown in this study) or PPARγ activation (7). In addition, PPARγ activity was increased in brain tissue compared with either vascular segment, suggesting that PPARγ-responsive genes in neurons and astrocytes within the brain parenchyma that are closely associated with microvessels may be affecting vascular structure.

Our results also demonstrate that both pregnancy and PPARγ activation with rosiglitazone increased capillary density in the posterior cerebral cortex, an effect that may contribute to the propensity for edema formation to occur in this region of the brain during severe preeclampsia and eclampsia (14, 23, 40). The finding that PPARγ inhibition with GW9662 did not prevent the increase in capillary density during the last half of pregnancy may be because changes in capillary density occurred earlier in gestation, before GW9662 treatment. We assessed changes in vessel structure and capillary density during late gestation because this is when severe preeclampsia and eclampsia occur most often (40). However, we do not know at what stage of gestation changes in capillary density occurred.

We characterized cerebral hemodynamic changes during normal pregnancy, which may have important implications for understanding the development of neurological complications associated with severe preeclampsia and eclampsia. Pre-
Eclampsia is defined as hypertension after the 20th week of gestation with significant proteinuria (32, 40). Thus elevated arterial pressure associated with preeclampsia may be present for a few weeks but is not truly chronic like many forms of hypertension. While chronic hypertension has profound effects on the structure of the cerebral circulation, including causing inward remodeling and capillary rarefaction that would increase CVR, both pregnancy and PPARγ activation prevent and reverse these structural changes (9, 12). Thus structural changes in the cerebral circulation during preeclampsia may not be fundamentally different from those seen during pregnancy. However, the endogenous ligands for PPARγ have been shown to be decreased in serum from preeclamptic women (38), an effect that may prevent decreases in small vessel resistance and as a result, increase CVR instead of producing a reduction as shown here. It is worth noting that how the preeclamptic state truly affects the cerebral circulation is not known and may be very difficult to accurately assess using animal models because to our knowledge, preeclampsia occurs spontaneously only in bipedal species and thus no true animal model has been developed. In addition, the role of PPARγ in pregnancy and preeclampsia may be further complicated by the recent finding that PPARγ is phosphorylated in disease states such as obesity, preventing transcription of specific PPARγ targets (8). Whether PPARγ is phosphorylated in other disease states such as preeclampsia remains to be determined.

In summary, normal pregnancy was associated with increased BBB permeability during acute hypertension that was not associated with changes in expression of tight junction proteins. Pregnancy caused selective outward remodeling of brain arterioles and increased capillary density due to PPARγ activation. Structural remodeling of brain arterioles during pregnancy and PPARγ activation was also associated with a significant decrease in total CVR and hyperperfusion during acute hypertension compared with NP animals, suggesting hemodynamic changes during pregnancy may contribute to increased BBB permeability and promote the neurological complications of eclampsia.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

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