Uterine artery dysfunction in pregnant ACE2 knockout mice is associated with placental hypoxia and reduced umbilical blood flow velocity

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1The Hypertension and Vascular Research Center, Wake Forest School of Medicine, Winston-Salem, North Carolina; 2Department of Obstetrics and Gynecology, Wake Forest School of Medicine, Winston-Salem, North Carolina; 3Department of Pharmacology, Tulane University, New Orleans, Louisiana; and 4Department of Medicine, Duke University and Durham Veterans Affairs Medical Centers, Durham, North Carolina

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Yamaleyeva LM, Pulgar VM, Lindsey SH, Yamane L, Varagic J, McGee C, daSilva M, Lopes Bonfa P, Gurley SB, Brosnihan KB. Uterine artery dysfunction in pregnant ACE2 knockout mice is associated with placental hypoxia and reduced umbilical blood flow velocity. Am J Physiol Endocrinol Metab 309: E84–E94, 2015. First published May 12, 2015; doi:10.1152/ajpendo.00596.2014.—Angiotensin-converting enzyme 2 (ACE2) knockout is associated with reduced fetal weight at late gestation; however, whether uteroplacental vascular and/or hemodynamic disturbances underlie this growth-restricted phenotype is unknown. Uterine artery reactivity and flow velocities, umbilical flow velocities, trophoblast invasion, and placental hypoxia were determined in ACE2 knockout (KO) and C57Bl/6 wild-type (WT) mice at day 14 of gestation. Although systolic blood pressure was higher in pregnant ACE2 KO vs. WT mice (102.3 ± 1.9 mmHg, n = 5–6), the magnitude of difference was similar to that observed in nonpregnant ACE2 KO vs. WT mice. Maternal urinary protein excretion, serum creatinine, and kidney or heart weights were not different in ACE2 KO vs. WT. Fetal weight and pup-to-placental weight ratio were lower in ACE2 KO vs. WT mice. A higher sensitivity to Ang II [pD2 8.64 ± 0.04 vs. 8.5 ± 0.03 (−log EC50)] and greater maximal contraction to phenylephrine (169.0 ± 9.0 vs. 139.0 ± 7.0% KMAX), were associated with lower immunostaining for Ang II receptor 2 and fibrinoid content of the uterine artery in ACE2 KO mice. Uterine artery flow velocities and trophoblast invasion were similar between study groups. In contrast, umbilical artery peak systolic velocities (60.2 ± 4.5 vs. 75.1 ± 4.5 mm/s) and the resistance index measured using VEVO 2100 ultrasound were lower in the ACE2 KO vs. WT mice. Immunostaining for pimonidazole, a marker of hypoxia, and hypoxia-inducible factor-2α were higher in the trophospongium and placental labyrinth of the ACE2 KO vs. WT. In summary, placental hypoxia and uterine artery dysfunction develop before major growth of the fetus occurs and may explain the fetal growth restricted phenotype.

Intrauterine growth restriction (IUGR) is a leading cause of perinatal morbidity and mortality in humans (31). Maternal health factors such as chronic hypertension, preeclampsia, diabetes mellitus, chronic renal disease, poor nutrition, and smoking (57) and fetal genetic abnormalities increase the risk of IUGR. The uteroplacental vasculature undergoes tremendous adaptations during pregnancy, including vasculo/angiogenesis and remodeling of spiral arteries (44). These changes allow the expansion of blood volume in the uteroplacental unit and sufficient blood flow from the placenta to the fetus (44). Fetal metabolic demands progressively increase in the second half of pregnancy (37). Normal fetal growth is vastly dependent on adequate placental development, whereas increased vascular resistance and hypoxia are associated with reduced fetal weight (10a). However, the molecular basis of uteroplacental dysfunction in IUGR is not well understood.

The components of the renin-angiotensin system (RAS) are important mediators of uteroplacental vasculature. Angiotensin-converting enzyme 2 (ACE2) is a key enzyme of the RAS that degrades angiotensin II (Ang II) and forms Ang-(1–7). ACE2 plays a key regulatory role in the control of arterial pressure and vascular function (24) by balancing the vasoconstrictor Ang II/Ang II receptor 1 (AT1R) and vasodilator Ang-(1–7)/MAS (AT1–7R) arms of the renin-angiotensin system. ACE2 expression in human placenta was characterized by Valdes et al. (56) in the invading and intravascular trophoblasts, decidual cells, and umbilical cord, suggesting a paracrine influence of this enzyme in the uteroplacental unit. Moreover, human umbilical vein endothelial cells (HUVECs) isolated from pregnancies with small for gestational age (SGA) newborns had significantly lower levels of ACE2 mRNA compared with pregnancies associated with average for gestational age (AGA) newborns (48), suggesting that lower ACE2 levels in HUVECs are associated with IUGR.

Several studies have investigated ACE2 expression in the uteroplacental unit of pregnant animals. ACE2 levels were higher in the uterus of normotensive pregnant rats compared with normotensive nonpregnant rats (39). ACE2 levels were lower in hypertensive pregnant rats that had reduced uterine perfusion pressure (RUPP) surgery compared with normotensive pregnant rats (39). RUPP surgery induces the reduction in uterine perfusion with subsequent placental ischemia by placing clips around the descending aorta and around both main uterine arteries (1, 39). It has been also shown that placentas generate threefold more ACE2 mRNA than gravid uterus or the kidneys, suggesting that the placenta is a significant contributor to the generation of ACE2 levels (systemic or uteroplacental) seen during rat pregnancy (27). In agreement with the hypothesis that ACE2 deficiency is associated with IUGR, a recent study from our group demonstrated that ACE2 knockout (KO) mice developed maternal and fetal growth restriction at late pregnancy (3). These changes were accompanied by increased levels of placental Ang II and decreased circulating Ang-(1–7), a result of ACE2 knockout and reduced degradation of Ang II (3). Mean blood pressure was elevated in virgin ACE2 KO
mice and did not change with pregnancy (3). Since cardiac output was similarly increased in ACE2 KO and C57Bl/6 mice (3), the absence of blood pressure response in ACE2 KO mice during pregnancy implies a higher peripheral resistance. These findings suggest that the dysregulated RAS has a pathogenic role in the development of IUGR (3). Moreover, a recent study by Ibrahim et al. (21) showed that ACE2 activator, xanthone, decreased blood pressure in hypertensive pregnant rats, suggesting that ACE2 activation is protective against hypertension during pregnancy.

In male animals, ACE2 knockout increases endothelial dysfunction and the expression of inflammatory mediators in the aorta (55). ACE2 knockout also exacerbates Ang II-mediated aortic remodeling in mice due to increased oxidative stress and vascular smooth muscle cell apoptosis (46). On the other hand, ACE2 overexpression in hypertensive rats improves endothelial function (52, 53), suggesting a protective effect of ACE2 in vasculature.

Disturbances in the uteroplacental circulation have been implicated in the development of IUGR; however, the role of ACE2 in the regulation of the uteroplacental vasculature is unknown. The use of a pregnant ACE2 KO mouse model allowed us to test the hypothesis that ACE2 knockout induces uteroplacental dysfunction as early as day 14 of gestation before major growth of the fetus occurs (10a).

Materials and Methods

Animals. The study was approved by the Institutional Animal Care and Use Committee of the Wake Forest School of Medicine (WFSM). ACE2 KO mice developed on a C57Bl/6 background were received from Susan B. Gurley MD and Thomas Coffman MD of Duke University; the colony was established at the Hypertension and Vascular Research Center at WFSM. As previously described (3), C57Bl/6 mice, purchased from Harlan Laboratories, were used in control experiments. Standard rodent chow (Lab Diet 5000 - Prolab RMH 3000; PMI Nutrition International, Brentwood, MO) and water were available ad libitum throughout the experimental protocols.

Timeline for the experiments. Homozygous female ACE2 KO mice between 12 and 18 wk of age were mated with male ACE2 KO mice. Day 0 of pregnancy was established by the presence of a vaginal plug or sperm in the vaginal smear. Mice received ultrasound scans at day 13 of gestation. In the evening of the same day, animals were placed in metabolic cages for 24-h urine collection (MMC 100; Hatteras Instruments, Cary, NC). Blood pressures were taken in the morning of the following day, and the animals were euthanized in the afternoon of day 14 of gestation (0.7 term) by decapitation. In addition, on the day of euthanasia, some animals were injected with hypoxyprobe-1 to expose arteries to six (10⁶ M) increasing concentrations of KCl and washed and rested, uterine artery segments were exposed to a cumulative concentration-response curve of phenylephrine (PE) by exposing arteries to six (10⁻¹⁰ to 10⁻⁵ M) increasing concentrations in one-log steps, with each subsequent dose being introduced only after a steady response had been reached. The responses to PE were measured in one-log steps, with each subsequent dose being introduced only after a steady response had been reached. The responses to PE were
Table 1. Physiological characteristics of ACE2 KO and C57Bl/6 mice at day 14 of gestation

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>C57Bl/6 (n = 5)</th>
<th>ACE2 KO (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mother’s BW (g)/tibia length (cm)</td>
<td>17.90 ± 0.20</td>
<td>16.42 ± 0.37*</td>
</tr>
<tr>
<td>(Mother’s BW–total pup BW), g/tibia length (cm)</td>
<td>16.63 ± 0.30</td>
<td>15.30 ± 0.38*</td>
</tr>
<tr>
<td>Pup BW (g)/tibia length (cm)</td>
<td>0.15 ± 0.01</td>
<td>0.11 ± 0.01*</td>
</tr>
<tr>
<td>Pup BW, unadjusted (g)</td>
<td>0.21 ± 0.01</td>
<td>0.17 ± 0.01*</td>
</tr>
<tr>
<td>Pup number</td>
<td>8.70 ± 0.35</td>
<td>8.0 ± 0.28</td>
</tr>
<tr>
<td>Placental wt (g)/tibia length (cm)</td>
<td>0.05 ± 0.002</td>
<td>0.05 ± 0.001</td>
</tr>
<tr>
<td>Placental wt, unadjusted (g)</td>
<td>0.07 ± 0.003</td>
<td>0.08 ± 0.003*</td>
</tr>
<tr>
<td>Pup BW/placental weight ratio (per tibia length)</td>
<td>3.15 ± 0.28</td>
<td>2.44 ± 0.11*</td>
</tr>
<tr>
<td>Pup BW/placental weight ratio (unadjusted)</td>
<td>2.91 ± 0.18</td>
<td>2.34 ± 0.13*</td>
</tr>
<tr>
<td>Mean kidney wt (g)/tibia length (cm)</td>
<td>0.15 ± 0.004</td>
<td>0.14 ± 0.003</td>
</tr>
<tr>
<td>Heart wt (g)/tibia length (cm)</td>
<td>0.11 ± 0.005</td>
<td>0.12 ± 0.004</td>
</tr>
<tr>
<td>Systolic blood pressure (mmHg)</td>
<td>85.10 ± 1.90</td>
<td>102.30 ± 5.10*</td>
</tr>
<tr>
<td>Maternal heart rate (beats/min)</td>
<td>361.20 ± 28.9</td>
<td>349.20 ± 30.20</td>
</tr>
<tr>
<td>Proteinuria (mg protein/g of mother’s BW)</td>
<td>1.02 ± 0.09</td>
<td>1.03 ± 0.42</td>
</tr>
<tr>
<td>Maternal serum creatinine (mg/dl)</td>
<td>0.29 ± 0.02</td>
<td>0.34 ± 0.03</td>
</tr>
<tr>
<td>Maternal Food Intake (g)</td>
<td>3.40 ± 0.24</td>
<td>4.0 ± 0.21</td>
</tr>
<tr>
<td>Placental wt (g)/tibia length (cm)</td>
<td>0.003 ± 0.001</td>
<td>0.001 ± 0.006</td>
</tr>
<tr>
<td>Maternal heart rate (beats/min)</td>
<td>0.003 ± 0.003</td>
<td>0.002 ± 0.001</td>
</tr>
<tr>
<td>Proteinuria (mg protein/g of mother’s BW)</td>
<td>0.002 ± 0.001</td>
<td>0.001 ± 0.001</td>
</tr>
<tr>
<td>Maternal serum creatinine (mg/dl)</td>
<td>0.001 ± 0.001</td>
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</tr>
<tr>
<td>Maternal Food Intake (g)</td>
<td>0.001 ± 0.001</td>
<td>0.001 ± 0.001</td>
</tr>
</tbody>
</table>

Data are means ± SE. ACE2 KO, angiotensin-converting enzyme 2 knockout mice; BW, body weight. *P < 0.05 vs. C57Bl/6 mice.

Expressed as the percentage of maximal contraction induced by KCl. Arteries were then washed again, and vasodilation to acetylcholine was tested in the uterine arteries preconstricted with a submaximal dose of PE (10⁻⁶ to 10⁻⁵ M). After attaining an equivalent level of contraction, a concentration response curve to acetylcholine (10⁻⁴ to 10⁻⁹ M) was calculated. Uterine artery segments were washed and, under resting tension, were exposed to a cumulative concentration-response curve of Ang II by exposing arteries to 10⁻¹⁰ to 10⁻⁷ M increasing concentrations in one-fourth log steps, with each subsequent dose being introduced after a steady response had been reached (every 2 min). The response to Ang II was expressed as the percent (%) of maximal contraction induced by KCl. Ang II response was also tested after preincubation with Ang-(1–7) (10⁶ M) alone or in the presence of MAS (AT1–7R) antagonist (10⁵ M) in some vessels.

Immunohistochemistry. After fixation in formalin and ethanol, one uterine artery segment and one placental section were embedded in separate paraffin blocks, and cut into 5-μm sections. Immunostaining was performed using the avidin biotin complex (ABC) method as described (62). Staining for all proteins required antigen retrieval treatment with sodium citrate buffer (pH 6.0) at 90–95°C for 30 min. Uterine arteries were incubated with the following primary antibodies: rabbit polyclonal affinity purified endothelial nitric oxide synthase, anti-eNOS (dilution: 1:100; BD Biosciences, San Diego, CA; cat. no. 610297), anti-AT1R (dilution: 1:400; Santa Cruz, cat. no. sc-1173), anti-AT2R (dilution: 1:400; Abcam, cat. no. ab19134), anti-MAS/Ang-(1–7)R (dilution: 1:400, Alomone Labs, cat. no. AAR-013), monoclonal anti-α-smooth muscle (2.5 μg/ml; Sigma–Aldrich, St. Louis, MO; cat. no. A5228), monoclonal anti-skeletal myosin (dilution: 1:800; Sigma–Aldrich; cat. no. M4276), and secondary biotinylated goat anti-rabbit or anti-mouse antibody (dilution: 1:400; Vector Laboratories, Burlingame, CA). Uteroplacental unit sections were stained with anti-cytokeratin KRT7 rabbit polyclonal antibody (dilution: 1:200; Proteintech Group; Chicago, IL; cat. no. 15539-1-AP). Mouse on mouse (M.o.m.) protocol was used for actin and myosin staining (Vector Laboratories, Burlingame, CA). One placenta

Fig. 1. Uterine artery responses in angiotensin-converting enzyme 2 knockout (ACE2 KO) and C57Bl/6 mice at day 14 of gestation. Stress-stretch response (A) and its rate constant (B) (n = 4 in each group); vasodilatory response to acetylcholine (C) and endothelial NOS immunostaining (D) (n = 4 in each group); contraction to phenylephrine (E) (n = 5–7). Data are means ± SE. *P < 0.05 vs. C57Bl/6.

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Table 2. Vascular reactivity in C57Bl/6 and ACE2 KO mice at day 14 of gestation

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>C57Bl/6</th>
<th>ACE2 KO</th>
</tr>
</thead>
<tbody>
<tr>
<td>K\textsubscript{MAX}</td>
<td>1.13 ± 0.12</td>
<td>1.90 ± 0.15*</td>
</tr>
<tr>
<td>Phe\textsubscript{MAX} (%K\textsubscript{MAX})</td>
<td>139.0 ± 7.0</td>
<td>169.0 ± 9.0*</td>
</tr>
<tr>
<td>pD\textsubscript{2} (−log EC\textsubscript{50})</td>
<td>6.76 ± 0.47</td>
<td>6.48 ± 0.13</td>
</tr>
<tr>
<td>ACh\textsubscript{MAX}</td>
<td>73 ± 7</td>
<td>76 ± 7</td>
</tr>
<tr>
<td>pD\textsubscript{2} (−log EC\textsubscript{50})</td>
<td>6.43 ± 0.4</td>
<td>6.19 ± 0.57</td>
</tr>
<tr>
<td>Ang II\textsubscript{MAX} (%K\textsubscript{MAX})</td>
<td>91.0 ± 5.0</td>
<td>93.0 ± 13.0</td>
</tr>
<tr>
<td>pD\textsubscript{2} (−log EC\textsubscript{50})</td>
<td>8.5 ± 0.03</td>
<td>8.64 ± 0.04*</td>
</tr>
</tbody>
</table>

Data are means ± SE. K\textsubscript{MAX}, maximal response to potassium chloride (K\textsuperscript+); Phe\textsubscript{MAX}, maximal response to phenylephrine; ACh, acetylcholine; pD\textsubscript{2}, negative logarithm of the molar concentration producing the half-maximum response (EC\textsubscript{50}).

... and one uterine artery per stain were examined under a light microscope and photographed at ×50 or ×200 magnifications with a QImaging Retiga 1300R CCD digital camera and SimplePCI (version 6) software: 6 fields per uterine artery section and 12 sections per one placenta (4 sections per each: labyrinth, junctional zone, and mesometrium). Images were analyzed using Adobe Photoshop 7.0 by the investigator blinded to the experimental groups. Staining for eNOS, actin, or myosin was normalized to the intensity of the background and to the maximal value of the red, green, and blue intensity (RGB) component and reported as relative intensity units (41, 62). The following stains were performed to assess morphological features of uterine arteries: periodic acid Schiff stain (PAS, Sigma-Aldrich; cat. no. 395B-1KT) to detect fibrinoid content, Verhoeff’s stain (American MasterTech; cat. no. KTVEL) to detect elastic fibers, and Picrosirius red stain (Sigma-Aldrich; assay components cat. no. 197378-100G; P6744-16A; 36-554-8) to assess connective tissue components (collagen and muscle cells). The area of cells stained by PAS and Verhoeff’s stain was normalized to the total area of vessel. The Picrosirius red intensity was expressed as the media-to-adventitia area ratio. PAS intensity in the media of uterine artery was normalized to the intensity of the background and to the maximal value of 255 of the RGB component and reported as relative intensity units (41, 62).

Trophoblast invasion. Decidual and mesometrial areas of the placenta of ACE2 KO and C57Bl/6 mice were examined for the depth of the trophoblast invasion and for the presence of trophoblast cells in the arterial walls (47). Trophoblast cells were identified by positive staining for cytokeratin KR7T, as described above. The distribution of extravillous (EVC) and arterial trophoblasts (ATB) and the extent of their invasion into mesometrium were analyzed using semiquantitative analysis as described by Pijnenborg et al. (47) as follows: 1 = high numbers evenly spread; 2 = high numbers focally spread; 3 = low numbers evenly spread; 4 = low numbers focally spread.

Assessments of placental hypoxia. 1) Hypoxyprobe-1 was injected intraperitoneally in the ACE2 KO and C57Bl/6 mice at day 14 of gestation (60 mg/kg maternal body wt). One hour later, the mother was euthanized, and placentas were fixed in 10% formalin for 24 h followed by 70% ethanol. After the fixation, placentas were embedded in paraffin, cut into 5-μm sections, and immunostained for hypoxyprobe-1 following the manufacturer’s protocol (25, 44). Hypoxic areas were identified in sections of the placenta using a Hypoxyprobe-1TM kit (Chemicon, Temecula, CA; cat. no. HPI-100kit) that contains pimonidazole hydrochloride and a primary antibody for the detection of pimonidazole. Pimonidazole binds to thiol-containing proteins in hypoxic cells; its level in the cells has been correlated with oxygen electrode measurements (51). 2) HIF-2α is a transcription factor that induces the expression of hypoxia-regulated genes. Levels of HIF-2α are increased under hypoxic conditions (11, 19). In addition, HIF-2α protein, but not HIF-1α, was induced in cytotrophoblast cells by hypoxia (18). Immunostaining for HIF-2α (1:100 antibody dilution, Abcam, San Francisco, CA; cat. no. ab199) was performed on paraffin-embedded sections using the ABC-DAB protocol described above. The relative intensities of pimonidazole and HIF-2α staining were analyzed in the whole placenta section as described above.

Statistical analysis. Comparisons between ACE2 KO and C57Bl/6 groups were evaluated using unpaired t-tests. Data obtained from the concentration-dependent responses of each arterial segment in each group were fitted to a logistic curve to determine maximal response and sensitivity. The curve had the form Y = bottom + (top - bottom)/(1 + 10\textsuperscript{(logEC\textsubscript{50} − X) × Hill Slope}) where X represents the logit of the drug concentration and Y the response. Values of
sensitivity were expressed as pD₂ (pD₂ = -Log EC₅₀), with EC₅₀ values obtained from the curve fittings. GraphPad Prism IV (San Diego, CA) plotting and statistical software were used. All measurements were expressed as means ± SE. The criterion for statistical significance was P < 0.05.

RESULTS

Physiological indexes. SBP was higher in pregnant ACE2 KO than in WT C57Bl/6 mice (Table 1) as previously observed at late gestation in the ACE2 KO pregnant mouse (3). The magnitude of difference in SBP in pregnant mice was similar to the difference observed in nonpregnant mice (ACE2 KO: 106.8 ± 3.2 vs. C57Bl/6: 94.2 ± 2.2 mmHg, n = 4). Moreover, maternal urinary protein excretion, serum creatinine, and kidney and heart weights were similar between groups (Table 1). Maternal weight was significantly lower in ACE2 KO mice, and this difference was sustained when total fetal weight was subtracted from the maternal weight. Maternal weight was independent of maternal food intake (Table 1). Fetal weight was lower in the ACE2 KO mice than in WT mice. There were no differences in placental weights; however, pup-to-placental weight ratio, an indirect measure of placental insufficiency, was significantly lower in the ACE2 KO vs. WT mice (Table 1).

Uterine artery reactivity and immunohistochemistry. ODs of uterine artery segments were not different between groups (236.0 ± 12.0 vs. 240.0 ± 7.0 μm, n = 4 in each group). Resting tension also was similar in both groups (1.75 ± 0.09 vs. 1.77 ± 0.09 mN/mm²). Similarly, the stress-stretch response and the rate constant were not statistically different between studied groups (Fig. 1, A and B). No difference in vasodilation in response to acetylcholine was observed in C57Bl/6 vs. ACE2 KO mice (Fig. 1C and Table 2). In addition, the intensity of the uterine artery eNOS immunostaining was similar between C57Bl/6 and ACE2 KO mice (Fig. 1D).

In contrast to the acetylcholine response, active tension, assessed as a response to 75 mM KCl, was significantly greater in uterine arteries of ACE2 KO (Table 2). In addition, as shown in Fig. 1E and Table 2, uterine arteries from ACE2 KO mice displayed greater maximal response to phenylephrine, with no difference in sensitivity. Since the sensitivity to Ang II decreases during pregnancy, we compared the reactivity of uterine arteries to Ang II. Uterine arteries from ACE2 KO mice were more sensitive to Ang II compared with C57Bl/6 mice (n = 5–6; Fig. 2A and Table 2). Preincubation with Ang-(1–7) at the concentration of 1 μM for 30 min decreased maximal contraction to Ang II in ACE2 KO but not in WT mice (Fig. 2B). A preincubation with Ang-(1–7) antagonist, [D-Ala₇]-Ang-(1–7) increased the Ang II contraction in the uterine artery of ACE2 KO but not in WT mice (Fig. 2B). There were no differences in the expression of AT₁R or AT₄R/MAS receptors in the uterine arteries of ACE2 KO vs. C57Bl/6 mice (Fig. 2C). However, the expression of AT₂R determined by the immunostaining was lower in the uterine arteries of ACE2 KO vs. C57Bl/6 mice (Fig. 2C).

Fig. 3. Images (A) and semiquantitative analysis (B) of morphological markers of arterial stiffness (PSR), elasticity (VH), fibrinoid content (PAS), and structural proteins (actin, myosin) of uterine arteries in ACE2 KO and C57Bl/6 mice. PAS, periodic acid Schiff stain; PSR, Picrosirius red stain; VH, Verhoeff’s stain. Data are means ± SE. *P < 0.05 vs. C57Bl/6. Magnification ×40.
Greater responses to phenylephrine and Ang II in ACE2 KO mice were associated with lower fibrinoid content as assessed by PAS staining (\(n = 4\) in each group) and a tendency for a higher collagen expression in the media of uterine artery as assessed by Picrosirius red staining (\(P = 0.05\), \(n = 4–5\); Fig. 3B). There were no differences observed in the intensity of actin or myosin between ACE2 KO and C57Bl/6 mice (\(n = 3–4\)). The area of Verhoeff staining indicative of elastin distribution in the uterine arteries was also similar in the two strains (Fig. 3B; \(n = 3–4\)).

**Uterine artery ultrasound data.** There were no differences in the uterine artery peak systolic or minimum diastolic velocities or resistance index of ACE2 KO compared with C57Bl/6 mice (\(n = 4\) in each group; Fig. 4A).

**Trophoblast invasion.** The extent of extravillous (EVTB) and arterial trophoblast (ATB) invasion in the decidua and mesometrium was compared between ACE2 KO and C57Bl/6 mice. No differences in EVT B or ATB distribution were found between ACE2 KO and C57Bl/6 mice (3.7 ± 0.1 vs. 3.4 ± 0.4 number of EVT B and ATB combined). In both strains, the EVT Bs evenly invaded into the decidua, reaching the upper limit of the decidua (Fig. 4B). Both strains showed variable signs of ATB invasion into the decidual arteries, going from no invasion in some arteries to complete invasion (Fig. 4B, inset). There were low numbers of ATBs and EVT Bs in arterial walls within the mesometrium in both strains.

**Placental hypoxia.** Cross-sections of the placenta were immunostained for the hypoxia marker pimonidazole and HIF-2α. As shown in Fig. 5, A and B, pimonidazole staining was higher in the trophospongium and the labyrinth of the ACE2 KO vs. C57Bl/6 placentas (1.9-fold, \(n = 4–5\)). In addition, HIF-2α immunostaining (Fig. 5, C and D) was also greater in decidual and labyrinth areas of the ACE2 KO mice compared with C57Bl/6 (\(n = 4–5\)).

**Umbilical artery ultrasound data.** Peak systolic velocities of umbilical arteries were significantly lower in the ACE2 KO mice (Fig. 6; \(n = 8–9\)). Minimum diastolic velocities of the umbilical arteries were similar in ACE2 KO and C57Bl/6 mice (Fig. 6; \(n = 8–9\)). The resistance index of umbilical arteries in ACE2 KO was lower than that of C57Bl/6 mice (0.90 ± 0.01 vs. 0.95 ± 0.01, \(n = 8–9\); Fig. 6).

**DISCUSSION**

We recently reported that ACE2 knockout is associated with reduced fetal weight at late pregnancy (3); however, the mechanisms underlying this growth-restricted phenotype are not known. In the present study, we found that the reduced fetal weight in ACE2 KO mice at day 14 of gestation is associated with uteroplacental dysfunction evidenced by greater uterine artery reactivity to vasoconstrictors, abnormal uterine artery remodeling, and placental hypoxia.

Most fetal growth in mice occurs during the last trimester of pregnancy (30). Intrauterine growth restriction is characterized by an abnormal vascular resistance and compromised blood flow (22). During normal pregnancy, blood flow progressively increases in the uteroplacental circulation, including the uterine artery and its branches and the umbilical artery (10a). The main...
uterine arteries provide ~80% of total uteroplacental flow (44). As a result of proper remodeling, uteroplacental vessels become more resistant to vasoactive substances compared with nonremodeled vessels (44). In addition, local mediators play a prominent role in the regulation of uteroplacental vascular reactivity (44). The relaxation of uterine arteries during normal pregnancy is mediated by nitric oxide- and endothelial-derived hyperpolarizing factors and prostacyclin (10, 42). Contrary to the responses of uterine artery isolated from pregnant eNOS knockout IUGR mice or small myometrial arteries isolated from human IUGR pregnancies (26, 61), we found similar relaxation responses to acetylcholine in ACE2 KO and WT mice, suggesting that ACE2 may not interfere with endothelial-dependent relaxation at day 14 of gestation in mice. Moreover, global gene knockout may result in a series of compensatory events that may mask the effects of ACE2 knockout in pregnancy. For example the activation of nephrilysin or other enzymes that can generate Ang-(1–7) (13) may be upregulated in the placenta of ACE2 KO mice. The levels of placental Ang-(1–7) were similar in ACE2 KO and WT mice at late gestation (3). Since Ang-(1–7) increases the release of nitric oxide, it may contribute to the acetylcholine-induced relaxation of uteroplacental vessels.

Here, we demonstrate that ACE2 KO mice have a higher response of the uterine artery to potassium chloride than WT mice, suggesting increased hypertrophy or hyperplasia of vascular smooth muscle cells (43). However, immunostaining for contractile proteins such as α-smooth muscle cell actin showed no difference and myosin staining only tended to increase. It is possible that our study was underpowered to detect significant differences in contractile proteins between groups. Optimal diameters and the stress-stretch responses are directly related to the elastic properties of the arterial tissue; no difference in these parameters suggests similar elastic properties of uterine arteries in ACE2 KO and WT mice. Similarly, equivalent values of resting tension between studied groups would suggest that the vascular hypertrophic and hyperplastic processes are unaffected by ACE2 at least in midpregnancy at the level of the uterine artery. The arterial response to potassium chloride is dependent on the influx of extracellular calcium and the activity of voltage-gated calcium channels (23). It is possible that higher expression of these channels or increased calcium signaling may augment the response to potassium chloride in the uterine artery of ACE2 KO mice. We demonstrate that uterine arteries of ACE2 KO mice were more responsive to phenylephrine than WT controls. As an α1-adrenergic agonist, phenylephrine can constrict blood vessels through the opening of voltage-gated calcium channels and through G protein-coupled receptor signaling (9, 34, 66). The even higher KMAX of phenylephrine exceeding that of high potassium suggests that
the latter pathway may be accentuated in the uterine artery of ACE2 KO mice. Increased contraction of the main uterine artery to phenylephrine late in pregnancy was also seen in eNOS knockout mice, which develop fetal growth restriction at late pregnancy (26). Furthermore, compared with normal pregnant women, higher contraction to arginine vasopressin was reported in small myometrial arteries of pregnant women who had fetal growth restriction, suggesting that greater uterine artery contraction is associated with reduced fetal growth (61). Reduced sensitivity of pressor response to Ang II is a characteristic feature of normotensive pregnancy (2, 15, 16). The concentration-dependent vasoconstriction to Ang II was greater in the uterine arteries from pregnant ACE2 KO mice vs. WT mice. Upregulation of AT1R or increased infiltration of neutrophils in the uterine artery has been suggested to play a role in the increased sensitivity to Ang II during pregnancy (2, 5, 15, 16, 36). It is well documented that the response of uterine artery to Ang II is opposed by the AT2R possibly via mechanisms involving nitric oxide production (6, 32, 33). The activation of AT3R also reduces blood pressure and induces vasodilation of local vascular beds in normotensive pregnant rats. The expression of AT2R is reduced in the uterine arteries of ACE2 KO mice, it is possible that vasodilation mediated by the AT2R is attenuated in this vascular bed and the protection conferred by the AT2R may be lost. Of interest, total knockout of AT2R in mice induces late-pregnancy hypertension and a significant T cell phenotypic switch toward a proinflammatory T-helper 1 phenotype, emphasizing the role of AT2R in blood pressure regulation during pregnancy (35). Since the expression of AT2R was reduced in the uterine arteries of ACE2 KO mice, it is possible that vasodilation mediated by the AT2R is attenuated in this vascular bed and the protection conferred by the AT2R may be lost. Of interest, total knockout of AT2R in mice induces late-pregnancy hypertension and a significant T cell phenotypic switch toward a proinflammatory T-helper 1 phenotype, emphasizing the role of AT2R in blood pressure regulation during pregnancy (35). Similar to other models associated with fetal growth restriction such as a transgenic rat model (49) or testosterone propionate-treated rats (7), increased sensitivity to Ang II and higher maximal contraction to phenylephrine in the ACE2 KO mouse suggest an overall increased sensitivity of uterine artery to vasoconstrictors (2, 16). Although the exact mechanisms of this phenomenon in ACE2 KO mice is unknown, incomplete remodeling in the uterine artery of ACE2 KO mice may contribute to higher contractility to vasoconstrictors. These findings emphasize the role of ACE2 knockout in uterine artery dysfunction.

Our data also show Ang-(1–7) induced attenuation of Ang II constriction in the uterine artery of ACE2 KO mice. This effect was achieved, at least in part, via Ang-(1–7) acting on its own receptor, because the Ang-(1–7) antagonist increased the Ang-(1–7) attenuation of the vasoconstriction to Ang II. Tallant et al. (54) demonstrated that Ang-(1–7) can bind to AT1R in vitro when used at higher micromolar concentrations. Therefore, the possibility of Ang-(1–7) binding to AT1R and thereby limiting AT1R bioavailability for Ang II is feasible. In addition, Ang-(1–7) can activate AT2R so the lower density of AT2R might limit actions of Ang-(1–7) in vivo (58). Neves (40) reported that Ang-(1–7) induces vasodilation of mesentery artery in normotensive pregnant rats, suggesting a regulatory role for this peptide in regional blood flow adaptations in pregnancy. Moreover, we (64) recently reported that Ang-(1–7) increases skin blood flow in normotensive pregnant women, suggesting a protective role of Ang-(1–7) in skin microcirculation. Nevertheless, a beneficial role of Ang-(1–7) in the regulation of uterine vasculature during hypertensive pregnancy, particularly in one associated with the activation of the RAS, needs further investigation.

Increased uterine blood flow during normal pregnancy is likely due to remodeling of the uteroplacental vasculature. The predictive and diagnostic value of reduced uterine artery flow in pregnancies with IUGR is controversial. Absent or reversed diastolic flow has been shown in such pregnancies (17), but not consistently (45). Abnormal uterine artery resistance can be influenced by incomplete systemic and local adaptations to pregnancy, including endothelial dysfunction and stiffness of maternal vasculature and placental pathology alterations (12). In our study, we found no differences in uterine artery veloc-
As stated above, one of the limitations of this model is global pregnancy that may be critical to the development of IUGR. In summary, IUGR is a leading cause of perinatal morbidity and mortality in humans; however, the molecular mechanisms of this pregnancy-induced complication are not well understood. Using mice with total ACE2 knockout allowed us to investigate the contribution of ACE2 to the development of IUGR. Our study revealed that uterine artery dysfunction in ACE2 KO mice is associated with placental hypoxia and greater uterine artery reactivity to vasoconstrictors, suggesting a protective role of ACE2 in the utero-placental unit. Increased contractility of uterine artery in ACE2 KO mice may represent an early event that as pregnancy progresses may translate into hemodynamic changes in the uterine artery. Placental hypoxia and uterine artery dysfunction develop before the major growth of the fetus occurs and may explain the growth-restricted phenotype. Our findings also emphasize the similarities of the ACE2 KO model of fetal growth restriction to human pregnancy associated with fetal growth restriction.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s). The authors have no relationships to disclose.

AUTHOR CONTRIBUTIONS


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