Reduced feed intake of lactating primiparous sows is associated with increased insulin resistance during the peripartum period and is not modified through supplementation with dietary tryptophan

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ABSTRACT: The aim of this experiment was to investigate whether insulin resistance is related to the dietary concentration of Trp and the ADFI of primiparous sows having similar body conditions. Twenty-four primiparous sows were catheterized on d 97 of pregnancy. Blood samples were collected during 3 tests: after the ingestion of 1.5 kg of feed (meal test), after the intravenous infusion of 0.5 g of glucose/kg of BW (glucose tolerance test), and during an euglycemic hyperinsulinemic clamp with an infusion rate of 100 ng of insulin·kg of BW−1·min−1. Both tests were performed at 4 stages at approximately d 103 and 110 of pregnancy and at d 3 and 10 of lactation. Sows were fed a diet containing 0.16 or 0.26% of total Trp (suboptimal vs. slight excessive Trp supply according to recommendations for lactating sows) from d 104 of pregnancy after the first clamp until weaning. The dietary treatment did not result in differences in ADFI, BW, and backfat changes, and growth of piglets during lactation. Plasma Trp concentration was greater for the sows allocated to the slight excessive Trp diet than for the sows allocated to the suboptimal Trp diet (P < 0.05). Plasma glucose, NEFA, and urea profiles during the meal tests were not affected by the dietary treatment. At d 3 of lactation, the insulin concentration at 105 (P = 0.03) and 120 min (P = 0.04) after meal intake was less for the sows allocated to the slight excessive Trp diet than for the sows allocated to the suboptimal Trp diet. On d 10 of lactation, the glucose half life (P = 0.03) and the time needed to reach 25% of the area under the insulin curve (P = 0.04) during the tolerance test were less for the sows allocated to the slight excessive Trp diet than for the sows allocated to the suboptimal Trp diet. The glucose infusion rate during euglycemic hyperinsulinemic clamps was similar in the 2 Trp groups of sows. Irrespective of the dietary treatment, the ADFI of the sows was negatively related to the glucose half life during the glucose tolerance test and positively related to the glucose infusion rate during the clamp (P < 0.05). This relationship observed with the tests performed during early lactation was already found with the tests performed during late pregnancy (P < 0.02). Present findings indicate that a dietary Trp supply of 0.26% does not increase feed intake in lactating primiparous sows. This result indicates that the interest in a Trp supplementation during the peripartum period can be questioned. Irrespective of the dietary treatment, the reasons why sows with similar rearing conditions develop different rates of insulin resistance during pregnancy remain to be elucidated.

Key words: farrowing, feed intake, insulin resistance, primiparous sow, tryptophan

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INTRODUCTION

During pregnancy and lactation, the sow undergoes numerous physiologic and metabolic changes such as a progressive and reversible insulin resistance corresponding to a decreased effectiveness of insulin to regulate blood glucose (Père and Etienne, 2007). Insulin resistance is characterized by a persistent hyperglycemia despite a greater insulin secretion after the meal and is assumed to increase the availability of glucose for the growth of fetuses during pregnancy and milk production during lactation (Le Cozler et al., 1998; Père and...
Animals and Housing

Sows having similar body conditions was also assessed. The relationship between ADFI and insulin resistance within favor ADFI of primiparous sows. The potential relationship between ADFI and insulin resistance may be involved in the decreased ADFI induced by a Trp-deficient diet. The present study was undertaken to investigate whether a slight supplementation of dietary Trp can decrease the insulin resistance and favor ADFI of primiparous sows. The potential relationship between ADFI and insulin resistance within sows having similar body conditions and be related to ADFI.

A deficient as well as an excessive dietary supply of Trp impairs the appetite of lactating sows (Lewis and Speer, 1974; Paulicks et al., 2006). The actual recommendation for the Trp:Lys ratio in the lactation diet is 18% (Dourmad et al., 1991; NRC, 1998) but was recently estimated at 24% on the basis of feed intake and uremia (Pampuch et al., 2006; Paulicks et al., 2006). However, these authors studied multiparous sows only, and the effect of such a dietary Trp concentration on the performance of lactating primiparous sows remains to be investigated. Apart from its function as the serotonin precursor, a neurotransmitter that acts on appetite (Blundell, 1984), Trp could act on feed intake through an action on insulin secretion and sensitivity (Sève, 1999). Indeed, Ponter et al. (1991) reported that piglets fed a Trp-deficient diet had greater plasma insulin and glucose concentration after an intragastric infusion of glucose than piglets fed a Trp-adequate diet. Therefore, these authors hypothesized that insulin resistance may be involved in the decreased ADFI induced by a Trp-deficient diet. The present study was undertaken to investigate whether a slight supplementation of dietary Trp could decrease the insulin resistance and favor ADFI of primiparous sows. The potential relationship between ADFI and insulin resistance within sows having similar body conditions was also assessed.

MATERIALS AND METHODS

The animals used in this experiment were reared according to the regulations of the French Ministry of Agriculture for humane care and use of animals in research.

Animals and Housing

Thirty-two French Landrace × Large White gilts were studied in 8 replicates (4 gilts per replicate). They were inseminated at 260 ± 3 d of age with semen from Pietrain boars and individually housed in pregnancy crates until surgery on d 97 of pregnancy. They were then housed in farrowing crates with stainless-steel slatted floors until weaning. Artificial lighting was provided between 0800 and 1800 h, and the ambient temperature was maintained between 22 and 25°C. In each farrow-

Surgery

On d 97 of pregnancy, an indwelling catheter (2.16 mm o.d. and 1.02 mm i.d.; Silastic, Dow Corning, Midland, MI) was inserted through a collateral vein in the right external jugular vein, and an indwelling catheter (2.29 mm o.d. and 1.27 mm i.d.; Tygon Tubing, Cole-Parmer Instrument Co., Vernon Hills, IL) was inserted in the carotid artery as described previously by Pére and Etienne (2007). General anesthesia was induced through intravenous injection of 1 g of sodium thio-
pental (Nesdonal, Rhône-Mérieux, Toulouse, France) combined with 1.2 mg of atropine (Aguettant, Lyon, France) per 100 kg of BW and maintained with 2 to 5% halothane (Fluothane, Belamont, Neuilly sur Seine, France) in oxygen (3 L/min). Sows were fasted on the evening before surgery and were fed again when they were housed in their farrowing crates. Catheters were flushed 3 times weekly with a 10-mL saline solution (154 mM NaCl) containing 200 IU of heparin/mL.

**Table 1. Composition of diets (as-fed basis)**

<table>
<thead>
<tr>
<th>Item</th>
<th>Pregnancy</th>
<th>Trp−</th>
<th>Trp+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ingredient, %</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barley</td>
<td>25.60</td>
<td>25.60</td>
<td>25.60</td>
</tr>
<tr>
<td>Wheat</td>
<td>15.00</td>
<td>15.00</td>
<td>15.00</td>
</tr>
<tr>
<td>Corn</td>
<td>29.14</td>
<td>25.23</td>
<td>25.11</td>
</tr>
<tr>
<td>Wheat bran</td>
<td>8.00</td>
<td>8.00</td>
<td>8.00</td>
</tr>
<tr>
<td>Linseed oil</td>
<td>2.00</td>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>Sugar beet molasses</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Sugar beet pulp</td>
<td>5.00</td>
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<td>5.00</td>
</tr>
<tr>
<td>Corn gluten meal</td>
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<tr>
<td>Potato protein concentrate</td>
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<td>3.00</td>
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<tr>
<td>Phytase</td>
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<td>0.01</td>
</tr>
<tr>
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<tr>
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<tr>
<td>l-Tryptophan</td>
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<tr>
<td>l-Threonine</td>
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<td>0.06</td>
<td></td>
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<tr>
<td>NE, MJ/kg</td>
<td>10.06</td>
<td>10.04</td>
<td>10.05</td>
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<td>CP, N × 6.25</td>
<td>14.70</td>
<td>16.70</td>
<td>16.90</td>
</tr>
<tr>
<td>AA, %</td>
<td>Lysine</td>
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<td>0.87</td>
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<tr>
<td></td>
<td>Threonine</td>
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<td>0.76</td>
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<td>Arginine</td>
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<tr>
<td></td>
<td>Histidine</td>
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<td>Isoleucine</td>
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<tr>
<td></td>
<td>Tryptophan</td>
<td>0.13</td>
<td>0.16</td>
</tr>
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</table>

1Supplied per kilogram of diet: vitamin A, 10,000 IU; vitamin D₃, 1,500 IU; vitamin E, 30 IU; vitamin K, 2 mg; thiamin, 2 mg; riboflavin, 4 mg; niacin, 20 mg; d-pantothenic acid, 10 mg; pyridoxine, 3 mg; d-biotin, 0.2 mg; folic acid, 3 mg; vitamin B₁₂, 20 µg; choline, 500 mg; Fe, 80 mg as ferrous carbonate; Cu, 10 mg as copper sulfate; Mn, 40 mg as manganous oxide; Zn, 100 mg as zinc oxide; Co, 0.1 mg as cobalt sulfate; I, 0.6 mg as calcium iodate; and Se, 0.15 mg as sodium selenite. Additional niacin and pyridoxine were added in both lactation diets at 10 and 2 mg/kg, respectively.

2Calculated from INRA-AFZ (2002) tables.

3Analyzed.

Evaluation of Insulin Resistance

**Experimental Design.** Three tests (meal test, glucose tolerance test, and euglycemic hyperinsulinemic clamp) were performed on each sow at 4 stages around farrowing [i.e., on d 103.4 ± 0.1 (LP = late pregnancy) and d 110.5 ± 0.2 (BF = before farrowing) of pregnancy and on d 3.8 ± 0.2 (AF = after farrowing) and d 10.5 ± 0.2 (LAC = lactation) of lactation]. The meal test was performed during the morning meal and was followed by the glucose tolerance test in the afternoon. The clamp was performed on the morning of the next day. Until the first set of tests, all sows received the pregnancy diet and were allocated to 1 of the 2 experimental lactation diets thereafter (i.e., after the first clamp performed at d 104 of pregnancy). The meal test and the euglycemic hyperinsulinemic clamp were performed after an overnight fasting period of 16 h during pregnancy and 12 h during lactation. Injections were made via the venous catheter, and blood was sampled via the arterial catheter.

**Meal Test.** Blood (6 mL) was collected at −30, −5, 15, 30, 45, 60, 75, 90, 105, 120, 150, 180, 210, and 240 min with time 0 corresponding to the delivery of 1.5 kg of the pregnancy diet at LP and of the experimental lactation diet at BF, AF, and LAC. The meal lasted...
about 10 to 15 min. Plasma glucose concentration was measured in all samples. Plasma concentration of insulin was determined at −30 and −5 min, at 15-min intervals from 0 to 120 min, and then at 180 and 240 min after the meal delivery. Plasma concentrations of NEFA and Trp were measured at −30, −5, 30, 60, 120, 180, and 240 min after the meal delivery. Finally, plasma concentration of urea was measured once before and hourly after the meal delivery.

**Glucose Tolerance Test.** This test consisted of the injection of 0.5 g of glucose/kg of BW (1.665 M sterile glucose, Braun, Boulogne, France). Blood (3 mL) was collected at −5, 0, 3, 6, 10, 15, 20, 25, 30, 35, 40, 50, 60, and 75 min after the injection, which lasted less than 5 min. Time 0 corresponded to the first blood sample collected just after the injection of a 10-mL saline solution (154 mM NaCl) that followed the glucose injection to rinse the catheter. Plasma glucose and insulin concentrations were determined in all samples.

**Euglycemic Hyperinsulinemic Clamp.** During the 60 min before the perfusion, 5 mL of blood were collected every 15 min. Among these 5 mL, 1 mL was used to immediately measure the total blood glucose concentration using a glucometer (OneTouch GlucoTouch Plus, LifeScan, Issy les Moulineaux, France). The average of these basal concentrations determined the glucose concentration to be maintained throughout the test. The remaining 4 mL of blood was centrifuged, and plasma samples were frozen for further analyses. Additionally, 8 mL of blood of the tested gilt was collected to prepare the infused insulin solution. About 34 mL of a saline solution (154 mM NaCl) was mixed with 4 mL of blood plasma and 2 mL of insulin (human insulin, 100 IU/mL, Umuline Rapide, Lilly France S.A.S, Suresnes, France) to obtain a solution containing about 200 ng of insulin/µL. Time 0 corresponded to the beginning of the infusion of the insulin and glucose solution (1.665 M sterile glucose, Braun, Boulogne, France). The insulin solution was infused continuously using a syringe pump (kdS model 260, KD Scientific, Boston, MA) at a constant rate calculated to provide 100 ng of insulin·kg of BW·min−1. During the first 10 min of the clamp, this rate was 4-fold increased to accelerate the effect of the exogenous insulin on the blood glucose of the sow. Infusion lasted 180 min and was associated with the infusion of glucose at a variable rate using a peristaltic pump (IPC-04, Ismatec SA, Zürich, Switzerland). Every 5 min, 1 mL of blood was collected to immediately measure the glucose concentration and then adapt the infusion rate of glucose to maintain euglycemia. At the same time, the weight of the flask of glucose placed on a scale was registered to measure the glucose infusion rate. Every 15 min, 5 mL of blood was collected for further analyses of plasma glucose, insulin, and NEFA concentrations. Steady-state conditions of euglycemia were generally achieved before 60 min after the beginning of infusion. During the clamps performed at AF and LAC, litters were moved to a separate room to prevent a possible effect of suckling on sow glycemia.

**Blood Preparation and Physiological Measurements**

For each test, blood samples were transferred immediately after collection in heparinized tubes kept on ice and centrifuged for 8 min at 2,750 × g at 4°C. Then, plasma samples were stored at −20°C until analyses. Plasma Trp was determined using 200 µL of plasma mixed with the same volume of potassium phosphate buffer (0.05 M, pH 6.0) and 50 µL of 2 M trichloroacetic acid. After centrifugation, supernatant was analyzed by HPLC on a reverse phase C18 column (Alliance System, Waters, Milford, MA). The 3-nitro-l-tyrosine was used as an internal standard. Tryptophan was then detected by fluorometry as described by Widner et al. (1997). Plasma concentrations of NEFA (NEFA C ref. 754664, Wako, Dardilly, France), glucose, and urea (bio-Mérieux kits ref. 61269 and 61974, respectively, Marcy l’Etoile, France) were determined using enzymatic methods adapted on a Cobas Mira multichannel analyzer (Roche, Basel, Switzerland). Plasma concentration of insulin was measured using a commercial RIA kit (CIS Bio International, Gif sur Yvette, France). The sensitivity was 3 μIU/mL, and intra- and interassay CV were 6.4 and 13.2% at 83.7 μIU/mL, respectively.

**Calculations and Statistical Analyses**

All data were subjected to an ANOVA using the MIXED procedure (SAS Inst. Inc., Cary, NC). Among the 32 sows inseminated, 4 sows were discarded from the experiment. Two sows had leg problems, 1 sow stopped eating in mid-gestation, and 1 sow stopped eating from the end of gestation to the middle of lactation. The causes of the appetite problems were not determined. Therefore, data on BW, backfat depth, and ADFI of sows and on piglets BW were analyzed for 28 sows (14 Trp− vs. 14 Trp+). The sow represented the experimental unit in the model, which included the effect of the experimental diet, replicate, and interaction between both.

Among the 28 sows kept in the experiment, 4 sows could not be subjected to the physiological tests because of nonfunctional catheters. Data on meal and glucose tolerance tests were then obtained on 24 sows (12 Trp− vs. 12 Trp+). During each clamp, the glucose infusion rate of 1 sow allocated to the Trp− diet was about 2-fold greater than in other sows in relation to its increased activity during the infusion time. Because calculation of the glucose infusion rate is relevant only when the sow is lying down and quiet (Père and Etienne, 2007), this sow was excluded from the analyses of the data on the euglycemic hyperinsulinemic clamp. For each meal test, the mean of the 2 fasting concentrations of the blood variables was further considered as time 0. For the glucose tolerance test, the glucose half life was estimated from individual regression equations as described previously by Père and Etienne (2007).
The area under the insulin curve was determined by linear interpolation of insulin concentrations between the measurements, with the fasting insulin value as the base line. It was estimated between time 0 and the time at which insulin concentration returned to the fasting value. The time to reach 25, 50, or 75% of this area was also determined by interpolation. For each euglycemic hyperinsulinemic clamp, the mean of the 4 fasting concentrations of the blood variables was further considered as time 0. The values of the glucose infusion rate obtained when the sow was agitated or standing were eliminated. The glucose infusion rate used in the calculations was the average of the remaining values measured between 60 and 180 min. The model used to analyze the blood measurements obtained in both meal test, glucose tolerance test, and euglycemic hyperinsulinemic clamp included the effect of experimental diet, stage, time of sampling, replicate, and interactions between experimental diet and stage of measurement, between stage of measurement and time of sampling, and between experimental diet, stage of measurement, and time of sampling.

Regression equations were calculated between ADFI from d 1 to 3 of lactation and glucose half life during the glucose tolerance test or glucose infusion rate during the clamp. Irrespective of the dietary treatment, the experimental sows were partitioned in 2 groups according to their ADFI between d 1 and 3 of lactation, d 3 of lactation corresponding to the first stage of measurement of insulin resistance after farrowing. Eleven sows had a less ADFI than the mean calculated for all sows and were then allocated to the low ADFI group. The effect of the group was analyzed for ADFI, BW, and backfat depth of the sows, growth rate of piglets, glucose infusion rate, glucose half life, and time needed to reach 50% of area under the insulin curve.

RESULTS

Sow and Piglet Performance According to the Dietary Supply of Trp

The dietary treatment did not affect the ADFI of sows during lactation ($P > 0.10$; Figure 1). Feed intake slowly increased during the first 13 d after farrowing ($P < 0.05$) and remained constant thereafter. The variations of BW and backfat depth of sows during pregnancy and lactation were not affected by the dietary treatment (Table 2). The BW and backfat losses of sows during lactation averaged 27.4 ± 4.7 kg and 6.2 ± 0.7 mm, respectively. Similarly, regardless of age, the BW and the number of piglets nursed by the sow were not affected by the experimental diet allowed to the dam.

Meal Test According to the Dietary Supply of Trp

Fasting Plasma Concentrations. The dietary treatment did not affect the fasting concentrations of glucose, insulin, NEFA (Figure 2), and urea (Figure 3). The fasting glucose concentration was less at LAC than at the other stages ($P < 0.01$; Figure 2, panels A1 and A2). Fasting NEFA concentrations were greater during lactation than during pregnancy ($P < 0.05$) with the greatest value at LAC ($P < 0.001$; Figure 2, panels C1.
An interaction between the dietary treatment and the stage of measurement was observed for plasma Trp concentration ($P < 0.001$; Figure 3, panels A1 and A2). The fasting Trp concentrations did not differ during the 4 stages of measurement for the Trp+ sows, but they were less during lactation than during pregnancy for the Trp− sows ($P < 0.05$).

**Plasma Concentrations After the Meal.**

There was no effect of the dietary Trp treatment on the variations of plasma glucose concentration after feed intake (Figure 2, panels A1 and A2). The glucose concentrations measured between 30 and 105 min after the meal were less at LP than at the other stages ($P < 0.05$). Glucose concentration measured between 60 and 90 min after the meal was greater during lactation than during pregnancy ($P < 0.05$). At each stage, the plasma concentration of glucose measured at 240 min after the meal remained greater than the concentration measured before the meal ($P < 0.02$). At AF, the insulin concentration at 105 ($P = 0.03$) and 120 min ($P = 0.04$) after the meal was less for the Trp+ sows than for the Trp− sows (Figure 2, panel B2), whereas the interaction between dietary treatment and stage of measurement was not significant. Regardless of the supply of dietary Trp, insulin concentration in plasma increased within 30 min after the meal at LP ($P = 0.005$) and within 45 min at BF, AF, and LAC ($P < 0.05$) and then returned to the fasting value within 240 min ($P < 0.05$; Figure 2, panels B1 and B2). Between 45 and 90 min after the meal, insulin concentration was less at LP than at the other stages. Between 30 and 60 min after the meal, insulin concentration was greater at LAC than at the other stages. There was no effect of the dietary treatment on the variations of plasma NEFA. Irrespective of the physiological stage, plasma NEFA concentrations decreased within 60 min after the meal ($P < 0.01$; Figure 2, panels C1 and C2).

**Insulin Resistance, Tryptophan, and Feed Intake**

The Trp content of the lactation diet did not affect the glucose profile obtained after the injection of glu-
Glucose returned to its basal concentration at 30, 35, 40, and 50 min after the end of the injection for LP, BF, AF, and LAC, respectively (Figure 4, panels A1 and A2). An interaction between the dietary treatment and the stage of measurement was observed for the glucose half life ($P = 0.03$; Table 3). At AF, the glucose half life tended to be greater for the Trp+ sows than for the Trp− sows ($P = 0.08$), whereas at LAC, it was less for the Trp+ sows than for the Trp− sows ($P = 0.03$).

Regardless of the dietary supply of Trp, glucose half life was less during pregnancy than during lactation ($P < 0.05$). An interaction between the dietary treatment and the stage of measurement was observed for the glucose half life ($P < 0.05$; Table 3). At AF, the glucose half life tended to be greater for the Trp+ sows than for the Trp− sows ($P = 0.08$), whereas at LAC, it was less for the Trp+ sows than for the Trp− sows ($P = 0.03$).
ment and the stage of measurement was also observed for the insulin profile during the test \( (P < 0.001) \). At AF, the plasma insulin concentration during the 15 min after infusion was less for the Trp+ sows than for the Trp− sows \( (P < 0.05) \); Figure 4, panel B2). At LAC, the insulin concentration at 75 min tended to be less for the Trp+ sows than for the Trp− sows \( (P = 0.07) \). Finally, the area under the insulin curve did not differ among dietary treatments, but the time needed to reach 25% of the area under the insulin curve at LAC was less for the Trp+ sows than for the Trp− sows \( (P = 0.04; \text{Table 3}) \). Similar trends were observed for the time needed to reach 50 \( (P = 0.06) \) and 75% of the area under the insulin curve \( (P = 0.06) \).

**Euglycemic Hyperinsulinemic Clamp According to the Dietary Supply of Trp**

The dietary treatment of the sows had no effect on the measurements made during the clamp. In sows fed the Trp+ diet, the glucose infusion rate decreased between LP and BF \( (P = 0.04; \text{Table 3}) \). Then, the glucose infusion rate of the Trp+ sows progressively returned to the value measured at LP. The glucose infusion rate measured from 60 to 180 min did not vary throughout the experimental period for the Trp− sows. However, the interaction between the dietary treatment and the stage of measurement was never significant. Irrespective of the dietary treatment and the physiological stage, plasma NEFA expressed as a percentage of their basal concentration decreased within the first 60 min of infusion \( (P < 0.05; \text{Figure 5}) \).

**Insulin Resistance and Feed Intake**

Irrespective of the dietary treatment, the ADFI of the sows during the first 3 d after farrowing was negatively related to the glucose half life during the glucose tolerance test and positively related to the glucose infusion rate during the clamp \( (P < 0.05; \text{Figure 6}) \). The 2 groups of sows created according to their ADFI after farrowing had similar backfat depth at 112 d of pregnancy and BW after farrowing (Table 4). Regardless of dietary treatment, sows with decreased ADFI between...
d 1 and 3 of lactation also had decreased ADFI between d 4 and 10 of lactation ($P < 0.01$). Sows with decreased ADFI after farrowing had less glucose infusion rates during the clamps and greater glucose half life at LP, BF, and AF, and longer time to reach 50% of the area under the insulin curve at LP and AF than sows with increased high ADFI ($P < 0.05$). The growth rate of the piglets did not differ according to the ADFI of the sow after farrowing and averaged 185 ± 6, 262 ± 6, and 260 ± 8 g/d during the first, second, and third week of lactation, respectively.

**DISCUSSION**

**Voluntary Feed Intake and Dietary Supply of Trp**

The ADFI of the primiparous sows studied in the present experiment did not differ with the dietary supply of Trp. This is in contradiction with the results obtained on multiparous sows by Paulicks et al. (2006), who observed a progressive increase of ADFI from 4.7 to 6.1 kg when the Trp content of the lactation diet was augmented from 1.5 to 2.4 g/kg. In the present experiment, the ADFI of the sows over the entire lactation was 4.8 and 4.5 kg for a dietary Trp supply of 1.6 and 2.6 g/kg, respectively. The effect of the dietary supply of Trp could be attenuated in primiparous sows because of their decreased abilities to increase their ADFI during lactation than multiparous sows (Koketsu et al., 1996). Furthermore, the German Landrace used by Paulicks et al. (2006) could have different Trp requirement than the French Landrace × Large White gilts used in the present study. Urea is an indicator of AA catabolism in the liver. It increases in case of imbalance between the requirement and the dietary profile of AA and with increased feed intake. In the present experiment, plasma urea did not differ between the 2 groups of sows. This is in agreement with the similar ADFI and suggests that 1.6 g of Trp/kg of diet may not be as suboptimal in primiparous sows as it is in the multiparous sows from the study of Paulicks et al. (2006).
Indeed, the Trp:Lys ratio of the Trp− diet used in our study was 18%, which is less than the recommendation given by Paulicks et al. (2006), but corresponds to the recommendation for lactating sows given by Dourmad et al. (1991) and NRC (1998). In agreement with the similar ADFI between the 2 groups of sows, the BW and backfat losses of the sows and the piglets growth rate did not vary with the dietary supply of Trp.

**Insulin Resistance and Dietary Supply of Trp**

In the present experiment, 3 tests (meal test, glucose tolerance test, and euglycemic hyperinsulinemic clamp) were performed to evaluate the effectiveness of insulin to regulate blood glucose. The meal test assesses the variations of both endogenous glucose and insulin in normal conditions of feed intake (i.e., within a physiological range of values). The glucose tolerance test evaluates the responsiveness of insulin after an intravenous load of glucose (Weldon et al., 1994). Finally, during the euglycemic hyperinsulinemic clamp, glucose and insulin are infused. Glucose infusion rate is adjusted to be equivalent to the rate of glucose uptake by body tissues. Therefore, the clamp measures the tissue sensitivity to insulin (DeFronzo et al., 1979). The advantage of the glucose tolerance test is to study the response of endogenous insulin, whereas the clamp uses exogenous insulin. The advantage of the euglycemic hyperinsulinemic clamp is to study the insulin resistance in steady-state conditions of glycemia and insulinemia, whereas insulin and glucose concentrations vary with time during the glucose tolerance test.

Previous studies provided evidence of a relationship between Trp and glucose metabolism in young pigs. Ponter et al. (1991) observed that after an intragastric load of glucose, piglets previously fed a diet with a deficient concentration of Trp have greater glycemia despite greater plasma insulin concentration than piglets fed a diet with adequate Trp. Moreover, Matte et al. (1997) showed that glycemia decreases more rapidly after the infusion of 5.4 g of glucose plus 26 mg of Trp per kg of BW than after the infusion of glucose only, whereas the insulin secretion was similar. These results suggest that Trp could promote the uptake of glucose through increasing insulin sensitivity. The meal tests performed in our experiment showed that the increase in the supply of dietary Trp increased the plasma Trp concentration in agreement with the previous results of Sève et al. (1991) and Pampuch et al. (2006). The blood concentrations of the other variables measured after the meal did not vary according to the dietary treatment except for the plasma insulin response, which was less in the Trp+ sows than in the Trp− sows at AF. The glucose profile being similar between the 2 diets, this result suggests a greater effectiveness of insulin to decrease blood glucose in the Trp+ sows in early lactation. Concerning the glucose tolerance test performed at AF, the insulin concentration during the 15 min after the load of glucose was less for the Trp+ than for the Trp−

### Table 3. Glucose half life, insulin concentration at 75 min (T75), and time to reach 25, 50, and 75% of the area under the insulin curve according to the dietary supply of Trp from d 104 of pregnancy until weaning

<table>
<thead>
<tr>
<th>Stage</th>
<th>LP</th>
<th>AF</th>
<th>BF</th>
<th>LAC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Item</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glucose half life, min</td>
<td>13.5 a</td>
<td>13.7 a</td>
<td>16.2 a b</td>
<td>15.4 a</td>
</tr>
<tr>
<td>Glucose concentration at T75, µU/mL</td>
<td>12.7 a b</td>
<td>12.9 a b</td>
<td>12.0 a b</td>
<td>19.0 a b</td>
</tr>
<tr>
<td>Area under the insulin curve, mIU·mL−1·min</td>
<td>4.5 a b</td>
<td>4.6 a b</td>
<td>4.6 a b</td>
<td>10.0 a b</td>
</tr>
<tr>
<td>Time to reach 25% of the area under the insulin curve, min</td>
<td>7 a b</td>
<td>7 a b</td>
<td>7 a b</td>
<td>8 a b</td>
</tr>
<tr>
<td>Time to reach 50% of the area under the insulin curve, min</td>
<td>14 a b</td>
<td>14 a b</td>
<td>14 a b</td>
<td>14 a b</td>
</tr>
<tr>
<td>Time to reach 75% of the area under the insulin curve, min</td>
<td>21 a b</td>
<td>21 a b</td>
<td>21 a b</td>
<td>21 a b</td>
</tr>
<tr>
<td>Glucose infusion rate, mg·kg−1·min−1</td>
<td>30.7 a b</td>
<td>29.8 a b</td>
<td>29.8 a b</td>
<td>29.8 a b</td>
</tr>
<tr>
<td>Insulin concentration at T75, µIU/mL</td>
<td>18.7 a b</td>
<td>19.5 a b</td>
<td>19.5 a b</td>
<td>19.5 a b</td>
</tr>
<tr>
<td>Area under the insulin curve, mIU·mL−1·min</td>
<td>4.5 a b</td>
<td>4.6 a b</td>
<td>4.6 a b</td>
<td>10.0 a b</td>
</tr>
<tr>
<td>Time to reach 25% of the area under the insulin curve, min</td>
<td>7 a b</td>
<td>7 a b</td>
<td>7 a b</td>
<td>8 a b</td>
</tr>
<tr>
<td>Time to reach 50% of the area under the insulin curve, min</td>
<td>14 a b</td>
<td>14 a b</td>
<td>14 a b</td>
<td>14 a b</td>
</tr>
<tr>
<td>Time to reach 75% of the area under the insulin curve, min</td>
<td>21 a b</td>
<td>21 a b</td>
<td>21 a b</td>
<td>21 a b</td>
</tr>
</tbody>
</table>

Within a row, means without a common superscript letter differ (P < 0.05).
Figure 5. Plasma profile of NEFA (expressed as a percentage of the basal concentration) during the euglycemic hyperinsulinemic clamp for sows receiving a suboptimal (Trp− = 1.6 g/kg; n = 11) or a slight excessive (Trp+ = 2.6 g/kg; n = 12) supply of dietary Trp from d 104 of pregnancy until weaning (LP = late pregnancy; BF = before farrowing; AF = after farrowing; L = lactation). Time 0 corresponded to the beginning of perfusion of insulin and glucose. No interaction was observed between the dietary treatment and the stage of measurement. Fasting NEFA were greater at L than at LP, BF, and AF (P < 0.05). The NEFA decreased within 60 min after the beginning of the infusion (P < 0.05).

Figure 6. Relationship between ADFI during the first 3 d after farrowing (ADFI d1-3) and insulin resistance during the peripartum period. GHL = glucose half life during the glucose tolerance tests; GIR = glucose infusion rate during clamps; LP = late pregnancy; BF = before farrowing; AF = after farrowing.
sows. However, the area under the insulin curve did not differ between the 2 groups of sows suggesting a similar but delayed insulin secretion in the Trp+ sows. In the same time, the half life of glucose tended to be less for the Trp− than for the Trp+ sows. Concerning the clamp, the glucose infusion rate at AF did not differ according to the dietary treatment. Therefore, we cannot conclude about a difference in insulin resistance in early lactation between the 2 groups of sows. At LAC, the glucose half life, the insulin concentration at 75 min after the infusion of glucose, and the time needed to reach 25, 50, and 75% of the area under the insulin curve during the glucose tolerance test were less for the Trp+ than for the Trp− sows. These results may indicate that the increased dietary supply of Trp decreased the insulin resistance of the sows at this stage. However, the glucose infusion rate during the clamp was similar between the 2 Trp groups. Therefore, the effect of the dietary levels of Trp used in the present experiment on the insulin resistance of primiparous sows can be questioned.

The lack of effect of the dietary Trp on the insulin resistance could be related to the duration of the experimental treatment, the levels of Trp supply used, or a combination of both. However, Ponter et al. (1991) measured an increased insulin secretion after an intragastric infusion of glucose between piglets receiving an adequate or a deficient supply of Trp during 3 d. In our study, the sows received the experimental diets during 6 d before the first measure of the insulin resistance. Moreover, present results showed an increase in the plasma Trp concentration in the Trp+ sows in comparison with the Trp− sows from the first meal test performed after the beginning of the treatment. Thus, the duration of the treatment does not seem involved in the lack of effect of the dietary supply of Trp on the insulin sensitivity. The secretion of insulin after the intragastric infusion of glucose performed by Ponter et al. (1991) was increased in the piglets fed the adequate Trp diet in comparison with the piglets fed the deficient Trp diet, whereas it was intermediate for the piglets fed an excessive Trp diet. It can be then supposed that the lack of effect of the dietary Trp on insulin resistance could be related to the fact that neither of the 2 levels of Trp used in our experiment was deficient according to the requirement for the lactating primiparous sows. Finally, the interest of a supplementation in dietary Trp in the parturient sow can be questioned because neither ADFI nor insulin resistance was modified.

### Variations of Insulin Resistance and Feed Intake

Whatever the dietary treatment, the plasma concentrations of glucose and insulin during the meal test increased between LP and BF and between pregnancy and lactation, whereas the amount of feed provided for the test was the same. Moreover, the glucose half life measured during the glucose tolerance test was greater during lactation than during pregnancy. This is in agreement with the study of Père and Etienne (2007), who observed that the insulin resistance developed dur-
ing late gestation is accentuated during lactation. This phenomenon may allow the sparing of glucose for the milk production, which requires an increased amount of energy (Noblet et al., 1990). In such conditions, the lactating sow mobilizes its body reserves to provide energy for her own metabolism (Etienne et al., 1985) as shown by the increased plasma NEFA concentrations observed during lactation in the present experiment. Dourmad (1991) showed that fat sows have decreased ADFI than thin sows during early lactation and that this effect is related to the differences in adipose mass. In later studies, it was observed that the decreased ADFI of fat sows at farrowing in comparison with lean sows is associated with increased insulin resistance (Weldon et al., 1994; Le Cozler et al., 1998; Van der Peet-Schwering et al., 2004). Therefore, we investigated whether the ADFI during lactation was related to the insulin resistance of sows in conventional body conditions (i.e., restrictively fed during pregnancy). Our results showed that ADFI of sows was negatively related to the glucose half life during the glucose tolerance test and positively related to the glucose infusion rate during the clamp. The sows with a low ADFI after farrowing had a greater glucose half life at LP, BF, and AF, and a longer time to reach 50% of the area under the insulin curve after the infusion of 0.5 g of glucose/kg of BW at LP and AF. In addition, the glucose infusion rate during the euglycemic hyperinsulinemic clamps performed at LP, BF, and AF was less in sows with a reduced ADFI. This indicates that a reduced ADFI in early lactation is associated with increased insulin resistance at this time, but also in LP. However, all the pregnant sows were fed the same amount of feed and had similar body reserves as indicated by their similar BW and backfat depth. Therefore, the extent of development of insulin resistance in LP and early lactation seems related to individual characteristics of the sows, in addition to their fatness. No explanation is yet available concerning the variability in insulin resistance among individuals. The development of insulin resistance during pregnancy seems induced by some placental hormones (Ryan and Enns, 1988; Barbour et al., 2007). In rats, mice, and humans, the pancreatic islets that release insulin are directly regulated by the placental lactogen hormone (Brejle et al., 1993). These authors suggest that the placental lactogen hormone could be responsible for the increased islet function observed during pregnancy. More recently, Barbour et al. (2002) showed that transgenic mice overexpressing the human placental GH have an increased insulin resistance compared with normal littermate controls. The variations in insulin resistance among pregnant sows reared in similar conditions could be related to variations in the synthesis of placental hormones related to the pregnancy-induced insulin resistance. The identification of such factors would be of interest for the understanding of the increased variability of the voluntary feed intake of the sow after farrowing.

In conclusion, our results showed that primiparous sows fed a slight excessive amount of Trp (2.6 g/kg of diet) had similar ADFI during lactation than sows fed 1.6 g of Trp/kg of diet. Some variations in insulin secretion and glucose half life were observed but not clearly enough to conclude an effect of the dietary Trp used in this experiment on the insulin resistance of the sows around farrowing. Irrespective of the dietary supply of Trp and the body fatness, the reduced ADFI of sows in early lactation was related to their greater insulin resistance. This relationship was observed after farrowing, but the difference in insulin sensitivity existed already in LP. Therefore, the supplementation of dietary Trp was not efficient to increase the voluntary feed intake of the primiparous sows. Further research is needed to elucidate the reasons why sows with similar rearing conditions develop different degrees of insulin resistance during pregnancy.

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