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Improving adaptation to weaning: Effect of intermittent suckling regimes on piglet feed intake, growth, and gut characteristics

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ABSTRACT: Daily separation of sows and piglets during lactation, intermittent suckling (IS), improves feed intake and postweaning adaptation in piglets. The aim of the current study was to determine how, in piglets that have been subjected to IS, age at weaning and the duration of the preceding IS period contribute to postweaning adaptation through effects on feed intake, growth, and gut characteristics. All piglets had ad libitum access to creep feed from d 7. Litters were subjected to conventional weaning (CW) or to 1 of 3 IS regimens. In CW, litters (n = 29) had continuous access to the sow until weaning (d 26, d 0 = farrowing). During IS, litters had access to the sow between 1600 and 0600 h. Litters in the IS treatments were subjected to IS 1) from d 19 onward and weaned at d 26 (IS19–7D, n = 33), 2) from d 19 onward and weaned at d 33 (IS19–14D, n = 28), or 3) from d 26 onward and weaned at d 33 (IS26–7D, n = 33). The IS19–7D regimen resulted in a relative growth check within the first 2 d after weaning similar to CW litters (72 ± 13 and 90 ± 7%, respectively). In these litters, feed intake and growth within the first 2 d after weaning were slightly greater when piglets were subjected to IS for 2 wk (IS19–14D) rather than for 1 wk (IS26–7D; P = 0.032 and P = 0.037 for feed intake and growth, respectively). Irrespective of duration of IS, weaning at d 33 with IS was not associated with a reduction in villus height. Irrespective of treatment, plasma citrulline concentrations were reduced at d 2 and 8 postweaning compared with the values at weaning (P ≤ 0.01). No correlation was observed between postweaning plasma citrulline concentrations and postweaning small intestinal villus height. This study indicates that 1 wk of IS before weaning at d 26 of lactation improves postweaning adaptation markedly in terms of growth, feed intake, and gut characteristics. Increasing the duration of IS from 1 to 2 wk slightly improved growth and feed intake shortly after weaning, but the contribution to postweaning adaptation seemed to be relatively small compared with extending lactation.

Key words: citrulline, intermittent suckling, intestinal morphology, pig, weaning

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INTRODUCTION

Conventional weaning of piglets is associated with a reduced postweaning nutrient intake, reduced growth, and a greater susceptibility to diarrhea. Intermittent suckling (IS), a management strategy in which sow and piglets are separated during a fixed period of the day, stimulates preweaning creep feed intake and, as a result, improves postweaning feed intake and growth (IS from d 14, weaned at d 25; Kuller et al., 2004). Moreover, combining IS with an extended lactation period improved adaptation to weaning, as judged by the markedly reduced postweaning growth check and greater feed intake after weaning (Berkeveld et al., 2007b). Average feed intake during the first week of IS is less when 14-d-old piglets are subjected to IS, but is markedly increased when piglets are 1 wk older at initiation of IS (Berkeveld, 2008). One may question whether postponing the onset of IS to an older age, together with the associated greater feed intake, facilitates the adaptation to weaning. However, in the latter study, initiation of IS at a later age coincided with a later weaning age as well, making it hard to evaluate the relative contribution of weaning age and age at the start of IS. Moreover, no comparison was made to a conventional weaning (CW) regimen.

A 2-wk period of IS before weaning reduced the weaning-associated villus atrophy and increased postweaning small intestinal (SI) absorption, if creep feed was provided (Nabuurs et al., 1996); no data on piglet feed intake or piglet growth were presented. Recent IS studies focused on the effects of IS on piglet growth and feed intake (Kuller et al., 2007; Millet et al., 2008). Hence, the effect of IS regimens on postweaning SI variables, and the relation of these variables with feed intake and growth, remain to be elucidated.

The aim of the current study was to determine how age at weaning in piglets that have been subjected to IS, and the duration of the preceding IS period, each contribute to postweaning adaptation through effects on feed intake, growth, and gut characteristics. Besides macroscopic and morphologic variables of the small intestine, plasma citrulline concentration, a possible marker for SI function (Berkeveld et al., 2008), and its relation to SI morphology were determined.

MATERIALS AND METHODS

The Ethics Committee for animal experiments of Wageningen University and Research Centre approved the experimental design, including all procedures involving animals.

Animals, Housing, and Diet

The experiment was conducted in 4 replicates between April and November 2007 at the Sterksel research farm (Animal Sciences Group, Sterksel, the Netherlands). During these 4 replicates, a total of 124 sows [TOPIGS20 (Landrace × York), TOPIGS, Helvoirt, the Netherlands] and their litters with an average parity of 3.5 ± 0.1 (ranging from 1 to 9) were used. The numbers of sows used in replicates 1 to 4 were 29, 33, 29 and 33, respectively. Piglets were TOPIGS20 × TEMPO crossbreds (TOPIGS). One week before farrowing, pregnant sows were individually housed in a farrowing pen (2.4 × 1.8 m) with farrowing crate. An infrared heated area was provided for the piglets from birth until d 14. Artificial lighting was provided between 0600 and 1800 h and was dimmed during the night. At weaning, each litter was moved from their farrowing pen to its own nursery pen (1.77 × 2.65 m). Litters remained in the nursery pen until the end of the experiment (d 61).

Litter size was standardized within 2 d after farrowing by cross fostering, resulting in an average litter size of 12.4 ± 0.1 piglets. One day after farrowing, piglets were weighed and received an ear tag for individual identification. Within 1 wk after farrowing, piglets received a 1-mL (200 mg) intramuscular iron injection (Prevan 200, Eurovet Animal Health, Bladel, the Netherlands). Within each replicate, the beginning of the experimental procedure (d 0) was designated as the day at which most of the litters were born. Litters were born from 3 d before to 3 d after d 0, and piglet age at d 0 was 0.4 ± 0.2 on average.

All litters were offered ad libitum access to creep feed from d 7 onward. From d 7 to 12, a 1:1 mix of 2 commercial creep feed diets was offered in a feeding bowl (diet 1, 19% CP, 1.1% lysine, Babito, Havens Voeders, Maashees, the Netherlands; diet 2, 16.1% CP, 1.2% lysine, Almido Big, Havens Graanhandel NV). From d 12 until d 40, diet 2 was offered in a piglet feeder with 2 feeding places (15 cm/feeding place). From d 42 until the end of the experiment (d 61), a commercial creep feed for weaner pigs (diet 3; 17.1% CP, 1.15% lysine; Havo Opfok Sprint, Havens Voeders) was offered. During a 2-d transition period (d 40 to 42), diets 2 and 3 were mixed (1:1) for a gradual transition. During the entire experiment, drinking water was continuously available, provided by 1 drinking nipple per pen. Sows were fed an increasing amount of feed (Euro Airline Lactokorrel, 15% CP, 5.1% lysine, Cehave Landbouwbelang Voeders, Veghel, the Netherlands) after farrowing until the maximum allowance of 7.5 kg was reached at d 13 of lactation.

Treatments

Within each replicate, sows were allocated to treatments based on sow parity and BW 1 wk before farrowing. The sow and her litter were subjected to CW or to 1 of 3 IS regimens (Figure 1). Litters receiving different treatments were housed in separate similar farrowing rooms to prevent possible disturbing effects of nursing litters in the same room, whereas other litters were separated from their sow during IS. In CW litters (n = 29), piglets had continuous access to the sow until weaning.
at d 26. In the IS treatments, litters had continuous access to the sow until subjected to IS. Litters in the IS treatments were 1) subjected to IS from d 19 and weaned at d 26 (IS19–7D, n = 33); 2) subjected to IS from d 19 and weaned at d 33 (IS19–14D, n = 28); or 3) subjected to IS from d 26 and weaned at d 33 (IS26–7D, n = 33). During IS, sows were separated from their litter for 10 h/d (from 0600 until 1600 h) and housed individually in a different room to prevent visual and auditory contact. Only during absence of the sow, an infrared light provided heating for the piglets. Litters in the IS19–7D and CW treatments were weaned at d 26, and those in the IS19–14D and IS26–7D treatments were weaned after lactation was extended for 1 wk (d 33). Piglets were weighed at 1 d after farrowing, and at d 19, 21, 26, 28, 33, 40 and 61. Litters weaned at d 33 (IS19–14D and IS26–7D) had an additional weighing at d 35. Creep feed residuals per litter were determined simultaneously with the weighing of the piglets.

Collection of Samples

A total of 10 litters per treatment of the first 2 replicates were selected on d 25 based on litter feed intake (closest to treatment average). Within each of these litters, 3 piglets were selected based on their BW (closest to litter average), resulting in a total of 30 piglets per treatment (n = 120 piglets in total). The 3 piglets per litter were killed at weaning, or at d 2 and 8 postweaning, respectively, by intracardial injection of Euthesate (0.75 to 1 mL/kg of BW; Ceva Santé Animale, Naaldwijk, the Netherlands) after a 5-mL cardiac blood sample was obtained. The abdominal cavity was opened, and gut segments (3 cm) for microscopy were obtained at ~10, ~50, and ~90% of the SI length (duodenal, jejunal, and ileal sections). The gut segments were opened lengthwise and pinned on a piece of dental wax with the serosal side to the wax. Subsequently, the samples were fixed in 4% formalin solution with the mucosal side downwards to fix the villi vertically. The entire small intestine was dissected from the remaining mesentery, and the length and weight were determined. In the first replicate, SI weight was only determined with its contents. In the second replicate, the weight of the emptied small intestine was also determined (n = 5 per treatment). In both replicates, the large intestine (LI) was isolated, and the weight was determined, with and without its contents.

Histological Procedure

Two transverse tissue samples were cut from each segment using a stereo microscope. These parts of the tissue sample were dehydrated, embedded together in paraffin wax, and sectioned at 4 (or 5) µm. One section was transferred to a slide and stained with hematoxylin and eosin. Hence, each slide contained 2 transverse tissue samples of a gut segment. In each slide, villus height and crypt depth were determined for at least 10 villi and crypts (17.4 ± 0.2 observations per slide on average) using an image analysis system with a monitor (Image Tool version 3.0, UTHSCSA Dental Diagnostic Science, San Antonio, TX). Villi and crypts were only measured when there was a complete longitudinal section of a villus and an associated crypt. The average villus height and crypt depth per slide was used as experimental observation.

Plasma Citrulline Concentration

Plasma citrulline concentrations obtained before euthanization of the piglets were analyzed by automated ion-exchange chromatography performed on a Jeol Amino-Tac (JLC-500/V, Tokyo, Japan) with postcolumn ninhydrin derivatization (Berkeveld et al., 2008). The detection range was from 3 to 1,000 µM, with a maximal inaccuracy of 14%.
Calculations

Cumulative feed intake at each weighing was calculated by summing the total feed intake at all previous times of weighing. A relative growth check was defined as the reduction in ADG in the first 2 d after weaning, from d 26 to 28 for IS19–7D and CW litters, and from d 33 to 35 for IS19–14D and IS26–7D litters, compared with the ADG in the last 5 d before weaning, and expressed as a percentage. The relative growth check (%) was calculated as 100·(ADGd 21–26 – ADGd 26–28)/ADGd 21–26 for litters weaned at d 26 and as 100·(ADGd 28–33 – ADGd 33–35)/ADGd 28–33 for litters weaned at d 33.

Statistical Analysis

Data are presented as means ± SE. Normally distributed data were analyzed using the MIXED procedure (SAS Inst. Inc., Cary, NC). Litters were individually housed in a separate farrowing pen and, hence, considered as the experimental unit. In each replicate, the 7 to 9 pens (= litters) of 1 treatment were located in 1 of the 4 very similar farrowing rooms. The experiment was conducted during 4 replicates, and each replicate contained all 4 treatments. As mentioned previously, the different farrowing room per treatment was used to prevent possible disturbing effects of nursing litters in the room, whereas other litters were separated from their sows.

The applied experimental design did not include a treatment group with an extended lactation (weaning at d 33) without IS. This means that only pair-wise comparisons were made between litters weaned at d 26 (CW vs. IS19–7D) or those at d 33 (IS19–14D vs. IS26–7D), or between litters with 1 wk of IS weaned at d 26 or 33 (IS19–7D vs. IS26–7D). Moreover, we want to emphasize that possible treatment effects in litters weaned at d 33 cannot be entirely contributed to age at weaning or IS alone.

Although litter was the experimental unit for ADFI, ADG, and BW, and used as such in statistical analyses, all data were expressed per piglet. Effects were considered significant when P < 0.05; in posthoc testing the Bonferroni correction was applied. Correlations were calculated using Pearson correlation coefficients of SAS.

Because feed intake data of the first 3 wk (until d 21) were not normally distributed, they were analyzed using PROC NPAR1WAY, a nonparametric Kruskal-Wallis test. If this test detected an overall treatment effect, data of treatments were tested pairwise. Feed intake data (from d 26 onward), BW, and ADG were analyzed as litter characteristics with treatment as fixed factor, replicate and sow as random factors, and age at d 0 and BW at d 19 as co-variables. Body weight at d 19 was omitted as co-variable from the model for analysis on piglet birth weight and replaced by birth weight for analysis on mean litter ADG and BW at d 19.

Data on intestinal macroscopic variables, plasma citrulline concentration, and intestinal morphology (villus height and crypt depth) were analyzed with treatment, day, and sex as fixed factors, sow and replicate as random factors, and age at d 0 and BW at d 19 as co-variables. Only during analysis of intestinal macroscopic variables, the effect of the interaction of treatment and day was significant in several cases and therefore added to the model. For analysis of intestinal morphology data, sampling location (duodenum, jejunum, and ileum section) was added as a fixed factor to the model.

Measurements on villus height and crypt depth at the 3 sampling locations (duodenal, jejunal, and ileal sections) were averaged per piglet. These average values were used to present data on villus height and crypt depth per treatment and to relate intestinal morphology to other variables obtained in the study (such as piglet growth and plasma citrulline).

RESULTS

Feed Intake

Creep feed intake before d 19 was negligible for all treatments. Between d 19 and 26, IS19–7D and IS19–14D litters were subjected to IS, whereas CW and IS26–7D litters were still continuously suckled. Feed intake of litters subjected to IS in this period (d 19 to 26) was still small, however, and did not differ from that of the continuously suckled CW and IS26–7D litters (Table 1). At d 26 both CW and IS19–7D litters were weaned, whereas the 2 other treatments (IS19–14D and IS26–7D) were weaned 1 wk later at d 33. Weaning (d 26) markedly increased feed intake in CW and IS19–7D litters compared with the unweaned IS19–14D and IS26–7D litters, both during the first 2 d after weaning and from d 28 to 33. In the first 2 d after weaning, feed intake did not differ between litters weaned at d 26, but feed intake between d 28 and 33 was greater in IS19–7D litters compared with CW litters (P = 0.001).

In litters with extended lactation (weaning at d 33), no differences in feed intake were observed between IS19–14D and IS26–7D treatments during the suckling period. However, in the first 2 d after weaning feed intake was greater for litters subjected to 14 d of IS as compared with litters subjected to 7 d of IS (P = 0.032; Table 1). Thereafter, feed intake of both treatments was similar. Between d 35 and 40, feed intake of litters weaned at d 33 was less than that of litters weaned 1 wk earlier (P < 0.012; Table 1). During the last 3 wk of the experiment (d 40 to 61), feed intake was still greater for IS19–7D litters than for IS19–14D and IS26–7D litters (P < 0.007) and also greater in CW compared with IS26–7D litters (P = 0.003; Table 1).

In all treatments, cumulative feed intake during lactation (Table 1) was correlated to feed intake in the first 2 d postweaning (r > 0.57; P < 0.002). At the end
of the experiment, cumulative feed intake of IS litters weaned after extended lactation (IS19–14D and IS26–7D) was less than for litters weaned at d 26 (CW and IS19–7D; P < 0.002; Table 1).

**Piglet Performance**

Piglet mortality up to d 19, before onset of treatments, was 9%. Piglet loss from d 19 until the end of the experiment (d 61) was similar in all treatments (3.4 ± 0.2% on average).

Piglet BW at the start of treatments (d 19) was slightly greater in IS26–7D litters compared with IS19–7D litters (P = 0.026); CW and IS19–14D litters were intermediate (Table 2). Therefore, treatment effects on BW and ADG were always corrected for BW at d 19 (see Statistical Analysis section). Intermittent suckling (starting at d 19) resulted in a reduced growth in IS19–7D and IS19–14D litters between d 19 and 21, and between d 21 and 26 of lactation when compared with that of the continuously suckled CW and IS26–7D litters in these periods (P < 0.001; Figure 2). This reduced growth after onset of IS resulted in a lighter BW for IS19–7D and IS19–14D litters at d 26 compared with CW and IS26–7D litters (P < 0.001; Table 2). Weaning (d 26) resulted in a dramatic decrease in piglet growth in IS19–7D and CW litters (Figure 2), with a relative growth check of 72 ± 13 and 90 ± 7%, respectively (P > 0.05). However, piglet growth between d 2 and 7 postweaning was greater for IS19–7D litters than for CW litters (P = 0.014; Figure 2; d 28 to 33). The reduced growth after weaning resulted in a lighter BW for IS19–7D and CW litters at d 33 compared with the intermittently suckled IS19–14D and IS26–7D litters (P < 0.0001).

### Table 1. Feed intake of piglets per treatment during lactation and after weaning (W)

<table>
<thead>
<tr>
<th>Item</th>
<th>Day&lt;sup&gt;1&lt;/sup&gt;</th>
<th>CW</th>
<th>IS19–7D</th>
<th>IS19–14D</th>
<th>IS26–7D</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADFI&lt;sup&gt;1,2&lt;/sup&gt; g·piglet&lt;sup&gt;−1&lt;/sup&gt;·d&lt;sup&gt;−1&lt;/sup&gt;</td>
<td>19 to 21</td>
<td>7 ± 2</td>
<td>5 ± 1</td>
<td>5 ± 1</td>
<td>7 ± 1</td>
</tr>
<tr>
<td></td>
<td>21 to 26</td>
<td>14 ± 3</td>
<td>19 ± 3</td>
<td>20 ± 4</td>
<td>20 ± 3</td>
</tr>
<tr>
<td></td>
<td>26 to 28</td>
<td>103 ± 7&lt;sup&gt;a&lt;/sup&gt;</td>
<td>112 ± 9&lt;sup&gt;b&lt;/sup&gt;</td>
<td>37 ± 5&lt;sup&gt;b&lt;/sup&gt;</td>
<td>34 ± 6&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>28 to 33</td>
<td>164 ± 9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>203 ± 9&lt;sup&gt;b&lt;/sup&gt;</td>
<td>75 ± 10&lt;sup&gt;b&lt;/sup&gt;</td>
<td>55 ± 6&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>33 to 35</td>
<td>—</td>
<td>244 ± 17&lt;sup&gt;b&lt;/sup&gt;</td>
<td>201 ± 14&lt;sup&gt;b&lt;/sup&gt;</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>35 to 40&lt;sup&gt;b&lt;/sup&gt;</td>
<td>362 ± 13&lt;sup&gt;a&lt;/sup&gt;</td>
<td>375 ± 15&lt;sup&gt;b&lt;/sup&gt;</td>
<td>325 ± 12&lt;sup&gt;b&lt;/sup&gt;</td>
<td>322 ± 16&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>40 to 61</td>
<td>808 ± 21&lt;sup&gt;b&lt;/sup&gt;</td>
<td>829 ± 21&lt;sup&gt;b&lt;/sup&gt;</td>
<td>775 ± 19&lt;sup&gt;b&lt;/sup&gt;</td>
<td>752 ± 24&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>CUMFI&lt;sup&gt;1&lt;/sup&gt;</td>
<td>12 to W, g/piglet</td>
<td>103 ± 2&lt;sup&gt;a&lt;/sup&gt;</td>
<td>126 ± 2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>587 ± 8&lt;sup&gt;b&lt;/sup&gt;</td>
<td>484 ± 6&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>12 to 61, kg/piglet</td>
<td>20.6 ± 0.5&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21.4 ± 0.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>18.7 ± 0.5&lt;sup&gt;b&lt;/sup&gt;</td>
<td>18.7 ± 0.6&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a–cWithin a row, means without a common superscript letter differ (P < 0.05).</sup>

<sup>1</sup>Day = day of the experiment; d 0 = day on which most of the litters were born, litters were born from 3 d before to 3 d after d 0.

<sup>2</sup>CW = conventional weaning at d 26 (n = 29); IS = intermittent suckling; IS19–7D = IS from d 19, weaning at d 26 (n = 33); IS19–14D = IS from d 19, weaning at d 33 (n = 28); IS26–7D = IS from d 26, weaning at d 33 (n = 33).

<sup>3</sup>ADFI (g/d) per piglet in the indicated period.

<sup>4</sup>Because feed residuals were not determined in the CW and IS19–7D litters on d 35, the ADFI was calculated between d 33 and 40.

<sup>5</sup>CUMFI = average cumulative feed intake (g or kg) per piglet in the indicated period.

<sup>*Indicates the first experimental period after weaning.</sup>

### Table 2. Body weight of piglets (kg) during lactation and after weaning

<table>
<thead>
<tr>
<th>Day&lt;sup&gt;1&lt;/sup&gt;</th>
<th>CW</th>
<th>IS19–7D</th>
<th>IS19–14D</th>
<th>IS26–7D</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.41 ± 0.04</td>
<td>1.41 ± 0.03</td>
<td>1.38 ± 0.04</td>
<td>1.42 ± 0.04</td>
</tr>
<tr>
<td>19</td>
<td>6.22 ± 0.14&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.00 ± 0.14&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.16 ± 0.17&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.35 ± 0.13&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>21</td>
<td>6.80 ± 0.15&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.44 ± 0.14&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.58 ± 0.18&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6.80 ± 0.14&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>26</td>
<td>8.16 ± 0.19&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.50 ± 0.16&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.68 ± 0.20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.12 ± 0.15&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>28</td>
<td>8.15 ± 0.18&lt;sup&gt;b&lt;/sup&gt;</td>
<td>7.54 ± 0.16&lt;sup&gt;b&lt;/sup&gt;</td>
<td>8.21 ± 0.21&lt;sup&gt;b&lt;/sup&gt;</td>
<td>8.66 ± 0.16&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>33</td>
<td>8.68 ± 0.19&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.33 ± 0.19&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.50 ± 0.24&lt;sup&gt;a&lt;/sup&gt;</td>
<td>9.84 ± 0.19&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>35</td>
<td>—</td>
<td>—</td>
<td>9.86 ± 0.20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.06 ± 0.21&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>40</td>
<td>10.54 ± 0.25&lt;sup&gt;a&lt;/sup&gt;</td>
<td>10.23 ± 0.25&lt;sup&gt;a&lt;/sup&gt;</td>
<td>11.03 ± 0.27&lt;sup&gt;b&lt;/sup&gt;</td>
<td>11.30 ± 0.24&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>61</td>
<td>21.28 ± 0.47</td>
<td>21.48 ± 0.53</td>
<td>21.52 ± 0.47</td>
<td>21.72 ± 0.47</td>
</tr>
</tbody>
</table>

<sup>a–cWithin a row, means without a common superscript letter differ (P < 0.05).</sup>

<sup>1</sup>Day = day of the experiment; d 0 = day on which most of the litters were born, litters were born from 3 d before to 3 d after d 0.

<sup>2</sup>CW = conventional weaning at d 26 (n = 29); IS = intermittent suckling; IS19–7D = IS from d 19, weaning at d 26 (n = 33); IS19–14D = IS from d 19, weaning at d 33 (n = 28); IS26–7D = IS from d 26, weaning at d 33 (n = 33).

<sup>*Indicates the first weighing after weaning.</sup>
Weaning after extended lactation (d 33) also reduced piglet growth, more so for litters subjected to 1 wk of IS (IS26–7D) than for litters with 2 wk of IS before weaning (IS19–14D; \( P = 0.037 \); Figure 2). However, the relative postweaning growth check was markedly reduced after an extended lactation compared with the earlier weaned IS19–7D and CW litters (\( P < 0.05 \)): 11 ± 18% in IS19–14D and 32 ± 19% in IS26–7D litters. During the last 3 wk of the experiment (d 40 to 61), piglet growth was greater for IS19–7D than for IS26–7D litters (536 ± 16 and 481 ± 18 g/piglet/d, respectively; \( P = 0.009 \)); CW and IS19–14D litters were intermediate (512 ± 16 g/piglet/d and 499 ± 12 g/piglet/d, respectively). However, no differences in piglet BW were observed at the end of the experiment (d 61; Table 2).

After an extended lactation, piglet growth in the first 2 d postweaning was correlated to the cumulative feed intake during lactation (\( r = 0.44 \) and \( P = 0.021 \) for IS19–14D, and \( r = 0.52 \) and \( P = 0.003 \) for IS26–7D litters). This correlation was not observed in litters weaned at d 26 (\( r = 0.31 \) and \( P = 0.102 \) for CW, and \( r = 0.32 \) and \( P = 0.072 \) for IS19–7D litters).

**Postweaning Intestinal Macroscopy**

Irrespective of treatment, SI length did not change in the first 2 d after weaning (\( P > 0.05 \)), but increased thereafter, resulting in a longer SI at d 8 postweaning compared with d 2 postweaning (overall \( P < 0.001 \); Table 3). The relative increase in SI length between d 2 and d 8 postweaning seemed to be greater for piglets weaned at d 33 (~23% for IS19–14D and 12% for IS26–7D) than for piglets weaned at d 26 (~6% for CW and ~7% for IS19–7D). Overall, CW piglets had a smaller SI length compared with IS piglets, irrespective of IS regime (overall \( P < 0.013 \)). Small intestinal length did not differ overall between the IS treatments.

Small intestinal empty weight was similar in all treatments at weaning (\( P > 0.10 \)). At d 8 postweaning, piglets weaned after extended lactation (IS19–14D and IS26–7D treatment) had a greater SI empty weight compared with piglets weaned at d 26 (IS19–7D and CW treatment; \( P < 0.020 \)).

The empty weight of the LI increased after weaning in all treatments, resulting in greater values at d 2 compared with the values at weaning (overall \( P = 0.017 \)) and in greater values at d 8 postweaning compared with the preceding values (overall \( P < 0.001 \)). The empty weight of the LI was greater for IS19–14D and IS26–7D piglets than for the earlier weaned IS19–7D and CW piglets (\( P < 0.001 \)).

Cumulative feed intake during lactation was not correlated to the SI and LI empty weight in piglets weaned at d 26 or 33. Moreover, empty weight of the SI and LI at d 2 and 8 postweaning correlated to the feed intake in the first 2 d postweaning (overall \( r > 0.74, P < 0.001 \) and between d 2 and 7 postweaning (overall \( r > 0.70, P < 0.001 \)), respectively. Only length of the SI at d 8 postweaning was correlated to feed intake (between d 2 and 7 postweaning; overall \( r = 0.50, P = 0.001 \)).
Table 3. Gut variables at weaning and at d 2 and 8 postweaning in each treatment

<table>
<thead>
<tr>
<th>Variable</th>
<th>P-value</th>
<th>Day postweaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI length, cm</td>
<td>Treatment (P &lt; 0.001)</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td>Day (P &lt; 0.001)</td>
<td>656 ± 25</td>
</tr>
<tr>
<td></td>
<td>P 0.001</td>
<td>IS19-14D</td>
</tr>
<tr>
<td>SI full weight, g</td>
<td>Treatment (P &lt; 0.001)</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td>Day (P &lt; 0.001)</td>
<td>316 ± 24</td>
</tr>
<tr>
<td></td>
<td>P 0.001</td>
<td>IS26-7D</td>
</tr>
<tr>
<td>SI empty weight, g</td>
<td>Treatment (P &lt; 0.001)</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td>Day (P &lt; 0.001)</td>
<td>262 ± 29</td>
</tr>
<tr>
<td></td>
<td>P 0.001</td>
<td>IS26-7D</td>
</tr>
<tr>
<td>LI full weight, g</td>
<td>Treatment (P &lt; 0.001)</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td>Day (P &lt; 0.001)</td>
<td>159 ± 13</td>
</tr>
<tr>
<td></td>
<td>P 0.001</td>
<td>IS26-7D</td>
</tr>
<tr>
<td>LI empty weight, g</td>
<td>Treatment (P &lt; 0.001)</td>
<td>CW</td>
</tr>
<tr>
<td></td>
<td>Day (P &lt; 0.001)</td>
<td>89 ± 8</td>
</tr>
<tr>
<td></td>
<td>P 0.001</td>
<td>IS26-7D</td>
</tr>
</tbody>
</table>

*Within a row, means within each treatment with a different superscript letter are significantly different (P < 0.05).
*Within a column, means within each day with a different superscript letter are significantly different (P < 0.05).

Postweaning Intestinal Morphology

Villus height and crypt depth were different among sample locations, with greatest values at the proximal intestine, intermediate at the mid small intestine, and least at the distal end of the small intestine (overall P < 0.001; data not shown).

Weaning reduced villus height in piglets of the CW treatment, resulting in shorter villi at d 2 postweaning compared with the values at weaning (P = 0.009); villus height at d 8 was intermediate (Figure 3). In contrast, villus height at d 2 postweaning was not different from the values observed at weaning in the IS treatments. Moreover, at d 8 postweaning, piglets weaned after an extended lactation (IS19–14D and IS26–7D treatments) had longer villi compared with CW piglets (P = 0.038 and P < 0.001; Figure 3). Irrespective of treatment, weaning resulted in deeper crypts at d 8 postweaning compared with values at weaning or 2 d after weaning (overall P < 0.001; Figure 3).

Villus height and crypt depth at d 2 postweaning were both correlated to the ADFI in the first d postweaning (overall r = 0.58, P < 0.001 and r = 0.62, P < 0.001; Figure 4). Moreover, villus height and crypt depth at d 2 postweaning were both correlated to the relative growth check in the first 2 d postweaning (overall r = −0.49, P = 0.002 and r = −0.60, P < 0.001). Villus height and crypt depth at d 8 postweaning were also correlated to the ADFI between d 2 and 7 postweaning (overall r = 0.59, P < 0.0001 and r = 0.53, P < 0.001, respectively). Only a weak correlation was found for villus height at d 8 postweaning and ADG between d 2 and 7 postweaning (overall r = 0.38, P = 0.04), but not for crypt depth.

Postweaning Plasma Citrulline Concentration

Weaning reduced plasma citrulline concentrations resulting in reduced concentrations on d 2 and 8 postweaning compared with the values observed at weaning (overall P = 0.01 and P < 0.001; Figure 5). Postweaning plasma citrulline concentrations were not different between treatments. At weaning, plasma citrulline concentrations were negatively correlated to crypt depth (overall r = −0.36, P = 0.022). At d 2 postweaning, plasma citrulline concentrations were negatively correlated to crypt depth (r = −0.46, P = 0.003) and SI empty weight (r = −0.62, P = 0.004). No correlation was observed between plasma citrulline concentration at d 2 postweaning and the relative growth check, ADG, or ADFI during the first 2 d postweaning. At d 8 postweaning, plasma citrulline was correlated to SI length (r = 0.37, P = 0.017).
DISCUSSION

The aim of the current study was to determine how age at weaning, after a period of IS, and the duration of IS, each contribute to the prevention of the detrimental effects on piglet performance and on gut characteristics associated with CW. In contrast to expectations, results of the current study demonstrate that the wean-
ing-associated growth check during the first 2 d after weaning was not prevented or reduced by 1 wk of IS before weaning (d 26). However, it did result in a greater feed intake and piglet growth from d 2 to 7 postweaning. Moreover, there was no (further) reduction of villus height at d 2 postweaning as observed in CW piglets. The combination of 1 wk of IS with an extended lactation length (weaning at d 33) reduced the postweaning check considerably compared with piglets weaned at d 26, with or without 1 wk of IS before weaning. This latter effect on the growth check was slightly more pronounced when IS was applied for 2 wk before weaning at d 33. Irrespective of its duration, IS combined with extended lactation was not associated with a significant reduction in villus height after weaning.

Unexpectedly, subjecting litters to IS from d 19 to 26 of lactation did not stimulate their feed intake during this period as compared with that of continuously suckled litters in the current study. Previous experiments of our research group demonstrated a consistent stimulation of feed intake by IS during lactation, although the level of stimulation varied considerably, even among experiments under the same experimental conditions (Kuller et al., 2004, 2007; Berkeveld et al., 2007b). In the current study, sow and piglets were, for practical reasons, separated for 10 h/d instead of the 12 h/d applied in the mentioned studies. A duration of daily separa-

ation of only 7 h was found not to be associated with any stimulatory effects of a 2-wk period of IS (d 14 to 28) on preweaning feed intake of piglets (Millet et al., 2008). Therefore, the 10-h separation period applied in the current experiment may have contributed to the lack of feed intake stimulation during lactation after 1 wk of IS. Even though preweaning feed intake was not stimulated by 1 wk of IS (from d 19 to 26), growth and feed intake between d 2 and 7 postweaning were greater for these IS litters than for CW litters. Such an effect of IS has been observed previously in litters with a low preweaning feed intake level (Kuller et al., 2004). Apparently, IS not only influences preweaning feed intake, but may also have another influence causing a better postweaning performance (to be discussed in more detail below).

One week of IS between d 19 and 26 did not stimulate feed intake and resulted in less piglet ADG and lighter BW of IS litters compared with litters still continuously suckled at that time. Similarly, a reduced preweaning piglet growth and weaning weight were also observed in previous IS studies, despite the fact that preweaning feed intake in these studies was stimulated by IS litters (Kuller et al., 2004, 2007). The preweaning dry feed intake of IS piglets or the ability to process the ingested dry feed might have been still too small to compensate for the milk deficit due to the absence of the sow. Hence, it might be that IS is associated with similar problems as complete weaning, thereby shifting (part of) the weaning problems to the lactation period. However, the growth reduction after IS is much smaller compared with that seen in conventionally weaned piglets, and the nutrient intake is still secured by the intermittent presence of the sow (and the increasing dry feed intake). Furthermore, one might postulate that 2 periods of slightly reduced piglet performance (onset of IS and complete weaning) might be advantageous with respect to disease risk and piglet loss, compared with 1 period of severely reduced piglet performance as observed after CW.

While 1 wk of IS before weaning at a conventional age (d 26) did not reduce the postweaning growth check, prolongation or postponing the period of IS for 1 wk before weaning did reduce the postweaning growth check markedly. This is in line with a previous study (Berkeveld et al., 2007b), in which IS (d 14 onward) combined with an extended lactation period (weaning at 43 ± 1 d) reduced the postweaning growth check to 14%. The shortened lactation length (from 43 to 33 d) and duration of IS (from 4 to 1 or 2 wk) of the current study seemed to have been equally effective in the prevention of a postweaning growth check. These positive effects on postweaning performance cannot entirely be ascribed to the restriction in nursing time during the applied IS regimens. Age at weaning itself apparently has a crucial impact on how well piglets can cope with weaning because a severe postweaning growth check was absent only when 1 wk of IS starting at 26 d of age, and not when starting at 19 d of age. In addition

![Figure 5. Plasma citrulline concentration (µM) per treatment in jugular blood samples at weaning and at d 2 and 8 postweaning (n = 10 piglets/treatment). CW = conventional weaning at d 26; IS = intermittent suckling; IS19–7D = IS from d 19, weaning at d 26; IS19–14D = IS from d 19, weaning at d 33; IS26–7D = IS from d 26, weaning at d 33.](http://jas.fass.org)
to increasing weaning age, subjecting piglets to an IS regimen does facilitate their adaptation because feed intake and growth shortly after weaning (at d 33) were improved by a longer period of IS during lactation.

The observed values of villus height and crypt depth in the CW piglets of the current study correspond to previously reported values (Nabuurs et al., 1993; van Beers-Schreurs et al., 1998). Villus height of CW piglets was reduced by about 21% at d 2 postweaning compared with preweaning values. Similar reductions in villus height after weaning were shown to have a profound effect on intestinal absorption values (Nabuurs et al., 1996). Higher villi and deeper crypts were observed at d 8 after weaning in litters with an extended lactation combined with 1 or 2 wk of IS compared with CW piglets, which is in line with previous findings of Nabuurs et al. (1996) that a 2-wk period of IS (8 h/d) with supplemental feeding before weaning (at d 35) attenuates villus atrophy and improves intestinal absorption postweaning. Because no differences in intestinal morphology were observed in the current study between piglets weaned at a conventional age with or without 1 wk of IS, this appears to be an effect of age, rather than of the limited suckling time. Multiple authors (Pluske et al., 1996; van Beers-Schreurs et al., 1998), as well as the data of the current study, have shown a positive correlation between villus height and feed intake, indicating the importance of feed intake for proper intestinal function. Therefore, the effect of age on gut morphology seemed to be mediated by the greater stimulation of feed intake when piglets were subjected to IS at an older age (339 ± 18 vs. 104 ± 18 g/piglet in the first wk of IS, and 2,013 ± 94 vs. 1,239 ± 56 g/piglet in the first wk postweaning for IS26–7D and IS19–7D treatments, respectively).

At weaning, villus height of piglets in the CW treatment was not different from IS19–7D piglets. This is in accordance with Nabuurs et al. (1993, 1996) who showed that the supplementation of creep feed or subjecting piglets to IS (and creep feed) from 2 wk before weaning did not affect villus height in the small intestine of piglets weaned around 32 d of age. Surprisingly, 1 wk of IS before weaning at d 26 did not result in a significant reduction in villus height as observed in CW piglets, despite the fact that feed intake before and within the first 2 d after weaning was not improved compared with the latter. Although the small sample size in the present study could have complicated detection of a reduction in villus height after weaning, beneficial effects of IS might also be mediated by factors other than an increased feed intake. One possible explanation could be the habituation of IS piglets to separation from their mother at the time they are weaned permanently. An attempt to eliminate nutritional stress at weaning by feeding piglets increased quantity of milk from the sow attenuated, but did not completely prevent, the weaning-associated villus atrophy (van Beers-Schreurs et al., 1998). Overnight maternal separation has been found to be associated with elevated basal cortisol concentrations in piglets (Klemcke and Pond, 1991). Moreover, weaning of 19-d-old piglets has been shown to activate stress signaling pathways, which mediate and contribute to the intestinal dysfunction (i.e., increased SI permeability), associated with weaning (Moeser et al., 2007). Therefore, piglets habituated to repeated maternal separation in the IS regimen may have had a reduced stress response after weaning, and this could have prevented or attenuated intestinal damage. Although an IS regimen could result in more stress before weaning, subjecting piglets to IS was not associated with any behavioral patterns indicative of piglet distress (Berkeveld et al., 2007a).

The plasma citrulline concentrations of the piglets at the day of weaning (d 26 or 33) correspond well to the concentrations of 29-d-old suckling piglets reported previously [122 ± 25 µM; n = 7; jugular vein sample; Flynn and Wu (1997)]. In line with previous findings of our group (Berkeveld et al., 2008), weaning reduced plasma citrulline concentrations. Plasma citrulline concentrations are less in human patients with villus atrophy associated with small bowel diseases compared with healthy subjects and are considered to be a marker of enterocyte mass (Crenn et al., 2003). It was therefore anticipated that the postweaning reduction in plasma citrulline concentrations would be caused by the villus atrophy and impaired intestinal function associated with weaning. Unexpectedly, weaning of IS and CW litters in the current study resulted in a similar reduction of plasma citrulline concentrations, despite the fact that IS prevented a weaning-associated villus atrophy and resulted in a greater postweaning feed intake. Moreover, only a few and rather weak correlations were observed between plasma citrulline and SI morphology. Because the plasma citrulline concentration was determined in cardiac blood samples, it is the net resultant of SI citrulline production and cellular uptake and metabolism.

Weaning is associated with numerous changes in the piglet environment, but one of the most important changes is the transition from a diet consisting mainly of milk to a nonmilk diet. Despite the fact that creep feed intake is already substantial in IS litters during extended lactation, the complete deprivation of milk of the sow after weaning might possibly have altered the metabolism of citrulline produced in the small intestine after weaning, and thereby resulted in the decreased plasma values, as observed after weaning in piglets of all treatments. So, to gain more insight into the relation between SI citrulline production and morphological characteristics, a sampling location closer to the site of citrulline production [e.g., the portal vein; Wu et al. (1994)] would be desirable.

In European conventional pig husbandry, piglets are weaned around 3 or 4 wk of age. As a result, weaning is associated with a reduced nutrient intake and growth and has a detrimental effect on intestinal structure and function. Results of the current study demonstrate that 1 wk of IS before weaning at the conventional age (d
26) decreases weaning weight and does not prevent the weaning-associated growth check in the first 2 d after weaning, but does result in a greater feed intake and growth of piglets between d 2 and 7 after weaning. Moreover, it prevents a (further) reduction in villus height as observed in CW piglets. However, postponing the weaning age of IS piglets by 1 wk (IS26–7D) largely prevented the weaning-associated growth check, indicating that age at weaning itself has a crucial impact on how well piglets can cope with weaning. Moreover, a longer period of IS before weaning (2 wk instead of 1 wk) at this older age improves the postweaning feed intake and growth of piglets shortly after weaning, suggesting an even more gradual adaptation to weaning. Similar to 1 wk of IS before weaning at a conventional age (d 26) and irrespective of duration, villi were not (further) shortened after weaning when IS was applied before weaning at an older age (d 33). Despite the profound effects of IS (irrespective of regimen) on piglet performance in the short-term postweaning period, no differences in piglet BW were observed at the end of the experiment. It is postulated, however, that the beneficial effects of IS on postweaning performance might become even more pronounced (or long-lived) when piglets are weaned under suboptimal conditions [e.g., at farms with a history of postweaning diarrhea (with or without mortality)].

Although 1 wk of IS before weaning at a conventional age (d 26) was found to have a modest, short-lasting beneficial effect on piglet postweaning performance, this effect was more profound when 1 wk of IS was combined with an extended lactation (weaning at d 33). The effect of a prolonged 2-wk period of IS during extended lactation was only limited. To conclude, we suggest that IS combined with an extended lactation might be a promising management strategy to improve the adaptation of piglets to weaning. The specific contribution of age at weaning or IS to this improved adaptation remains to be elucidated.

**LITERATURE CITED**

Berkeveld, M. 2008. Intermittent suckling and extended lactation: Improving adaptation of piglets to postweaning challenges. PhD Diss. Faculty of Veterinary Medicine, Utrecht University, Utrecht, the Netherlands.


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