

Effect of Feeding a Milk Replacer to Early-Weaned Pigs on Growth, Body Composition, and Small Intestinal Morphology, Compared with Suckled Littermates^{1,2}

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ABSTRACT: Feeding of milk replacer to early-weaned pigs was evaluated in two experiments. In Exp. 1, 18 litters of pigs were either weaned conventionally (d 21), split-weaned and fed milk replacer plus starter diet (d 14 and 21), or weaned and fed milk replacer plus starter diet (d 21). Split weaning combined with feeding a milk replacer increased ADG 22% from d 14 and d 28 compared to conventional weaning ($P < .05$). Feeding a milk replacer plus starter diet after weaning increased ADG 30% between d 21 and 28 compared to conventional weaning ($P < .01$). In Experiment 2, four litters of 12 pigs each were divided at d 18 into six heavy and six light pigs and randomized across sow-suckled, milk replacer, or starter diet groups. After 1 wk, pigs fed milk replacer

weighed 20% more ($P < .001$), contained 10% more protein ($P < .01$) and 17% more fat ($P < .05$), and had 74% longer villi in the proximal small intestine ($P < .001$) than suckled pigs. In contrast, pigs fed starter diet weighed 19% less ($P < .001$), contained 20% less protein and fat ($P < .001$), and had 28% shorter villi in the proximal small intestine ($P < .05$) than suckled pigs. Therefore, milk replacer feeding the 1st wk after weaning stimulates pig development, both locally in the small intestine and on a whole-body basis, most likely by an increased energy and nutrient intake. Suckling beyond 18 d postnatally inhibits pigs to reach maximal potential weight gain. In conclusion, milk replacer feeding might be beneficial to reach maximal pig weight gain at weaning.

Key Words: Pigs, Weaning, Milk Replacer, Body Composition, Insulin, Small Intestine

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Introduction

Weaning age has declined over time in order to increase sow productivity. Moreover, approximately 3 wk after farrowing, milk yield of sows becomes insufficient to support maximal pig weight gain (Aherne, 1980). However, decreasing weaning age has increased postweaning stress in pigs (Leibbrandt et al., 1975; Okai et al., 1976). Weaning stressors are environmental, behavioral, immunological, and nutritional in origin (Makkink, 1993). The diet changes

from sow's milk containing highly digestible nutrients to a diet of different digestibility, texture, composition, smell, and taste. As a consequence, the digestive system must adapt with respect to pH regulation, enzyme secretions, motility, and absorption (Hansen et al., 1993; Makkink, 1993). Signs of postweaning stress include reduced feed intake, villus atrophy, and diarrhea, resulting in lower digestive and absorptive capacity and, ultimately, reduced weight gain (Cera et al., 1988). Economic performance is affected if protein growth is reduced or time needed to reach market weight is increased.

Special diets and management schemes have been developed to overcome nutritional problems associated with early weaning. Diets containing milk proteins were developed because non-milk proteins cause digestive disorders (Cline, 1991). Systems using liquid diets have demonstrated pig growth performance comparable to suckled pigs (Lecce, 1969); however, liquid diets have failed under practical conditions. Within special weaning-management schemes, split weaning (i.e., weaning lighter pigs later than heavier pigs) has been shown to reduce time to reach market weight (Mahan, 1993). Further-

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more, medicated (Thaler et al., 1996) and segregated (Dritz et al., 1996) early weaning procedures were developed, which improve weight gain of pigs after weaning.

Two experiments were conducted to examine effects of feeding management alternatives on growth characteristics of early-weaned pigs. Experiment 1 evaluated differences in growth performance among conventionally-weaned pigs, split-weaned pigs, and pigs weaned to liquid milk replacer. Experiment 2 evaluated differences in growth performance, body composition and small intestinal morphology among suckled pigs and pigs weaned at 18 d of age and fed milk replacer or dry starter diet for 7 d.

Materials and Methods

Animals and Design

Two experiments were conducted at the University of Illinois Swine Research Center, using F₂ (Yorkshire×Duroc) × Hampshire crossbreds. The experiments were approved by the University of Illinois Laboratory Animal Care Advisory Committee and were conducted according to the principles set forth in the *Guide for the Care and Use of Laboratory Animals*, Institute of Laboratory Animal Resources, National Research Council, NIH Publ. No. 85-23.

Experiment 1. A total of 180 pigs from 18 litters were allotted by litter to three weaning management schemes (Figure 1) for a total of six litters per treatment:

1. Conventional weaning: Pigs weaned at d $21 \pm .17$ to a starter diet (Transition Formula 1, Intensive Care Nursery, Colfax, IL) in a conventional nursery (described below).
2. Split weaning: The larger (determined by body weight) half of the pigs in a litter were weaned at d $14 \pm .37$. The smaller half of the pigs remained with the same sow (housing facilities described below) and were weaned at d $21 \pm .37$. For both large and small pigs, a milk replacer (ICN Milk Replacer, Intensive Care Nursery) was provided the first 4 d after weaning and starter diet the first 7 d after weaning within a specialized nursery building (Nursery-14 building, described below). Milk replacer and starter diet were in the pen at the same time. When milk replacer was provided, pigs had no access to water; when only starter diet was provided (4 to 7 d after weaning), pigs had free access to water. At d 21, large pigs were transferred to a conventional nursery and fed starter diet.
3. Milk replacer: Pigs weaned at d $21 \pm .65$ to milk replacer for the first 4 d after weaning and starter diet the first 7 d after weaning within the specialized Nursery-14 building.

Both milk replacer and starter diet were based on ingredients containing cow milk proteins and met or exceeded NRC vitamin and mineral requirements (NRC, 1988). Pigs were weighed at d 14, 21, and 28.

Housing Environments. Conventionally weaned pigs were housed in groups in a conventional nursery with raised-deck pens (1.2 × 1.3 m) that had expanded metal floors and solid side walls. Pigs had ad libitum access to starter diet and water in a heated, thermostatically controlled (26°C) nursery.

Split-weaned pigs that remained suckled for an extra week were housed with their dam in conventional farrowing crates in a room maintained at 18°C. Pigs had ad libitum access to water, and no creep feed was provided.

Pigs fed milk replacer were housed in groups in the specialized Nursery-14 building (Intensive Care Nursery) in raised-deck pens (1.9 × 1.3 m) that had expanded metal floors and solid side walls. One half of each pen (.95 × 1.3 m) had a solid top cover with a 250-W radiant heat lamp. Within the hover, the local temperature (~32°C) was maintained above the critical temperature of an early-weaned pig (Close and Stanier, 1984), whereas the temperature outside the hover was maintained below the pigs' critical temperature. Pigs had ad libitum access to milk replacer by a nipple feeding system in the open half of the pen. Milk replacer powder was mixed with heated (37°C) water in a mixing compartment (.5 L) equipped with electronic controls. Volume in the compartment, and not time, was controlled to ensure unlimited supply of freshly mixed milk replacer. Milk replacer was distributed by gravity from the mixing compartment to nipple drinkers via plastic tubing.

Experiment 2: Main study. Four litters were standardized to 12 pigs each after birth (n = 48; initial weight = $1.54 \pm .02$ kg). Because milk production of sows is dependent on parity number (Hartmann and Holmes, 1989), number of suckled pigs (Berge and Indrebo, 1954), and possibly number of pigs born (De Passillé et al., 1993), only second or higher parity sows with 10 or more pigs born were used. Missing cells were filled by cross-fostering pigs born to other F₁ Yorkshire×Duroc sows within 2 d, so that for each sow a group of pigs was formed with the same weight distribution around the average birth weight within that litter. Sows had ad libitum access to a standard corn-soybean sow diet formulated to meet or exceed NRC requirements (NRC, 1988). Pigs that died before d 18 were not replaced by other pigs. Pigs were suckled from birth until d 18. No creep feed was provided during this period, but pigs had access to sow feed. At d $18 \pm .25$, pigs were divided within a litter into weight blocks of six large and six small pigs. Pigs were then randomly assigned within each weight block to treatment. One pig from each weight block was stunned by electric shock and then killed by exsanguination. Remaining pigs were placed on the following treatments from d 18 to d 25 (Figure 2):

	Conventional weaning	Split weaning		Milk replacer
		large pigs	small pigs	
day 14		Nursery-14		
day 18	whole litter on sow	milk replacer + starter diet	on sow	whole litter on sow
day 21		starter diet		
day 25	conventional nursery starter diet	conventional nursery starter diet	Nursery-14 milk replacer + starter diet starter diet	Nursery-14 milk replacer + starter diet starter diet
day 28				

Figure 1. Experimental design illustrated for the three treatments in Exp. 1: Conventional weaning, weaning at d 21 to starter diet; Split weaning, weaning large pigs at d 14 and small pigs at d 21, both groups weaned to milk replacer plus starter diet; Milk replacer, weaning at d 21 to milk replacer plus starter diet.

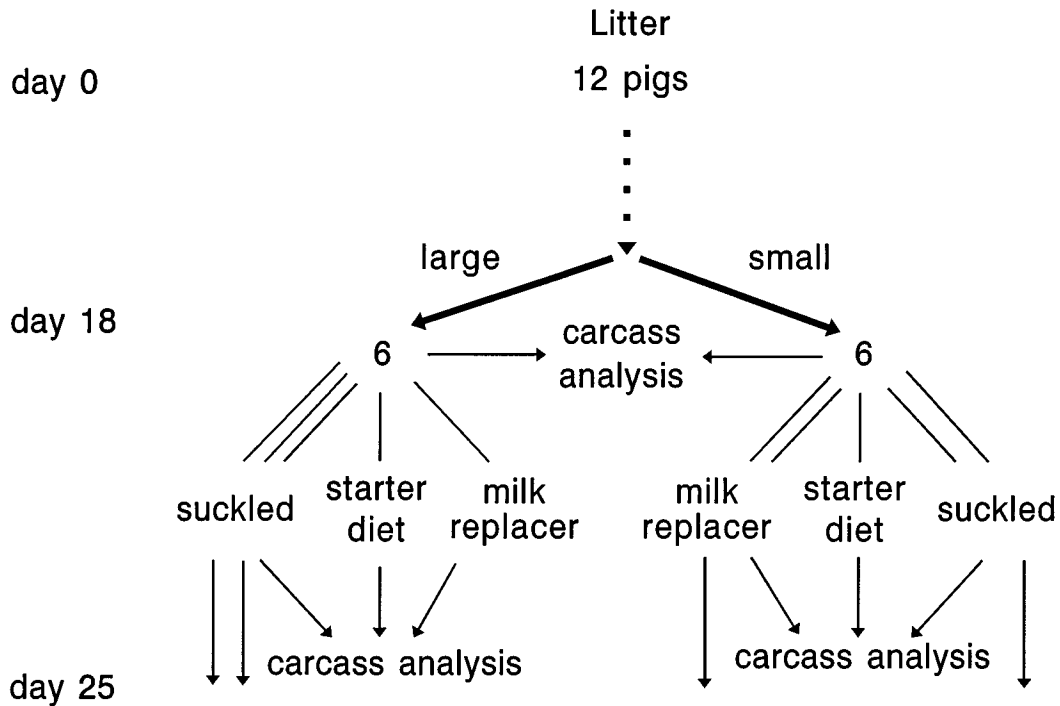


Figure 2. Experimental design illustrated for one litter in Exp. 2. Down from d 18, each line symbolizes one pig.

1. Suckled: pigs (three large and two small) remained on the same sow.
2. Milk replacer: pigs (one large and two small) were housed in groups in the Nursery-14 building.
3. Starter diet: pigs (one large and one small) were housed in groups in a conventional nursery.

Housing facilities for the pigs, with their environmental differences, are described in detail under Exp. 1. For the suckled pigs, it was assumed that ad libitum access to sow's milk was achieved because only 5 out of 12 pigs continued to suckle each sow after d 18. For the pigs fed starter diet, initial feed intake was stimulated by dispensing some feed on a rubber strip placed on the flooring.

Calculated analysis of the starter diet, milk replacer, and sow milk are given in Table 1. A commercial milk replacer (Milk Specialties Co., Dundee, IL; 160 g milk powder/1 L water) containing dried whey protein, dried skim milk, dried whey, animal fat, lecithin, vegetable fat, vitamin mix, mineral mix, and antibiotics was fed (percentage of ingredients is proprietary). A high-quality starter contained the following (percentage as-fed): corn (29.1), soybean meal (10), dried skim milk (20), dried whey (20), lactose (10), plasma protein (5), soybean oil (4), dicalcium phosphate (.78), limestone (.32), vitamin mix (.20), mineral mix (.35), and antibiotics (.25). Both milk replacer and starter diet met or exceeded NRC vitamin and mineral requirements (NRC, 1988).

Pigs were weighed daily from d 16 until d 25. Feed intake of starter diet was measured daily. Total overall milk replacer powder usage was measured. From one litter of Exp. 2, all 10 pigs that stayed on trial after d 18 were bled after a 2-h fast on d 18 and d 20. Pigs from a second litter not included in Exp. 2, but treated according to the outlined procedures, were also bled, for a total of 20 pigs bled in replicate. Blood was collected by jugular vena puncture into heparinized tubes (Vacutainer, Becton Dickinson, Rutherford, NJ). On d 25, one pig from each treatment \times weight-block combination was stunned by electric shock and then killed by exsanguination.

Sampling and Assay Techniques

Body Composition. Except for contents of the gastrointestinal tract and urinary bladder and small intestinal samples taken, the whole body was ground three times, first two times through a .64-cm die and then once through a .32-cm die (Hobart Co., Troy, OH). Each time the material was thoroughly mixed. Subsamples of the final mixture were taken and stored at -20°C until analysis for dry matter, ash, protein (macro-Kjeldahl; nitrogen \times 6.25), and fat (AOAC, 1990). Water content was calculated by weight loss after drying at 105°C for 24 h in a forced-air oven. Samples were then extracted for 24 h in 87%

Table 1. Calculated analysis of diets; Experiment 1

	Starter diet	Milk replacer ^a	Sow milk ^b
Protein, % DM	20.0	25.0	21.9
Lysine, % DM	1.38	2.25	1.73
Ca, % DM	.80	.62	1.02
P, % DM	.65	.56	.80
ME, Mcal/kg DM	3.87	4.19	5.56

^aSupplied by Milk Specialties Company, Dundee, IL.

^bNo analysis was done on sow milk in this experiment; however, data from milk samples of the same herd (Donovan et al., 1994) and literature are provided for comparison. Between 18 and 25 d after farrowing, sow milk contains 18.7% dry matter (Klobasa et al., 1987), 4.1 g of protein/L (Donovan et al., 1994), 7.9 g of lysine per 100 g of protein (Davis et al., 1994), and .19% calcium and .15% phosphorus (Lucas and Lodge, 1961). Calculated energy density of 1 kg of sow milk, based on 6.6% fat, 4.1% protein, and 5.8% lactose, is: $9.11 \times 66 + 5.12 \times 41 + 3.95 \times 58 = 1.04$ Mcal (Lucas and Lodge, 1961; Klobasa et al., 1987; Donovan et al., 1994).

chloroform: 13% methanol (vol:vol) in a Soxhlet apparatus, and fat content was calculated by weight loss. Dry ashing was accomplished by heating at 550°C for 24 h. Analyses were repeated until a sample mass balance of 99 to 101% was obtained.

Small Intestine. Following exsanguination, the abdominal cavity was opened and the gastrointestinal tract was removed. The small intestine was dissected free, weighed, and laid out so that it formed four parts of equal length. Total small intestinal length was measured. Then, 3-cm segments were collected at 25, 50, and 75% of the small intestinal length (defined as proximal, medial, and distal, respectively), weighed, and immersed in 10% neutral buffered formalin. The remainder of the small intestine was emptied and weighed. The stomach, cecum, and colon were also emptied. Three cross-sections of each small intestinal sample were processed in low-melt paraffin (Peel-A-Way, Scientific Products, McGaw Park, IL), sectioned at 5 μm thickness, and mounted on glass slides. Villus heights and crypt depths were quantified using a binocular microscope (Nikon Diaphot, Fryer Company, Carpentersville, IL) with mounted video camera and screen, and connected computer. For each intestinal segment, nine villus heights and nine crypt depths were measured using the software Image-measure (Microscience Inc, Federal Way, WA), and mean villus height and crypt depth were calculated.

Plasma Insulin and Glucagon. After withdrawal, blood samples were placed on ice and centrifuged at $3,000 \times g$ and plasma was frozen at -20°C until analyzed. Plasma insulin and glucagon were determined by RIA in duplicate using mono- ^{125}I -porcine insulin or glucagon, guinea pig anti-porcine insulin or glucagon, goat anti-guinea pig serum, and normal guinea pig serum as a carrier (Morgan and Lazarow, 1963). Human insulin and glucagon were used as standards. The RIA materials were purchased as kits from Linco Research Inc. (St. Louis, MO). Immune

Table 2. Effect of weaning management scheme on daily gain of early-weaned pigs in the pre- and early postweaning period; Experiment 1^a

Item	Conventional weaning	Split weaning	Milk replacer	Pooled SEM
All pigs				
Body weight, kg				
Day 14	3.67	4.04	3.70	.14
Day 21	5.22	5.89*	5.01	.18
Day 28	6.93	8.01**	7.25	.22
ADG, g				
Days 14–21	220 ^c	264*	187 ^c	14
Days 21–28	245	303*	319**	16
Days 14–28	233	284*	253	13
Small pigs ^b				
Body weight, kg				
Day 14	3.16	3.61	3.27	.12
Day 21	4.56	5.68**	4.50	.15
Day 28	6.24	7.48**	6.69	.18
ADG, g				
Days 14–21	200 ^c	295 ^{c,***}	198 ^c	14
Days 21–28	240	258	314**	18
Days 14–28	220	276**	245	13
Large pigs ^b				
Body weight, kg				
Day 14	4.19	4.47	4.14	.12
Day 21	5.87	6.10	5.53	.15
Day 28	7.63	8.54*	7.80	.18
ADG, g				
Days 14–21	241 ^c	232	198 ^c	18
Days 21–28	250	349***	325**	15
Days 14–28	246	291*	261	13

^aConventionally weaned pigs and pigs weaned to milk replacer were weaned at d 21, and large split-weaned pigs were weaned to milk replacer at d 14 and small split-weaned pigs at d 21. Each treatment had 60 pigs, 30 small and 30 large.

^bInitial body weight at d 14 was 3.35 kg ± .12 for small pigs and 4.26 ± .12 for large pigs.

^cPigs were suckled until d 21.

*Different from conventional weaning, $P < .05$.

**Different from conventional weaning, $P < .01$.

***Different from conventional weaning, $P < .001$.

complexes were counted in a Cobra II auto-gamma counter (Packard Instrument Company, Meriden, CT).

Statistical Analyses

For Exp. 1, litter was used as the experimental unit. To evaluate treatment differences in Exp. 2, weight block (large and small) and treatment (suckled, milk replacer, and starter diet) were used in a 2 × 3 factorial arrangement in four randomized complete blocks with each block representing one litter (Steel and Torrie, 1980). Using contrasts, suckled pigs were compared with pigs fed either milk replacer or starter diet. Suckled pigs at d 25 were compared with suckled pigs at d 18. Litter was used as experimental unit for growth performance data. The individual pig was used as experimental unit for body composition and small intestinal morphology data. For analysis of growth performance, body weight at d 18 was used as covariate in a repeated measurement procedure. Treatment differences in body composition at d 25

were analyzed using body composition data obtained from pigs out of the same litter and weight block killed at d 18 as a covariate. Significance of difference was calculated using the general linear models procedure of SAS (1985).

Results

Experiment 1

Split weaning at d 14 combined with feeding a milk replacer increased ADG 22% from d 14 to d 28 compared with conventional weaning at d 21 (Table 2; $P < .05$). Specifically, small split-weaned pigs remaining on the sow at d 14 increased ADG 48% compared with small pigs nursing with complete litters, from d 14 to d 21 ($P < .001$). Large split-weaned pigs that were fed milk replacer from d 14 to d 18 increased ADG 40% compared with large pigs weaned directly to starter diet, from d 21 to d 28 ($P < .001$). Feeding a milk replacer plus starter diet to pigs weaned at d 21

Table 3. Effect of weaning regimen on daily gain of early-weaned pigs in the early postweaning period; Experiment 2^a

ADG (d 18–25), g	Suckled	Milk replacer	Starter diet	Pooled SEM
All pigs	288	471***	123***	26
Large pigs	296	487**	122**	17
Small pigs	280	455**	125**	29

^a20 pigs (12 large, 8 small) for Suckled, 12 pigs (4 large, 8 small) for Milk replacer, and 8 pigs (4 large and 4 small) for Starter diet.

**Different from suckled pigs, $P < .01$.

***Different from suckled pigs, $P < .001$.

increased ADG 30% compared with conventional weaning, from d 21 to d 28 ($P < .01$).

From d 14 to d 21, ADFI of large split-weaned pigs was 305 g (146 g of milk powder, 159 g of starter diet). From d 21 to 28, ADFI was 240 g of starter diet for conventionally weaned pigs, 356 g of starter diet for large split-weaned pigs, 351 g (130 g of milk powder, 221 g of starter diet) for small split-weaned pigs, and 332 g (222 g of milk powder, 110 g of starter diet) for pigs weaned at d 21 to milk replacer plus starter diet.

Experiment 2

Growth Performance. Mean body weight at d 18 was $4.66 \pm .09$ kg, with no difference among treatment groups, and was $5.10 \pm .08$ kg for large pigs and $4.23 \pm$

.11 kg for small pigs. Because no weight block effect or weight block \times treatment effect was detected from d 19 through 25 ($P = .22$ and $.97$ at d 25, respectively), growth data were grouped together by treatment (Figure 3). At d 25, pigs fed milk replacer weighed 20% more ($P < .001$) than suckled pigs, and pigs fed starter diet weighed 19% less ($P < .001$) than suckled pigs. From d 18 to 25, ADG of pigs fed milk replacer was 64% higher than ADG of suckled pigs (Table 3; $P < .001$), whereas ADG of pigs fed starter diet was 57% lower than that of suckled pigs ($P < .001$). No effect of weight block was observed ($P > .10$). Growth curves of both suckled pigs and pigs fed milk replacer showed a consistent weight gain, whereas pigs fed starter diet lost weight the 1st d after weaning before starting to gain weight. From d 18 to d 25, ADFI was 345 g for pigs fed milk replacer and 144 g for pigs fed starter diet. For pigs fed starter diet, ADFI was 30, 95, 180, 190, 145, 172, and 195 g for the first 7 d after weaning, respectively. No statistical analysis was performed on intake data, because milk replacer intake of individual litters was not measured.

Body Composition. The percentages of protein, fat, ash, and water in suckled pigs were similar at d 18 and d 25 (Table 4). At d 25, as a proportion, pigs fed milk replacer contained less protein ($P < .001$), less ash ($P < .001$), and more water ($P < .01$) than suckled pigs. Pigs fed starter diet contained less fat and more water than suckled pigs ($P < .001$). From d 18 to 25, suckled pigs accreted .35 kg protein, .27 kg fat, .07 kg ash, and 1.44 kg water (Figure 4; $P < .001$). At d 25, pigs fed milk replacer had accreted more protein ($P < .01$), fat ($P < .05$), and water ($P < .001$) than suckled pigs. Furthermore, pigs fed starter diet contained less protein, fat, ash, and water than suckled pigs ($P < .001$).

Small Intestine. From d 18 to d 25, the small intestine (SI) of suckled pigs increased in weight (Table 5; $P < .001$) and length ($P < .05$). At d 25, SI length was similar among treatments. However, the SI of pigs fed milk replacer was heavier than that of suckled pigs when expressed as total SI weight ($P < .001$), weight per unit body weight ($P < .001$), or weight per unit SI length in proximal, medial, and distal SI ($P < .01$). Expressed per unit of body weight,

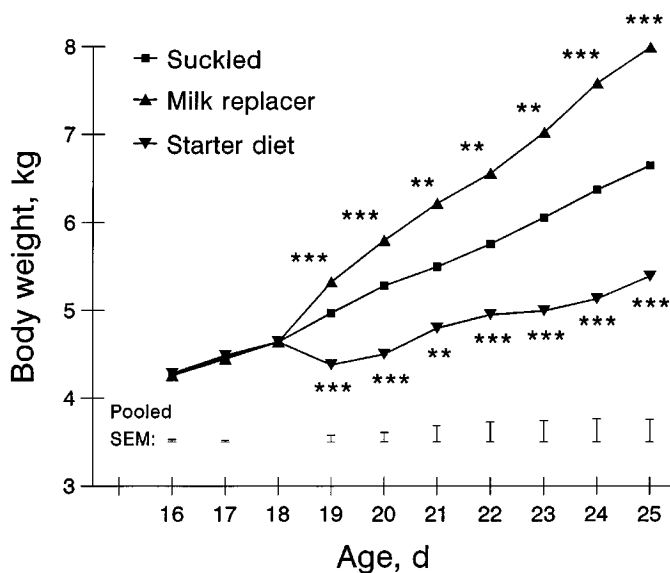


Figure 3. Mean daily body weight (kg) from d 16 to d 25 of pigs, either suckled, fed milk replacer, or starter diet; Exp. 2. Pooled SEM per day is symbolized as error bars; $n = 20$, 12, and 8 for suckled pigs, pigs fed milk replacer, and pigs fed starter diet, respectively. **Differs from suckled pigs, $P < .01$; ***differs from suckled pigs, $P < .001$.

Table 4. Effect of weaning regimen on whole-body composition of early-weaned pigs during the early postweaning period; Experiment 2^a

Treatment	Day 18	Day 25			Pooled SEM
		Suckled	Milk replacer	Starter diet	
Percentage body weight					
Protein, %	15.51	15.83	14.61***	15.75	.17
Fat, %	11.24	11.79	11.52	8.53***	.35
Ash, %	2.93	3.11	2.49***	3.07	.07
Water, %	70.75	69.99	71.66**	73.31***	.32

^aEight pigs per treatment group.

**Different from d-25 suckled pigs, $P < .01$.

***Different from d-25 suckled pigs, $P < .001$.

the SI of pigs fed starter diet was heavier ($P < .001$) than that of suckled pigs.

From d 18 to d 25, villus height remained similar in suckled pigs (Figure 5), whereas crypt depth increased ($P < .05$) in the proximal SI. At d 25, when compared with that of suckled pigs, villus height was greater in the proximal ($P < .001$) and medial ($P < .05$) SI and crypt depth increased in the medial ($P < .05$) and distal ($P < .05$) SI in pigs fed milk replacer. In contrast, in pigs fed starter diet, villus height was decreased in the proximal ($P < .05$) and medial ($P <$

.01) SI and crypt depth was greater throughout the SI ($P < .01$).

Plasma Insulin and Glucagon. Removal of seven pigs from the sow at d 18 did not alter the plasma insulin/glucagon ratio in the five remaining pigs at d 20 (Table 6). Interestingly, the insulin/glucagon ratio at d 20 followed the same pattern as body weight gain from d 18 to d 20 (i.e., pigs fed milk replacer had a higher ratio than suckled pigs and suckled pigs had a higher ratio than pigs fed starter diet). However, due to the large SEM of plasma glucagon in pigs fed

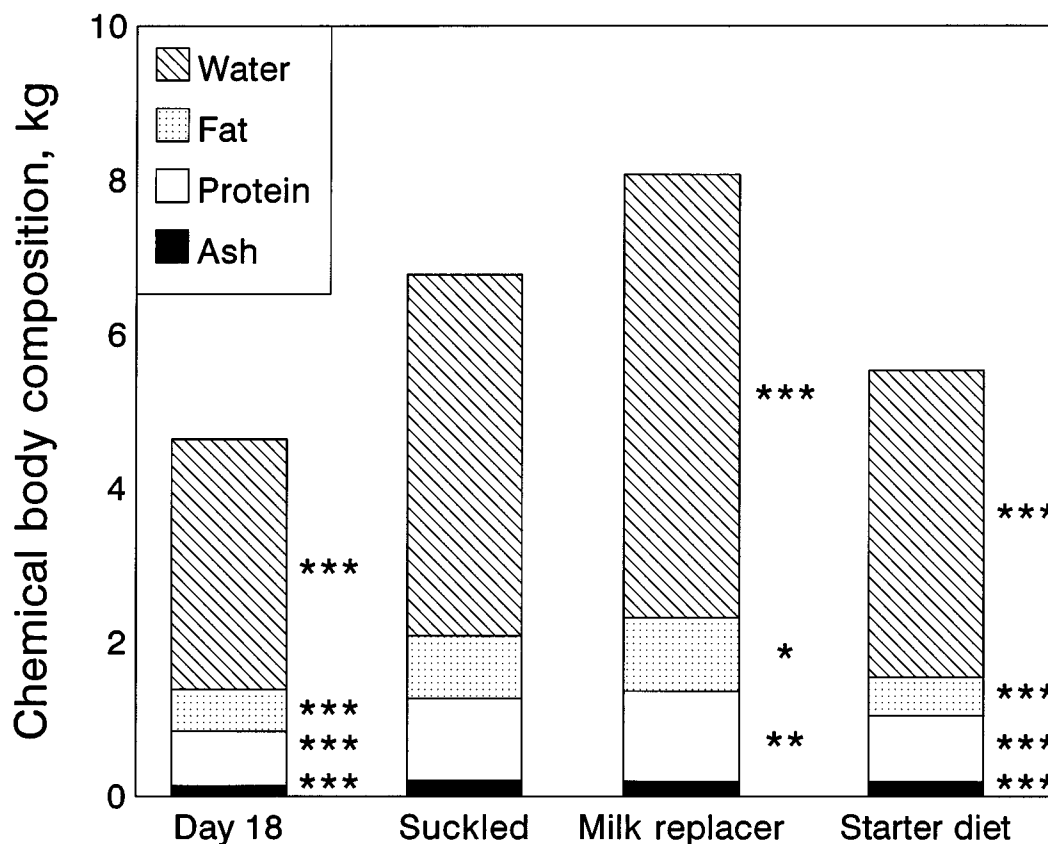


Figure 4. Mean chemical body composition (kg) of 18-d-old and 25-d-old suckled pigs and pigs fed milk replacer or starter diet; Exp. 2. $n = 8$ for each treatment. *Differs from d-25 suckled, $P < .05$; **differs from d-25 suckled, $P < .01$; ***differs from d-25 suckled, $P < .001$.

Table 5. Effect of weaning regimen on weight and length measurements of the small intestine (SI); Experiment 2^a

Treatment	Day 18	Day 25			Pooled SEM
		Suckled	Milk replacer	Starter diet	
Total SI					
Length, m	6.28*	7.51	7.79	7.76	.31
Weight, g	134.66***	194.64	276.45***	213.68	8.74
Length/kg body wt	1.30*	1.14	.96*	1.32**	.04
Weight/kg body wt	27.49	28.22	34.11***	34.87***	.74
Weight/Length	21.34*	25.84	36.58***	26.97	1.32
Segment weight (g/3 cm)					
Proximal	.77	.85	1.43***	.94	.07
Medial	.82*	1.03	1.36***	1.12	.05
Distal	.81	1.05	1.55**	.95	.10

^aEight pigs per treatment group.

*Different from d-25 suckled pigs, $P < .05$.

**Different from d-25 suckled pigs, $P < .01$.

***Different from d-25 suckled pigs, $P < .001$.

starter diet, no statistical differences were detected ($P > .10$).

Discussion

During weaning, pigs make many transitions, one of which is the transition from liquid to solid diet. The primary objective of this research was to examine whether elimination of this transition at weaning might reduce the postweaning lag, which is mostly due to extremely low feed intake during first 2 d after weaning (McCracken et al., 1995). Frequent feeding of liquid diet at weaning to 2- to 4-wk old pigs ameliorated the postweaning lag (Lecce et al., 1979). However, pigs were housed individually and fed hourly in this study by Lecce et al., which is not a practical approach. Weaned pigs have been housed in groups with hourly milk replacer feeding using electronic control (Muhs, 1989); however, control of individual feed intake was not established in this system. Feeding milk replacer to pigs at a very early age (1 to 2 d old) has been employed in many studies (Lecce, 1975) and is known as artificial rearing. Objectives of artificial rearing programs were to reduce farrowing interval and to reach maximum growth potential of pigs. In earlier experiments and under practical conditions, artificial rearing of newborn pigs resulted in diarrhea and subsequent poor survival, due to uncontrolled intake of milk replacer and need for a nearly sterile environment (Lecce, 1986). In recent experiments, artificially reared pigs showed similar or superior weight gains compared with sow-reared pigs (McClead et al., 1990; Harrell et al., 1993). In both of our experiments, no diarrhea or sick pigs were observed. This is partially due to the environment in the Nursery-14 building, which in-

fluences behavior, reduces metabolic rate, and probably controls feed intake (Swiergiel and Ingram, 1986). In this building, pigs need to leave a warm environment to eat in a cold environment, which influences meal frequency and meal volume but not total daily intake (Johnson and Cabanac, 1982). During visits to the facility, pigs were usually sleeping within the heated hover. Further behavioral research is necessary to support these observations.

Experiment 1

Milk replacer (in combination with starter diet) was fed the first 4 d after weaning before the final transition to starter diet was made. Feeding of milk replacer elevated total DM intake compared with feeding starter diet only, and resulted in a superior weight gain. However, pigs fed milk replacer were weaned in the Nursery-14 building, whereas pigs fed starter diet were weaned into a conventional nursery, which added an environmental factor that in our current experiment could not be separated. It would be of interest to house weaned pigs fed starter diet in the Nursery-14 building to quantify the environmental component of weaning. Recently, split weaning has been introduced to give lightweight pigs an extra time period to suckle (Mahan, 1993). Split weaning might ameliorate the weaning transition for lightweight pigs and achieve an overall decrease in time to reach market weight. Split weaning and milk replacer feeding were combined in one treatment group and compared with weaning pigs at 21 d to starter diet. From d 14 to d 21, heavy split-weaned pigs had a weight gain similar to that of heavy pigs in the group to be weaned conventionally, which were still suckling, indicating that intake of milk replacer and starter diet was enough to support growth similar to

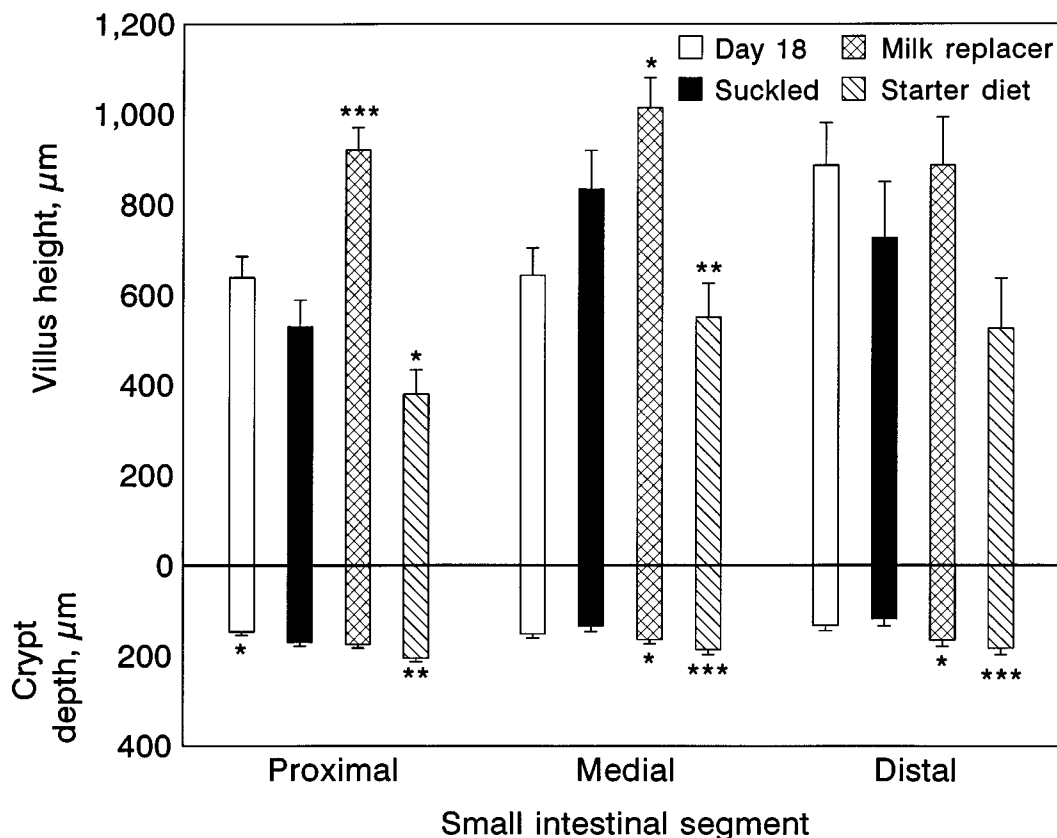


Figure 5. Mean villus height and crypt depth (μm) per treatment group of segments in the proximal, medial, and distal small intestine of 18-d-old and 25-d-old suckled pigs and pigs fed milk replacer or starter diet; Exp. 2. SEM is symbolized as error bars; $n = 8$ for each treatment. *Differs from d-25 suckled, $P < .05$; **differs from d-25 suckled, $P < .01$; ***differs from d-25 suckled, $P < .001$.

that of suckled pigs. From d 14 to 21, light split-weaned pigs had superior weight gains compared with lightweight conventionally weaned pigs (both groups were suckling), indicating that growth of lightweight pigs in large litters was suppressed during suckling. Overall, results indicated that feeding of a liquid milk replacer during the first 4 d after weaning increased feed intake compared to feeding of a dry starter diet, which consequently stimulated growth. These results indicate that feeding a liquid milk replacer may have application in the transition from sow's milk to solid feed.

Experiment 2

Performance. Milk replacer feeding was extended until the 7th d after weaning, without feeding of starter diet, to maximize weight gain in the 1st wk after weaning. Pigs were weaned at 18 d of age, 3 d earlier than pigs in the milk replacer group in Exp. 1. We expanded further on the results of Exp. 1, and divided pigs into light and heavy weight groups within litter. Surprisingly, no differences in weight gain between light and heavy pigs were observed after weaning. Furthermore, weight gains of pigs fed milk

replacer were superior to those of pigs that remained on the sow. Together, these observations indicate that sow milk production limited maximal pig growth at 18 d after farrowing. Earlier research demonstrated that pigs at 21 d of age were heavier with artificial rearing than with standard farming procedures (Jeppesen, 1981). More recent research with artificial rearing or supplementation of milk replacer during suckling suggested that the sow limits maximum pig weight gain as early as 7 d after farrowing (Harrell et al., 1996; Azain et al., 1996). A change during lactation in number of pigs suckling the sow can affect total milk production. Doubling the number of pigs suckled increased lactational capacity of the sow 50 to 100% (Sauber et al., 1994). In Exp. 2, total milk production might have been decreased due to the reduction of number of pigs suckling each sow after d 18, because no change in rate of gain of pigs remaining on the sow was observed. In contrast, in Exp. 1 in which heavier pigs were removed from the sow at d 14, total milk production might have been affected to a lesser extent, because lighter pigs increased their rate of gain from d 14 to d 21. Pigs weaned on starter diet performed poorly compared with pigs fed milk replacer or suckled pigs. The observed growth curve was similar to the

Table 6. Effect of weaning regimen on plasma insulin and glucagon of early-weaned pigs during the early postweaning period; Experiment 2^a

Treatment	Day 18	Day 25		
		Suckled	Milk replacer	Starter diet
Insulin, pmol/L	45.7 ± 4.2	87.0 ± 22.2	64.1 ± 7.7	40.0 ± 11.2
Glucagon, ng/L	123.7 ± 9.7	221.6 ± 22.5	138.2 ± 25.3	277.9 ± 117.2
Insulin/glucagon, mol/mol	1.4 ± .2	1.4 ± .3	1.8 ± .3	1.1 ± .8

^aTwenty pigs for d 18; for d 25, 10 pigs for Suckled, 6 pigs for Milk replacer, and 4 pigs for Starter diet.

postweaning growth curve observed in 3-wk-old pigs fed a complex starter diet (Okai et al., 1976). The poor performance was due to very low feed intake and probably not to soy hypersensitivity. This could be concluded because we weighed pigs and measured starter diet intake daily after weaning. In most experiments involving weaning, pigs were not weighed daily following weaning. Rather, the first weight measurement was typically taken at 1 or 2 wk after weaning, so that influence of either feed intake or soy hypersensitivity could not be established. To have a hypersensitivity response to dietary components, initial intake of diet is necessary (McCracken et al., 1995). A subsequent hypersensitivity response will then cause a decrease in intake. In Exp. 2, intake of starter diet was extremely low the first 2 d after weaning and started to increase thereafter. Low intake directly after weaning was, therefore, probably due to the early weaning age and lack of creep feeding during suckling.

Intake of milk replacer and starter diet were reported on a weight basis. Differences in intake would be more significant if expressed in ME, because milk replacer powder had a higher energy density than starter diet.

Body Composition. Additional body weight gain in pigs can potentially result in increased protein and/or fat deposition. Increased fat deposition alone might not be beneficial because fat deposition is costly and is not preferred by the current consumer market. However, increased weight gain in pigs fed milk replacer resulted in increases in protein and fat deposition similar to those in suckled pigs, indicating that maximal protein deposition was not established in 18- to 25-d-old suckled pigs (Whittemore, 1993). The increase in percentage of water in pigs fed milk replacer exceeded a proportional increase in protein accretion. This could indicate high intake of milk replacer with a high percentage of water retention in the body. Percentage of body composition was similar for suckled pigs at d 18 and d 25, suggesting that growth during this week continued at a rate similar to growth before d 18. Pigs fed starter diet received a complex high-quality diet, identical to the high-quality diet used in research that compared high- and low-quality starter diets (Whang, 1995). Weight gain was 34% lower in our study using 18-d-old weaned pigs

compared with 21-d-old weaned pigs from this earlier research. However, change in body composition over the 1st wk after weaning showed a similar pattern. Protein was accreted whereas body fat stores were reduced, indicating that body fat was used as an energy source during the 1st wk after weaning. Increased water percentage in pigs fed starter diet is probably related to the decrease in fat percentage.

Small Intestine. Gut morphology has been examined in several weaning studies and reduced villus height has been linked with the post weaning lag (Cera et al., 1988). Both soy hypersensitivity and reduced feed intake have been suggested as causes for reduction in villus height (Li et al., 1991; Kelly et al., 1991; McCracken et al., 1995). A strong relation ($r = .82$; $P < .001$) between total DM intake and villus height was recently established in pigs fed cow's milk for 5 d after weaning (Pluske et al., 1996). In our study, pigs fed milk replacer had longer villi than did suckled pigs, which supports the link established with feed intake. Villus height remained unchanged in suckled pigs from d 18 to d 25, which could indicate that daily intake of sow milk remained unchanged during this week. At 7 d after weaning, pigs fed starter diet had shorter villi than did suckled pigs, which could be due to reduced feed intake; however, a soy hypersensitivity response cannot be eliminated as a possible cause for villus atrophy at this time point after weaning (McCracken et al., 1995). Increased crypt depth throughout the small intestine indicated enhanced proliferation (Hampson, 1986). Weight of the small intestine, but not length, was altered by treatment, indicating that length may depend more on age and weight may depend on nutritional status of the pig. Feeding of a milk replacer increased weight per unit of length compared with suckled pigs, which coincides with the increase in rate of body weight gain.

Plasma Insulin and Glucagon. Systemic pancreatic hormone concentrations indicate whether metabolism is directed toward anabolism or catabolism. Insulin stimulates anabolism by enhancing uptake of amino acids into muscle cells and protein synthesis and by stimulating fat deposition and glycolysis (Newsholme et al., 1992). Glucagon stimulates catabolism by enhancing mobilization of energy stores. Both plasma insulin and glucagon concentrations are partially dependent on amount of digested and absorbed glucose

and amino acids. In our study, plasma glucagon was high in pigs fed starter diet, an indication of nutritional stress (McCracken et al., 1995). Plasma glucagon in pigs fed milk replacer was not elevated. However, differences between treatments were not significant; pigs weaned to starter diet might have substantially different intakes in the early postweaning period, which could explain the variation in plasma glucagon (Appleby et al., 1992). Although no statistical differences were observed, it is of interest that numerical differences in insulin/glucagon ratio reflected suggested differences in feed intake among treatments.

Implications

Collectively, results from these experiments indicate that feeding milk replacer in the early postweaning period may help the pig to overcome the postweaning growth lag. Enhanced weight gain in pigs fed milk replacer during this period was due to increased intake and consisted of a concerted increase in both protein and fat accretion. Some experiments have shown that increased weight gain in the early postweaning period resulted in reduced time to reach market weight; however, verification that feeding milk replacer in the early postweaning period will reduce time to market is needed.

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