Strategies to maintain nutrient intake, reduce weight loss, and improve livability in newly weaned pigs

by

Madison Renae Wensley

B.S., Michigan State University, 2018
M.S., Kansas State University, 2020

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Sciences and Industry
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Abstract

Low feed consumption after weaning disrupts nutrient intake and results in what is commonly known as a post-weaning growth check. While most pigs recover from this initial reduction in feed intake, some pigs fail to successfully transition after weaning, leading to decreased survivability. As nursery pig mortality continues to increase across the swine industry, there is need to optimize current intervention and management practices. Hence, two literature reviews were written to summarize several pre- and post-weaning strategies that can be used to improve feed intake after weaning. Increasing weaning age helps prevent many of the adverse effects associated with weaning stress. Other pre-weaning strategies include creep feeding and piglet socialization. These strategies familiarize pigs with solid feed, encourage exploratory behavior, and improve social skills prior to weaning. Post-weaning strategies include appropriate barn temperatures, nutrient resource availability, and placement strategies. Because young pigs are sensitive to palatability, diet form and complexity are also important considerations. To evaluate the gaps in knowledge identified from these literature reviews, 10 experiments were conducted using 16,183 pigs. The first series of experiments evaluated the effect of mat feeding on the growth performance, removal, and mortality of nursery pigs. A second series of experiments evaluated different sensory attractants offered pre- and post-weaning on the feed intake and body weight loss of nursery pigs after weaning. The effect of gruel feeding and supplemental oral dextrose on nursery pig survivability was also assessed. Lastly, a single experiment evaluated the effect of Duroc sire lines selected for either early or late maturing growth rates and creep feeding on the stress response, intestinal permeability, and growth performance of nursery and finishing pigs. Implementation of these strategies had limited effects on nursery pig growth performance; however, they did show we can successfully reduce the

percentage of pigs that lose weight after weaning. Likewise, mat feeding can be used to reduce the removal rate of pigs in the nursery. In contrast, gruel feeding four times per day vs two times per day or providing a dextrose supplement to pigs removed from the general population did not improve survivability. Nutritional attempts to maintain feed intake have minimal effects compared to genetic selection. Early maturing pigs had a lower stress response at weaning and improved ADG and ADFI until approximately 100 kg, at which point late maturing pigs began to exhibit higher ADG. Late maturing pigs had improved feed efficiency throughout the experiment. Additionally, creep feeding late maturing pigs resulted in improved growth performance compared to providing no creep feed, whereas creep feed did not impact early maturing pigs. In summary, innately low feed intake after weaning makes it difficult to influence nursery pig growth performance. However, these data indicate that feeding and management strategies can be used to successfully reduce the percentage of pigs that lose weight after weaning, as well as removal and mortality rates. These strategies also increase animal caretaker engagement in the barn. As important as feeding and management strategies, the health and genetics of pigs plays a crucial role in how pigs transition at weaning.

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Table of Contents

List of Figures

List of Tables

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“My life is not based on what I do, but what I empower others to do.” - Craig Groeschel

Chapter 1 - Maintaining continuity of nutrient intake after weaning.

I. Review of pre-weaning strategies

Abstract

Weaning is a crucial phase of swine production marked by a multitude of biological and environmental stressors, which have a significant impact on immediate postweaning behavior and feed intake (FI). During this time, the piglet's gastrointestinal (GI) system is also undergoing extensive epithelial, immune, and nervous system development. In this review, our objective is to describe the different preweaning strategies that can be used to minimize nutrient intake disruption and improve FI in the immediate postweaning period. Reducing nutrient disruption postweaning can be accomplished through the implementation of management and nutritional strategies. Research consistently demonstrates that weaning older, more developmentally mature pigs helps prevent many of the adverse GI effects associated with weaning stress. Providing creep feed to pigs during lactation is another reliable strategy that has been shown to increase immediate postweaning FI by acclimating pigs to solid feed prior to weaning. Likewise, socialization by allowing pigs to mix before weaning improves social skills, minimizing mixing stress, and aggression-related injury immediately postweaning. Supplemental milk replacer has also been shown to elicit a positive response in preweaning growth performance, which may help to reduce preweaning mortality. While socialization and milk replacer are acknowledged to ease the weaning transition, these strategies have not been widely adopted due to labor and application challenges. Additionally, the cost of milk replacer and logistics of retrofitting farrowing houses to accommodate litter socialization have limited adaptation. Further exploration of maternal nutrition strategies, particularly fetal imprinting, is needed to better understand the implications of perinatal learning. Other areas for future research include,

combining environmental enrichment with feeding strategies, such as large destructible pellets or play feeders, as well as determining at what time point producers should start socializing pigs before weaning. While more research is needed to develop strategic preweaning management programs, many of the strategies presented in this review provide opportunities for producers to minimize nutrient intake disruption by preventing feed neophobia, reducing stress, and easing the wean pig transition.

Introduction

Weaning is a stressful event in a pig's life, marked by maternal and littermate separation, dietary and environmental changes, in addition to co-mingling and social hierarchy establishment (Moeser et al., 2006). In the wild, pigs are gradually weaned around 12 weeks of age, whereas pigs reared in modern U.S. production systems are weaned between 2.5 and 4 weeks of age (Moeser et al., 2017), an outcome determined by lactation space, pig flow, and disease status. The period pre-weaning is characterized by exogenous and endogenous factors that act to limit immune activation until 2.5 to 4 weeks of age, at which time there is a reduction in maternal immunity and an increase in piglet lymphocyte development and Peyer's patches maturity (Moeser et al., 2017). During this time, the piglet's gastrointestinal (GI) system is also undergoing extensive epithelial, immune and nervous system development. This emphasizes the need for a sanitary environment to achieve long-term maturation of the immune system. However, this critical window of maturation is often interrupted by the weaning transition, which can have detrimental effects on gut health, nutrient utilization, and disease resistance (Moeser et al., 2017). Furthermore, the combination of stressors that occur at weaning have a significant impact on immediate post-weaning behavior and feed intake (FI; Pluske, 2016).

It is well established that stress plays a pivotal role in intestinal barrier breakdown (Hart and Kamm, 2002; Kelly et al., 2015). Exploration of the gut-brain axis has revealed the impacts of stress on the biochemical signaling that occurs between the GI tract and central nervous system (Hart and Kamm, 2002), suggesting an interactive relationship between the microbiome, intestinal barrier, and enteric nervous and mucosal immune systems (Yu et al., 2012; Kelly et al., 2015). Stress stimuli activates the hypothalamic pituitary adrenal (HPA) axis, the body's central stress response mechanism. Activation of this pathway is characterized by increased corticotropin release factor (CRF) activity, mast cell (MC) degranulation, and increased gut permeability (Hart and Kamm, 2002). Continuous activation of this stress response system can have detrimental effects on the protective, metabolic, structural, and immune functions of the gut coinciding with persistent inflammation, decreased nutrient utilization, and poor growth performance (Yu et al., 2012; Hart and Kamm, 2002).

In addition to weaning stressors, genetic selection for large litter sizes has increased demands on the sow to supply more nutrients, both in utero and during lactation, which has led to an increased proportion of light birth weight pigs ($\leq$ 1 kg). Data collected from 965 litters indicated that this proportion increased from 7 to 23% of total pigs born as litter size increased from $\leq$ 11 to $\geq$ 16 pigs, with 17% of light birth weight pigs dying within the first 24 h after farrowing (Quiniou et al., 2002). In more recent years, Feldpausch et al. (2019) observed that 43% of total pre-weaning mortalities occurred amongst the light birth weight population. In addition, Craig et al. (2017) observed that in gilt progeny, pigs were weaned and marketed at lighter weights than sow progeny, with significantly increased mortality rates. Differences in gilt progeny birth weights and subsequent growth is attributed to developmental delays associated with decreased organ weights, restricted colostrum digestion, and lower serum IgG concentrations (Craig et al., 2019). These data indicate an opportunity for producers to implement nutritional and management programs prior to weaning to better prepare pigs for the changes in FI and growth rate post-weaning. Therefore, the present review will focus on different pre-weaning strategies to minimize nutrient intake disruption and improve FI in the immediate (7 d) post-weaning period

Pre-Weaning Strategies To Increase Feed Intake After Weaning

Maternal nutrition

Lucas et al. (1991; derived from Davies and Norman, 2002) defined programming as the physiological 'setting' by an early stimulus or insult at a 'sensitive' period, resulting in long-term consequences for function. Fetal programming is the foundation for fetal growth and development and is influenced by maternal uterine conditions that are often categorized into nutritive and non-nutritive factors (Johnston et al., 2008). These conditions include uterine capacity, gestational stress from the environment, maternal under and over nutrition, and placental nutrient transport. These conditions impact post-natal growth and development, HPA activity, intestinal morphology, and offspring lifetime reproductive performance (Johnston et al., 2008; Ji et al., 2017). The final weeks leading to parturition are well documented as the most sensitive stage for fetal programming (Ji et al., 2017).

Nutritional strategies to influence uterine conditions have been suggested throughout the literature. It is understood that vitamin and mineral nutrition, glucose transport, and growth hormone circulation play crucial roles in fetal growth and development (Johnston et al., 2008). Specifically, L-glutamine supplementation during gestation has demonstrated encouraging physiological and developmental benefits, ameliorating intrauterine growth retardation in gilt progeny (Wu et al., 2011) and increasing the average birth weight of muliparous sow progeny

(Zhu et al., 2018). Dietary glutamine in lactating sow diets has also been shown to enhance glutamine concentrations in milk, increasing piglet growth and survival (Wu et al., 2011). While glutamine appears to have beneficial effects, limited research has prevented widespread adaptation. Glutamine is also not approved for feeding in all locations globally. Furthermore, Zhang et al. (2017) reviewed the effects of branched-chain amino acid (BCAA) supplementation in sow diets. Collectively, the data demonstrates that BCAAs stimulate mammary epithelial cell growth, increase percentage milk protein, and increases glutamine, glutamate, and asparate concentrations in the milk. Among all BCAA, leucine plays a vital role in mTOR pathway activation, enhancing blastocyte development and embryo implantation, as well as fetal protein synthesis. Supplementing sow diets with BCAA remains promising, however more research is needed in this area. Other interventions have reported that supplementing sow lactation diets with fatty acids (FA) infuence the transfer of *n*-3 and *n*-6 polyunsaturated fatty acids (PUFA) from the sow milk to the piglet (Lauridsen, 2020). Uptake of these FA into the piglets enteric tissues may impact gut health and function, while also providing immune system support. In a review by Rosero et al. (2016), supplemental FA also showed a consistent improvement in litter growth. Piglet survival however was less consistent and was therefore not reported. The authors concluded maximum sow reproductive efficiency can be achieved by providing a minimum dietary intake of 10 g/d of α-linolenic acid and 125 g/d of linoleic acid. Additionally, many studies evaluating the effects of PUFA in sow diets have shown improved intestinal glucose absorption, FA concentrations, and tissue glycogen stores in piglets (Jarocka-Cyrta et al., 1998; Gabler et al., 2007; Boudry et al., 2009). Perinatal flavor learning is another interesting concept. Research shows that young animals can learn flavors from the maternal diet that appear in the amniotic fluid and mother’s milk (Oostindjer et al., 2010). Prenatal exposure to flavors in addition to flavors in the maternal diet after birth have been shown to increase FI and BW gain of piglets in the immediate post-weaning period (Oostindjer et al., 2010; Blavi et al., 2016**)**, and decrease time to initial FI (Oostindjer et al., 2011)**.** Interestingly, when given a choice between feed with or without flavor after weaning, previous exposure did not effect flavor preference (Oostindjer et al., 2010; Figueroa et al., 2013); however, flavor learning did reduce aggressive tendencies following nursery placement (Oostindjer et al., 2010, 2011; Fuentes et al., 2010). This suggests that flavor learning in pigs works through a reduction of weaning stress rather than flavor preference, which may reduce feed neophobia at weaning.

While many of these strategies appear promising, few have gained industry wide application as a result of limited research. Additionally, the economics of implementing these strategies on farm is not well understood. Therefore, further research is needed in the area of sow nutrition to better understand its influence on fetal programming, as to develop more practical approaches to improving maternal uterine conditions and imprinting on subsequent offspring behavior and long-term growth performance

Management strategies

Cross fostering and split-suckling

Cross-fostering and split-suckling are management strategies widely used throughout the swine industry as a means to increase pre-weaning growth and survival. The process by which these strategies are carried out varies widely across production systems (Baxter et al., 2013); however, there is a consensus that age, birth order, litter size, and body weight (BW) play critical roles in the success of implementing these strategies.

Cross-fostering is the relocation of piglets from their biological mother to a foster sow in an attempt to equalize litter size and reduce mortality. It is well-recognized that fostering piglets is time sensitive. Ideally, fostering should take place 12-24 h after birth which allows piglets sufficient colostrum intake from their birth sow, while also preventing the disruption of teat hierarchy establishement (Heim et al., 2012; Baxter et al., 2013). When there is a risk that sow colostrum production will not meet piglets needs (> 200 g), fostering should occur earlier (Alexopoulos et al., 2018). Observations at the time of milk let down throughout lactation suggest that the number of fights associated with suckling tend to be lower in biologically related litters compared to cross-fostered litters; however, this does not impact the number of successful nursing episodes and the subsequent growth and survival of fostered pigs (Heim et al., 2012). Huting et al. (2017) utilized light and heavy birth weight pigs and assessed the impact of mixed- verses uniform-weight litters through cross-fostering. Not surprisingly, light weight piglets reared in uniform litters had heavier weaning weights and fewer removals than those reared in mixed litters. Conversely, heavier birth weight piglets performed better and had fewer removals in mixed litters. Both of these responses are related to the piglet’s ability to compete for a more productive anterior teat. These results are in agreement with Deen and Bilkei (2004) who observed greater mortality in low birth weight pigs reared with high birth weight littermates. More importantly, however, was the impact of litter size. Low birth weight pigs fostered into larger litters, regardless of littermate BW, missed more nursing episodes and had increased mortality compared to those fostered into smaller litters. Furthermore, piglets fostered into older litters had significantly reduced suckling activity compared to piglets fostered into younger litters (Pajžlar and Skok, 2019). Taken together, small piglets should be fostered into litters of other small pigs (Alexopoulos et al., 2018). When this is not feasible, litter size should be reduced by removal of larger pigs. There is some data that suggest cross-fostering may also impact long-term growth and survival; however, the results are inconsistent and seem to be more closely related to piglet birth weight (Baxter et al., 2013; Huting et al., 2017). When done correctly, cross-fostering allows producers to equalize litter size, which should reduce teat competition and give piglets more opportunity to consume milk.

Limited research has been conducted to determine the best approach for split-suckling. Morton et al. (2019) conducted a study evaluating two split-suckling methods, temporarily removing either the heaviest six pigs in the litter or the first half of the piglets born. It was concluded that while both birth weight and order are important for pre-weaning growth and survival, the two interact differently. Birth weight was closely related to colostrum intake, compared to birth order which was observed to affect immunocrit levels. Furthermore, Donovan and Dritz (2000) demonstrated that while split-suckling decreased variation in ADG of pigs from birth to weaning, this response was only significnat for pigs in large litters (≥ 9 pigs). These studies were conducted during the pre-weaning period, therefore the implications of split-suckling strategy on post-weaning nutrient intake and performance is unknown; however, split-suckling creates more opportunities for pigs to receive colostrum, which should provide greater immunity and promote healthy growth (Alexopoulos et al., 2018)

Intermittent suckling and socialization

Intermittent suckling (IS) is a strategy that is long-established but not commonly used throughout the swine industry due to labor implications. Intermittent suckling is a form of gradual weaning where piglets are removed from the sow for a period of time each day. This simulates the progressive maternal separation that occurs during natural weaning. Turpin et al. (2016a,b; 2017) conducted three trials evaluating the effects of IS on post-weaning behavior and performance. Litters exposed to IS 7 d prior to weaning had decreased pre-weaning mortality compared to conventionally weaned litters (Turpin et al., 2016a). Interestingly, 3 d after weaning

IS groups had a negative average daily gain (ADG) in contrast to conventionally weaned groups; however, gain recovered and surpassed that of the conventionally weaned group by d 7. Turpin et al. (2016b) also observed that combining IS with a 35 d wean age improved the post-weaning adaptation period, evident by increased FI and ADG through d 12 post-weaning. No difference was observed when combining IS with a 28 d wean age relative to the control group. Lastly, IS with co-mingling non-littermate piglets before weaning, in combination with grouping familiar pigs together after weaning, improved performance in an additive manner, resulting in increased FI and decreased expression of manipulative behavior immediately post-weaning (Turpin et al., 2017). This highlights the impact of familiarity on growth performance and the potential benefit of pre-weaning socialization on social skill development.

Hötzel et al. (2004) demonstrated that modern rearing systems have a significant impact on the development of piglet behavior. Compared to piglets reared in farrowing stalls, piglets reared in outdoor systems exhibit less social interaction with the sow and fewer nursing episodes, which appears to encourage earlier solid feed consumption during lactation and reduce manipulative social behaviors after weaning. Research conducted to mimic outdoor rearing systems by removing the barrier between two adjacent farrowing pens and allowing pigs to mix has shown a similar response in reducing agonistic behavior and lesion scores (North and Stewart, 2000; Hessel et al., 2006). Other studies have found that mixing pigs during lactation increases pre-weaning play behavior, reduces BW loss at weaning, and improves post-weaning growth rates (North and Stewart, 2000; Hessel et al., 2006; Salazar et al., 2018). D'Eath (2005) also observed that socialized pigs were able to more quickly form stable dominance hierarchies when faced with unfamiliar pigs compared to previously unsocialized pigs. These data demonstrate the importance of socialization prior to weaning as a strategy to minimize mixing stress and better prepare pigs for weaning. Despite these added benefits, early mixing strategies have not been widely adopted in practical operations. The logistics and cost of retrofitting farrowing houses to accommodate litter socialization, in addition to the potential disease spread when co-mingling litters has prevented application. However, as interest in this area increases, more research is needed to fully understand the effects of early mixing on post-weaning FI and growth performance.

Wean age

Emerging evidence indicates that early life adversities lead to the early onset and greater severity of intestinal disorders (Gresse et al., 2017; Pohl et al., 2017). In humans, early life stressors have been linked to irritable bowel syndrome and depression (Kelly et al., 2015). Moeser et al. (2006) evaluated the effects of weaning age induced stress on intestinal dysfunction in pigs 24 hours post-weaning. Compared to age-matched, unweaned littermates, pigs weaned at 19 d of age exhibited increased serum and peripheral CRF, a stress peptide hormone that is released in response to HPA axis stimuli. This neuroendocrine survival mechanism is responsible for bringing the body back to homeostasis after a stress event (Moeser et al., 2017). Additionally, HPA helps to regulate many body processes, including digestion and the immune system, thus playing a central role in gut health. This response was supported by ussing chamber analysis of jejunal tissue, which showed reduced tight junction integrity, increased intestinal permeability, and net ion transport, all of which suggest the role of CRF in intestinal permeability. In a follow up trial, Moeser et al. (2007) evaluated the effects of stress in delayed weaning. Compared to pigs weaned at d 19, pigs weaned at d 28 exhibited decreased CRF-recpetor1 expression, an indicator of CRF concentrations. Furthermore, pigs weaned at d 28 displayed decreased tryptase activity, a marker of MC activation. Tryptase, along with pro-inflammatory compounds

(Serotonin/5-hydroxytryptamin and histamine) are released from MC in response to immune stimuli. Under normal conditions, these mediators are designed to increase intestinal secretion and inflammation to rid the body of invading pathogens (Yu et al., 2012). However, when pigs weaned at 16 d of age were subjected to an *E. coli* challenge, these immune responses were suppressed and exacerbated intestinal injury was observed (McLamb et al., 2013). This suggests stress induced MC activation is different than pathogenic, and that stress compromises gut integrity, altering innate immune responses to subsequent health challenges. Interestingly, the *E. coli* challenge reduced growth rates in pigs weaned at 16 d , whereas growth was not affected in pigs weaned at 20 d of age; however, feed intake was similar between wean age groups. This data further demonstrates the importance of weaning an older, more biologically mature pig.

Further research investigating early weaning and its impact on gut integrity revealed that pigs weaned at 15 d of age developed chronic, relapsing diarrhea, with a more severe clinical response observed in females (Pohl et al., 2017). Others have shown that these clinical (Medland et al., 2016) and pathophysiological (Smith et al., 2010) responses can persist into later life, which supports the observations by Main et al. (2004) where they reported improved wean-to-finish performance as wean age increased from 12 to 21 d of age. Despite there being no difference in lifetime performance when analyzed on a common age, Faccin et al. (2020) observed that as wean age increased up to 25 d, belly nosing behavior, immediate post-weaning body weight loss, and nursery removal rates were reduced. As a result, BW sold per pig weaned increased with weaning age, which is in support of the Main et al. (2004) study.

The immediate post-weaning impacts of wean age have also been studied. van der Meulen et al. (2010) observed that increasing wean age from 4 to 7 weeks of age improved post-weaning FI and gain immediately after weaning. Furthermore, Pulske et al. (2003) reported GI underdevelopment in pigs weaned at either 2 weeks of age or at lighter body weight, regardless of age. Underdevelopment was marked by lighter GI organs and accessory organ weights, as well as lower specific maltase, glucoamylose, and pancreatic enzyme activity. Similarly, when pigs were divided into young (< 32.4 wean age) verses old (> 35.9 wean age) groups at a common wean date, higher mortality rates were observed in young (9.1%) compared to old pigs (5.0%; Huting et al., 2019). However, when divided into light verses heavy groups, no statistical differences were detected. Huting et al. (2019) also observed that increasing wean age and feeding allowance in the nursery benefited light weaned pigs compared to heavy weaned pigs. Regardless of BW though, Main et al. (2004) reported that feeding program complexity in the nursery phase did not impact wean-to-finish performance.

These data suggest that weaning older, more developmentally mature pigs helps prevent many of the clinical, pathophysiological, and economic consequences associated with stress

Nutrient intake

Topsoil

Aside from a more natural weaning process, outdoor rearing systems offer more physical and social environmental interactions for young pigs (Lau et al., 2015). Specifically, early exposure to topsoil during lactation has been shown to accelerate gut microbiota maturation in weanling pigs (Vo et al., 2017). In modern indoor systems, piglets do not have access to topsoil, therefore reducing their microbial load exposure. This may be associated with immune deficiencies and poorer lifetime health.

Exposure to topsoil 4 d post-farrow until weaning resulted in lower weaning weights compared to litters that were not exposed to topsoil (Tsai et al., 2016). However, during the nursery period, pigs provided topsoil during lactation had increased FI and ADG. Subsequent FI during the grow-finish period was also increased with a tendency for a 4.6 kg heavier market weight. Furthermore, when challenged with lipopolysaccharide on d 56, pigs provided topsoil pre-weaning had an improved immune response, represented by increased plasma IL1α concentration (Tsai et al., 2016). Vo et al. (2017) demonstrated that this response can be attributed to abundant *Prevotella* and short chain fatty acid producing taxa when pigs are exposed to soil early in life. Furthermore, because soil contains plant-derived carbohydrates and fibers it is also believed that early transfer of these compounds in the colon can prepare the piglet GI tract for solid food, preventing reductions in post-weaning FI and BW gain (Vo et al., 2017). Similar to outdoor rearing, these data suggest that exposure of naïve pigs to soil during lactation may help to develop a more functional immune response, which may provide subsequent health and performance benefits. More research however is needed to better understand the microbial implications of topsoil exposure on the piglet GI tract. Likewise, fecal microbiota transplantation (FMT) has gained attention in regulating gut microbial colonization. Exogenous FMT has been shown to improve the growth performance, intestinal barrier function, and innate immune system of piglets (Hu et al., 2018), so as to potentially alleviate the damage of weaning stress (Xiang et al., 2020). Furthermore, the transfer of feces from a healthy donor to a diseased recipient may offer the opportunity to alter the GI microbiota and reduce morbidity and mortality in health challenge herds (Niederwerder et al., 2018). While this strategy appears to have more relevance in human health, it does provide insight on specific bacteria or probiotics that may be used to create a more symbiotic microflora environment in the pig. Nevertheless, more research is needed to understand the interaction between the gut microbiota and the development of immune cells (Xiang et al., 2020).

Creep feeding

Offering creep feed pre-weaning is believed to ease the weaning transition by improving feed intake in the immediate post-weaning period. At first introduction, familiarization of solid feed is an exploratory behavior; however, as pigs begin to mature, creep feed consumption is largely driven by nutrient demand (Pajor et al., 1991). It has also been suggested that piglets with insufficient milk intake or those with low BW will compensate by increasing solid feed consumption (Pajor et al., 1991; Fraser et al., 1994; Huting et al., 2017). Recent data by Middelkoop et al. (2019) are in agreement, demonstrating that piglets reared on restrict-fed sows and provided creep feed had increased creep FI and percentage of eaters at weaning compared to piglets reared on full-fed sows. English et al. (1980; derived from Pluske et al., 2018) suggest that piglets should consume, on average, 600 g of creep feed before weaning to better prepare them for solid feed. Consequently, Pluske et al. (2018) indicated that the level of creep feed intake needed to completely alleviate the post-weaning growth check is not achievable considering wean age less than 28 days. Several others have reported relatively low creep FI up until the last week prior to weaning at 28 d of age (Pajor et al., 1991; Fraser et al., 1994; Bruininx et al., 2002), with FI having minimal effects on pre-weaning BW gain. These studies have also determined that creep feed consumption on an individual pig and within litter basis is highly variable.

While quantity and variability in total creep consumption are important considerations, the true value of creep feeding is found in the development of eaters, pigs that actually consume creep feed. Bruininx et al. (2002) observed that pigs designated as eaters had improved FI and ADG in the immediate post-weaning period compared to non-eaters. Furthermore, eaters required less time from weaning to initial consumption of dry feed. This was evident by the number of visits to the feeder during which feed consumption was higher for eaters than non-eaters. The authors suggest that familiarity with solid feed at weaning may be the result of pigs focusing more on FI and less on exploratory behavior of the pen. In an attempt to understand the impact of feeding duration on the proportion of eaters, Sulabo et al. (2010b) reported 10% more pigs designated as eaters when increasing the duration in which creep feed was offered from 6 to 13 d. Likewise, creep feeder design plays an important role in maximizing the proportion of eaters, as well as managing creep feed wastage. Sulabo et al. (2010a) observed that although feeder type did not impact pre-weaning BW, piglets that received creep from a rotary feeder with hopper had reduced feed disappearance and increased number of eaters than those provided creep in a pan feeder or rotary feeder without hopper. Moreover, the number of times feeders were filled compared to a rotary feeder with no hopper and pan feeder was reduced to once every 12 hours. This indicates that workers getting piglets up while filling feeders did not encourage pigs to consume more feed. Play feeders, or conventional rotary feeders with canvas cloth, braided cotton ropes, and PVC spiral tubes attached on the inside bottom of the feeder, have also been shown to elicit exploratory behavior, attracting more pigs to creep feed (Middelkoop et al., 2019). This response followed pigs through the immediate post-weaning period where increased FI and growth were observed. The authors suggested that providing creep feed in play feeders prior to weaning may develop a positive association between solid feed and object play, stimulating greater feed consumption. In contrast, research has shown that pellet size in the suckling period has no effect on the number of pigs designated as eaters. However, van den Brand et al. (2014) observed that feeding large pellets during lactation increased FI and BW gain after weaning. The authors attributed this response to greater pellet consumption in early lactation. Additionally, feeding a large pellet diameter has been reported to reduced pre-weaning mortality (Clark et al., 2015).

Research has also looked at increasing the diet complexity of creep feed to offer additional growth performance benefits. Results in the pre-weaning period indicate that increasing the diet complexity (Fraser et al., 1994) or energy density (Yan et al., 2011) of creep feed has little effect on BW gain prior to weaning. Conversley, Pajor et al. (2002) reported that pigs offered a complex diet consumed 50% more solid feed before weaning compared to pigs provided a simple diet. While this did not impact BW at weaning, the authors did observe that pigs who had received more compelx diets during lactation continued to eat more post-weaning and exhibited reduced BW loss immediately after weaning. Furthermore, pigs fed high complexity creep feed had improved growth performance in the post-weaning period (Fraser et al., 1994; Pajor et al., 2002; Yan et al., 2011) compared with those that had received a simple creep feed diet. Cabrera et al. (2013) noted that pigs who received glutamine supplementation in creep feed and throughout a 6-week nursery phase tended to have improved FG. This response was also observed in pigs that received either no creep or a control creep feed in the pre-weaning period and were later weaned onto a glutamine supplemented diet. Intestinal histology measures concluded that glutamine supplemented pigs had increased villous height and cell proliferation, similar to pigs who were weaned at a later age. Research evaluating flavored creep feed has demonstrated that adding flavor has no influence on total creep intake or the proportion of eaters (Sulabo et al., 2008); however, pigs exposed to flavored creep feed tended to have improved FI immediately post-weaning and increased gain when fed complex starter diets supplemented with the same flavor.

Several factors should be considered when implementing a creep feeding program, including duration of feeding, feeder design, pellet size, and diet complexity. It is expected that pigs may lose weight immediately post-weaning; however, these data indicate that the growth check associated with weaning can be reduced by acclimating pigs to feed during the suckling period. Providing creep feed to nursing pigs weaned at older ages (> approximately 25 days) may also have the opportunity to improve weaning weights (Tokach et al., 2020). Taken collectively, providing creep feed for 2 to 3 days prior to weaning is often satisfactory to observe the benefits in post-weaning performance (Tokach et al., 2020).

Water consumption and liquid milk replacer

Water access and intake of piglets in the first days after farrowing is often assumed to be of little relevance. Fraser et al. (1988) speculated that piglets who are not receiving enough milk from the sow may be at risk of dehydration. In agreement, the authors observed that litters of pigs with low growth during the first 4 d after farrowing used more water than faster gaining litters. This suggests that pigs may correct for low milk intake by compensating with increased water intake (Fraser et al., 1988). Other trials looking at water dispenser design have demonstrated that when water is visible in either an open bowl or cup, compared to a nipple or push-lever dispenser, discovery time is significantly reduced (Phillips and Fraser, 1991). Furthermore, bite nipples can be modified to reduce discovery time by adding either a chain to the valve lever or floor-mounting the nipple at an upward angle so that it's eye level with the pig (Phillips and Fraser, 2001). This data provides insight on dispenser systems that may be more advantageous to provide nutrition supplements, such as milk replacer, to pre-weaned pigs.

van Oostrum et al. (2016) evaluated the effects of supplementing milk replacer before or after weaning. The authors observed that pigs provided milk replacer pre-weaning had improved FI during the first week post-weaning compared to those supplemented with milk replacer after weaning. During the pre-weaning period, several studies have reported that pigs supplemented with milk replacer were heavier at weaning (Novotni-Dankó et al., 2015; de Greeff et al., 2016), with a more pronounced response observed in heavy birth weight pigs (Wolter et al., 2002). Furthermore, pigs that received milk replacer from birth to weaning had significantly reduced pre-weaning mortality (Novotni-Dankó et al., 2015). Nutrient dense complex milk replacer has also elicited increased concentrations of metabolic fermentation products and expression of cell proliferation in the crypts along the piglet GI tract, which may explain the performance response (de Greeff et al., 2016). Alternatively, research in the last decade has demonstrated that bovine colostrum may be a beneficial substitute for milk replacer because of its high immunoglobulin levels (de Lange et al., 2010). Piglets supplemented with bovine colostrum had reduced *E.coli* colonization in the intestine, similar to the colonization seen in suckling litters (Sugiharto et al., 2015). Likewise, the ileal microbiota population of pigs offered bovine colostrum more closely resembled sow-reared piglets compared to those that received milk replacer (Poulsen et al., 2017). Despite these benefits, milk replacer is not widely used throughout the industry due to increased labor and hygiene challenges. Additionally, the added cost of milk replacer has prevented further application.

While current data on water supplementation for suckling pigs is limited, previous research has demonstrated the importance of preventing dehydration in piglets. This is particularly important as litter size increases and sow milk yield remains relatively constant. These data also demonstrate that providing milk replacer to pigs prior to weaning offers an additional source of nutrients that may help improve weaning weights, decrease pre-weaning mortality, and increase FI post-weaning

Gaps in knowledge

Reducing nutrient disruption post-weaning can be accomplished through further exploration of multiple pre-weaning strategies that may be best implemented in combination to prevent feed neophobia, reduce stress, and improve the weaning transition. Areas where further research would be particularly beneficial include:

- **Maternal nutrition:** Gestation and lactation feeding programs to influence piglet growth and development (colostrum supply, BCAA, glutamine, and essential fatty acid concentrations).
- **Fetal imprinting:** Gestation and lactation feeding programs designed to reduce stress in the immediate post-weaning period by providing pigs with familiar olifactory stimuli.
- **Sow management:** When sow management trials (i.e. split suckling, cross fostering, etc.) are conducted, often piglets are not followed downstream into the nursery. Research instead focuses primarily on weaning weight. The question then becomes, does improving weaning weight, translate to improved post-weaning performance?
- **Socialization:** In socialization studies, pigs are often not regrouped at weaning with pigs they had previously been socialized with before weaning. This suggests an opportunity to assess the effects of post-weaning placement strategies in combination with pre-weaning socialization on latency to feed and potentially BW loss after weaning. At what time point should we start mixing pigs before weaning?
- **Environmental enrichment:** Combining enrichment with feeding strategies, such as large, destructible pellets or play feeders on feed consumption after weaning.
- **Creep feeding:** Providing lactation feed on farrowing stall mats prior to weaning as a strategy to familiarize pigs with solid feed.
- **Topsoil or other bacteria source:** Influence of bacteria exposure on the gut mircrobial population, piglet performance, and health.

Conclusion

Weaning is an important phase of swine production marked by some of the most profound stressors. It is during this time period that pigs exhibit low voluntary FI, much of which stems from their physiological response to stress and the behavioral mechanisms that follow, therefore prevent weanling pigs from searching out and consuming feed. Several factors are known to influence nutrient intake after weaning including:

- **Wean age:** Weaning older, more developmentally mature pigs helps prevent many of the adverse effects of weaning associated stressors.
- **Cross-fostering and split-suckling:** While there is limited research on the effects of these management strategies immediately after weaning, it is understood that providing greater opportunities for pigs to nurse prior to weaning should improve nutrient intake and weaning BW, creating a more robust pig for the post-weaning period.
- **Socialization:** Allowing pigs to mix prior to weaning improves social skills and encourages play behavior, minimizing mixing stress and injury from aggression immediately post-weaning.
- **Creep feeding:** Providing creep feed to pigs during lactation encourages exploratory behavior and familiarizes pigs with solid feed before weaning, increasing immediate post-weaning FI.
    - Water supplementation in combination with creep feed may help pigs learn the difference between hunger and thirst prior to weaning.
- **Milk supplementation:** Provides an additional source of nutrients that may help to reduce pre-weaning mortality, particularly in the lightweight pig population.

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Chapter 2 - Maintaining continuity of nutrient intake after weaning.

II. Review of post-weaning strategies

Abstract

Low feed consumption during the first 3 d post-weaning disrupts nutrient intake and results in what is commonly known as a post-weaning growth check. While most pigs recover from this initial reduction in feed intake (FI), some pigs fail to successfully make this transition leading to morbidity and mortality. In this review, our objective is to describe the different post-weaning strategies that can be used to minimize nutrient intake disruption and improve FI in the immediate post-weaning period. Providing weanling pigs with an environment that encourages them to search out and consume feed is important. This includes appropriate barn temperatures, resource availability, and nursery placement strategies. Research is needed to better understand the ideal environmental temperatures to encourage pen exploration and reduce time to initial FI. Likewise, mat and gruel feeding are commonly practiced throughout the industry to increase feed accessibility, however limited research data is available to validate protocols or benefits. Nursery placement strategies include sorting light weight pigs into uniform body weight groups and average or heavy weight pigs into variable body weight groups to provide benefit to light pigs while reducing initial aggression in heavy pigs. Furthermore, water enrichment with nutrient dense products have been shown to improve growth performance and reduce morbidity and mortality in the early post-weaning period. Because young pigs are sensitive to palatability, diet form and complexity should also be considered. Weanling pigs prefer diets manufactured with coarse ground corn (700 microns) compared to fine ground corn. Additionally, weanling pigs are more attracted to large diameter pellets (12 mm) compared with small pellets. Despite these preferences, impacts on growth are relatively small. Feeding complex diets with high levels of

lactose, animal protein products, or other palatable ingredients is another strategy shown to improve growth performance during the first week post-weaning; however, the initial benefits quickly diminished as pigs become older. Other strategies that warrant further investigation include the effect of crumble diets on feed preference and the concept of perinatal or social interaction flavor learning. In summary, strategic post-weaning nutrition and management practices must focus on maintaining continuity of nutrient intake in order to reduce morbidity and mortality in the immediate post-weaning period.

Introduction

In modern swine production, weaning often occurs during a critical window of gut maturation, marked by increased epithelial function, microbiota colonization, immune cell proliferation and enteric nervous system development (Moeser et al., 2017). Excessive immune stimuli in response to weaning stressors during this period has been linked to impaired neurodevelopment (Kelly et al., 2015) and gastrointestinal (GI) maturation (Moeser, 2016; Pluske, 2016). Williams et al (1997) also reported a reduction in FI, low protein accretion, and diminishing body leanness as a result of chronic immune system activation. Inflammatory cytokines which are released in response to immune stimuli are known to further suppress appetite and inhibit nutrient absorption (Escobar et al., 2004). In herds under chronic disease challenge, prolonged production of cytokines induces muscle and fat catabolism, as well as impaired carbohydrate metabolism (Matthys and Billiau, 1997; Escobar et al., 2004). This deterioration in energy metabolism can be detrimental to the central nervous system, altering the brains ability to function properly and elicit physical responses to stimuli, including the newly weaned pigs' decision to search out and consume feed.

Low FI after weaning reduces the flow of nutrients through the GI track, resulting in what is commonly known as a post-weaning growth check. This period is marked by body weight (BW) loss and intestinal disturbances that lead to a high occurrence of GI inflammation (McCracken et al., 1999) and diarrhea. While most pigs recover from the initial reduction in FI, some pigs fail to successfully make this transition leading to morbidity and mortality. The objective of this review is to describe the different post-weaning strategies to minimize nutrient intake disruption and improve FI in the immediate post-weaning period.

Post-weaning feed intake

The primary limiting factor affecting FI in newly weaned pigs is their physical capacity to ingest feed (Li and Patience, 2017). Therefore, low FI immediately post-weaning often does not provide enough nutrients to the pig to satisfy maintenance requirements, subsequently leading to reduced growth. However, it is important to understand what factors are involved in the regulation of FI in newly weaned pigs in order to develop successful management and feeding programs to better prepare pigs for FI after weaning. Factors that have a significant impact on post-weaning behavior and consequently FI, include barn temperatures, agonistic behavior or hierarchy establishment, lack of feeding stimuli, feed palatability, and resource availability (Brooks and Tsourgiannis, 2003), many of which will be covered herein. Furthermore, the transition from a single milk-based diet (sow's milk) to separate feed and water sources, requires an abrupt learning period that pigs must adapt to after weaning in order to familiarize themselves with the difference between hunger and thirst satiety (Brooks and Tsourgiannis, 2003). It is for this reason that water consumption remains elevated for the first several days post-weaning (Brooks et al., 1984). However, once feed is discovered and pigs become more comfortable in their new environment, normal eating and drinking patterns are established (Brooks et al., 1984).

The question then becomes how we can increase exploratory behavior and encourage FI early after weaning. In an attempt to investigate the social learning behavior of piglets after weaning, Morgan et al (2001) observed that experienced eaters were able to stimulate earlier feeding behavior in weanling pigs who were unfamiliar with solid feed. When housed in the same pen as experienced eaters, inexperienced eaters exhibited increased FI and more frequent visits to the feeder, compared to pens that housed only inexperienced eaters. These results indicate a potential mechanism where eating behavior and exploration is learned by non-eaters from those already consuming feed. Pairing inexperienced eaters with those familiar with solid feed may also encourage the pigs innate drive for synchronized feeding like suckling; however, this has not been fully proven. Interestingly, recent data suggests that the day of weaning may not be the best time for pigs to discovery solid feed, due to the stress of weaning on the pigs learning ability (Millet et al., 2019). The authors investigated the effect of allowing newly weaned pigs an opportunity to rest (18 h) and get acclimated with their new environment before feed was provided in the pen. Pigs that received feed 18 h after weaning had increased FI and average daily gain (ADG) from d 0 to 21 compared to pigs that received feed at weaning. This feed management strategy could offer a way to synchronize pigs to eat together, stimulating pigs to search out feed when they hear it dropped into feeders. This concept requires more research. Nonetheless, it is apparent that behavior plays a crucial role in initial feed intake.

While external stressors tend to be additive in their negative effects (Hyun et al., 1998), it is well established that increasing nutrient intake after weaning can minimize stress associated losses in intestinal barrier function (Wijtten et al., 2011; Verdonk, 2016). Consequently, feed deprivation (72 hr) has been reported to alter the endocrine and neuroendocrine axis and hypothalamic pituitary adrenal (HPA) axis hormones, negatively influencing FI (Salfen et al., 2003). Stress conditions, such as those surrounding the time of weaning are thought to suppress feed consumption due to the anorectic effects of corticotropin release factor (CRF, Pelleymounter et al., 2000). As a result, absence of nutrients to the lumen has been shown to increase active ion transport across the epithelial, an indicator of intestinal permeability (Carey et al., 1994). Likewise, increased intestinal permeability can reduce nutrient absorption capacity (Moeser et al., 2017), therefore leading to lower BW gain (Pluske et al., 2013).

In summary, there are several external and internal factors that influence FI after weaning. Consequently, low FI results in decreased intestinal barrier function and villous atrophy, followed by a period of BW loss that often takes several days from which to recover (Reviewed by Brooks and Tsourgiannis, 2003). Therefore, maintaining a continuous supply of nutrients post-weaning is crucial to minimizing the post-weaning growth check and ensure a more successful weaning transition.

Post-Weaning Strategies To Increase Feed Intake After Weaning

Environmental factors influencing nutrient intake after weaning

Thermoneutral zone

Caretaker understanding of the thermoneutral zone, or effective temperature, is important in order to prevent heat or cold stress of pigs at the time of weaning. In addition to room temperature, other environmental factors impacting effective temperature include heat loss via convection, conduction, and radiation which in turn are affected by air movement, floor type, and building insulation (Baker, 2004). Other contributing factors to the effective temperature include air quality and humidity (Lammers et al., 2007). According to PIC’s wean-to-finish guidelines

(2019), the recommended barn temperature for pigs at weaning ranges from 23 to 29 ºC depending on the use of zone heating. The use of zone-heating such as brooders, heat lamps, and floor mats during the first weeks post-weaning, particularly in wean-to-finish facilities with large pens sizes, can help accomplish a range of temperature zones that are suitable for pigs of all sizes. When temperatures reach the upper boundary of the thermoneutral zone, pigs will often search out cool, damp places to lay, spreading out across the pen in an attempt to avoid contact with other pigs. As a result, pigs will often decrease FI and increase water consumption. In contrast, when temperatures reach the lower boundary of the thermoneutral zone, pigs will often pile close together and if they have already found feed, will increase FI to compensate for energy used to maintain body heat (NRC, 1981). This may be less of a concern immediately after weaning because many pigs have not yet identified feed. Thus, temperatures below the thermoneutral zone may instead prevent weanling pigs from searching out feed. For these reasons, it is essential that caretakers provide an adequate thermal environment that encourages weanling pigs to discover feed.

Resource availability

Providing weanling pigs easy access to resources like feed and water is important. Increasing resource availability includes a variety of management practices for offering pigs feed and water, such as feeder design, wet and dry feeding systems, mat or gruel feeding, as well as drinker access.

Pluske and Williams (1996) tested the hypothesis that providing water in addition to feed from a single space, wet/dry feeder would stimulate FI compared to a single space, dry or multi-space feeder. However, the use of wet/dry single space feeders reduced gain in the first week after weaning. The authors observed that pigs had difficulty learning how to manage the wet/dry feeder, often filling the bowl with excess water. It is important to note that pigs per feeder space were not considered in this study. More recently, it was reported that decreasing the number of pigs per feeder hole decreased time to feeding. Pens of pigs with 3.75 pigs per feeder hole began consuming feed approximately 8 hours earlier compared to pens of pigs with 6.25 pigs per feeder hole (Laskoski et al., 2019).

Mat feeding in addition to standard trough feeding has been reported to reduce morbidity and mortality during the first 3-weeks post-weaning (Corrigan, 2000; Potter et al., 2010). Similarly, there is evidence that gruel feeding pigs reduces morbidity compared to pigs offered only dry feed (Corrigan, 2000). In a series of experiments, Corrigan (2000) observed that both gruel and mat feeding increased feed disappearance, but largely due to increased feed wastage. Potter et al. (2010) observed a similar response, with mat-fed pigs exhibiting poorer feed efficiency, particularly when mat-fed for 7 d as compared to 3 d after weaning. However, mat feeding increased eating behavior the first day after weaning (Corrigan, 2000) and resulted in fewer pig removals during the nursery period (Potter et al., 2010). Providing pigs feed in the form of a gruel increased consumption but reduced eating and drinking behavior at the feeder and drinker. Thus, gruel should not be used to meet all the feeding requirements. Rather, it is recommended gruel be provided intermittently (3-4 times daily) as to still encourage dry feed intake. This is to prevent pigs from needing a second transition to get them to the feeder once gruel feeding has ended. Generally, gruel is prepared with equal amounts of water and solid feed; however, the amount of gruel prepared often depends on the number of pigs per pen and should only be enough to last a short period of time to prevent feed spoilage. Depending on the health status of pigs receiving gruel feed, intensive care supplements which are highly palatable and often aromatic can be added to the gruel to further encourage FI. Similar to the events surrounding suckling, mat or gruel feeding after weaning may help stimulate group feeding behavior; however, more research is needed to fully understand the implications of mat and gruel feeding strategies.

Sorting pigs at nursery placement

Nursery placement strategies influence pig behavior and latency to first feed intake. While weaning into variable versus uniform BW groups has shown to have little effects on overall performance, heavy weight pigs in uniform groups have lower initial FI than heavy weight pigs in variable weight groups (Bruininx et al., 2001). More recently, Faccin et al (2019) observed increased aggressive behavior and delayed FI in pens sorted into all heavy pigs compared to pens sorted into light or medium weight pigs. It is likely that heavy pigs spend more time establishing dominance than consuming feed. Sex also has a known impact on the behavior and performance of pigs at placement. Bruininx et al (2001) observed that gilts had increased FI and gain compared to barrows during the first week after weaning. Similarly, initial mixing aggression tended to decrease when sorting groups of pigs by gender (Colson et al., 2006). Furthermore, data indicates that pigs weaned into familiar groups consume more feed and grow faster the first week post-weaning than pigs weaned into unfamiliar groups (Turpin et al., 2017). Hwang et al. (2016) also observed less agonistic behavior in groups of pigs that came from the same litter. These data are inconsistent with earlier reports that showed mixing unfamiliar pigs at weaning actually promotes FI and improves growth rate (Pluske and Willams, 1996).

Another strategy that has been evaluated is sorting by sow parity. Because gilt progeny often have poorer lifetime performance compared to sow progeny, Craig et al (2017) hypothesized that segregating gilt and sow progeny at placement would improve the growth and survival of both groups. However, this strategy resulted in no added benefits.

As group size increases, the number of dyadic relationships a pig must establish also increases (Turner and Edwards, 2004). This suggests that there is more opportunity for aggressive behavior between pigs when attempting to establish social hierarchy. However, Turner and Edwards (2004) observed no elevation in aggressive tendencies as group size increased above 50 pigs per pen compared with a more conventional group size (10-30 pigs). In an earlier review, Turner et al. (2003) reported that as group size increased, weanling pigs had significant reductions in ADG due to decreased FI. It is important to note that group number and space allowance ranged from 3-120 pigs per pen and 0.186-0.74 m^2 per pig, respectively. These results are consistent with previous findings, in which reduced floor-space allowance reduced pig growth performance during the nursery period (Wolter et al., 2000a). It has also been suggested that resource placement may affect feeding behavior, particularly in large groups. To quantify the effect of feeder location on the performance of weanling pigs, Wolter et al. (2000b) evaluated two pen designs using either five two-sided feeders in a single, central location or five two sided feeders in multiple locations throughout the pen. The use of multiple feeder locations in a large group pen design did not increase FI or growth. Additional research is needed to better characterize the eating behavior of pigs in different group sizes and spacing allowances, and how feeder arrangement relative to drinker location may affect FI and subsequent performance.

In summary, these data suggest that sorting light weight pigs into uniform groups may be beneficial, while remaining pigs should be randomly placed without sorting by weight to reduce aggression in the heavy weight pigs. In addition to BW, sorting by sex or socializing pigs prior to weaning reduces initial aggression and may also increase FI and immediate post-weaning growth.

Water consumption and enrichment

The recommended water requirement for nursery pigs up to 27.2 kg BW is 2.8 L per pig per day (NPB, 2003), which equates to 2.5 – 3 L per kg of feed consumed. However, in the first 5 d post-weaning, water consumption is typically not linked to feed intake or physiological need but rather weaning influenced consumption patterns (previously discussed; McLeese et al., 1992). Water intake tends to be the greatest in the first 24 hours, suggesting dietary supplements may be more beneficial when administered through the water rather than feed (Dybkjær et al., 2006). Options to enrich the water include acidification (De Busser et al., 2011; Escuredo et al., 2016), plasma-based globulin products, glucose or lactose-based energy products, electrolytes, or a combination of enrichments (Steidinger et al., 2002; Myers et al., 2011; Morris et al., 2017; Schmitt et al., 2018). Studies have reported improved growth performance in the early post-weaning period when water-soluble sources of animal plasma protein and energy are provided in the drinking water, with diminishing results thereafter (Steidinger et al., 2002; Vande Pol et al., 2017). Reductions in morbidity and mortality have also been observed with water enrichment (Morris et al., 2017; Schmitt et al., 2018). While most water enrichment strategies are administered during the first 3 to 7 d post-weaning, timing and duration of administration may influence efficacy.

According to the Swine Housing and Equipment Handbook (MWPS, 1983), there should be 10 nursery pigs per nipple drinker space; however, a ratio of 25:1 is more common in the US industry (Jackson, 2007). Because too few waterers can reduce water intake and consequently FI, Jackson (2007) investigated the effect of increasing water access in pens of 25 pigs. When pigs were offered more places to drink, they visited the water bowl more frequently. This tended to increase ADG throughout the nursery period. Interestingly, pigs demonstrated drinker location preference with the alley waterer receiving the fewest visits compared to waterers located on the same side of the pen as the feeder or on the back wall. Furthermore, Turner et al. (1999) reported that as pigs per pen increased without increasing water sources, total drinking time per pig decreased and drinking bouts terminated by aggression increased. Therefore, offering more water access points could minimize low water intake, subsequently improving FI; however, water access location within the pen should be considered.

Water intake, similar to feeding, is a social activity (Torrey and Widowski, 2006), and may be associated with an attempt to satisfy hunger by gut fill immediately after weaning (Torrey et al., 2008). In a series of experiments, Torrey and Widowski (2004, 2006) and Torrey et al. (2008) investigated different drinker types on pig preference, intake and wastage. Nipple drinkers resulted in increased water wastage and belly nosing behavior compared to push-lever bowl drinkers (Torrey and Widowski, 2004; Torrey et al., 2008). The authors suggest that motor patterns involved with ingesting water from bowl drinkers may mimic suckling stimuli that satisfies nosing motivation; therefore, decreasing belly nosing behavior. Furthermore, pigs with bowl drinkers spent more time at the feeder. This is in contrast to a later study that indicated pigs with push-lever bowls spent less time at the feeder (Torrey et al., 2008). Despite water usage and time spent at the feeder, drinker type did not influence FI or ADG. When given a choice between different drinker types, weanling pigs found nipple and float bowl drinkers faster than push-lever drinkers (Torrey and Widowski, 2006). Throughout the duration of the study, pigs continued to prefer nipple and float bowl drinkers over push-lever bowls, which may be due to easier water access. Based on these three experiments, the authors recommend the use of push-lever bowl drinkers to prevent excessive water wastage while not negatively affecting FI and BW gain (Torrey et al., 2008).

It is also important to consider the impact of water quality, particularly sulfate concentrations and total dissolved solids, on water and feed consumption. Patience et al (2004) observed that sulfate levels up to 1,650 mg/L did not hinder growth performance. Flohr et al (2014) observed that adding sodium sulfate at higher levels (3,000 mg/L) resulted in a significant impact on growth performance. Conversely, earlier reports suggest that water containing high levels of total dissolved solids (4,390 mg/L, 2,650 mg of SO_4/L, 947 mg of Na/L, 288 mg of *C/L*, 88 mg of Mg/L,70 mg of Cl/L, and 15 mg of K/L) may actually promote water and feed intake during the first 10 d post-weaning (Maenz et al., 1994). High levels of sulfate and dissolved solids may affect growth performance differently, however water quality is known to influence diarrhea scours and appearance of looseness (Maenz et al., 1994; Flohr et al., 2014).

Diet considerations

Feeding a nutrient dense, highly palatable, and readily digestible diet is necessary to stimulate nutrient intake and weanling pig growth. The advancements made in understanding GI metabolism have led to a wide range of feed ingredients that target enhancing the naïve pig's innate and adaptive immune responses, reducing pathogen loads and the occurrence of post-weaning diarrhea, encouraging microbial growth, and stimulating digestive maturation immediately after weaning (de Lange et al., 2010). All of which impacts nutrient intake and subsequent growth performance. Some of these nutritional strategies include diet acidification, fiber and crude protein content, fatty acid (FA) supplementation, and functional amino acid inclusion (AA). Additionally, the effect of liquid feeding and diet form, as well as diet complexity and palatability have been considered and offer opportunities to improve FI in the immediate post-weaning period.

Liquid feeding

Liquid feeding stimulates GI development in newly weaned pigs, with a linear correlation observed between villous height and DM intake (Pluske et al., 1996b), and ADG (Pluske et al., 1996a). During the first 3 d post-weaning, pigs provided ewes milk or a liquid milk replacer diet had increased DM intake compared to those offered starter feed; however, by d 5 DM intake was greatest for pigs consuming the dry starter feed (Pluske et al., 1996a; Bergstrom and McKilligan, 2006). If producers are able to improve DM intake, particularly in the lightweight population, Bergstrom and McKilligan (2006) showed that there may be an opportunity to decrease death loss and culling rates in the immediate post-weaning period. Liquid feeding can also be applied to improve ADG in pigs weaned younger than 21 d of age (Kim et al., 2001). In an attempt to compare the effectiveness of lactose vs. protein in preserving mucosal integrity, Spreeuwenberg et al. (2001) fed a low lactose/high protein- or high lactose/low protein-liquid milk replacer diet for 4 d post-weaning. The authors observed that pigs offered the high lactose/low protein milk replacer tended to have increased villous length and decreased intestinal permeability. However, the effect of diet composition on mucosal integrity was less important than the low energy intake observed in both treatment groups. Fermented liquid feeds is another strategy that may offer potential benefits by helping to decrease stomach pH through lactic acid production, thereby inhibiting the growth of pathogenic organisms (Moran, 2001). However, Lawlor et al. (2002) observed no added benefit from feeding weanling pigs a fresh liquid milk replacer or fermented liquid diet, as compared to a standard dry pelleted diet.

In summary, due to low FI immediately post-weaning, researchers often struggle to detect treatment differences between liquid and solid feeding programs. However, these data indicate that liquid feeding may have added benefits for lightweight or early weaned pigs. Regardless, liquid feeding strategies offer opportunities to increase DM intake in the immediate post-weaning period prior to solid feed consumption. This provides newly weaned pigs with a continued energy supply necessary for cognitive function and GI development. Conversely, offering liquid feed immediately after weaning may require a “second weaning” period when pigs are transitioned from liquid diet to solid feed. Limited research surrounding the potential adverse effects associated with a second weaning have not been conducted but should be considered.

Diet form

Common diet forms fed to weanling pigs are meal, pellet, or crumble. Feed efficiency is often improved with pelleted diets as compared to meal diets (Traylor et al., 1996; Groesbeck et al., 2009; Nemechek et al., 2015). There is limited published research available on the effects of feeding crumble diets compared to meal or pelleted diets. Medel et al. (2004) also observed increased nutrient digestibility when pigs were provided pelleted diets. Likewise, steam cooking cereal grains prior to grinding and pelleting has been shown to improve nutrient digestibility and ADG of pigs in the immediate post-weaning period (Medel et al., 2004). It is well established that particle size also influences nutrient digestibility and growth performance in nursery pigs (Goodband et al.,1995), as well as feed preference (Bokelman et al., 2015; Gebhardt et al., 2018). For meal diets, a particle size of 600 microns is known to improve feed efficiency, whereas for pelleted diets, a particle size as fine as 350 microns has been reported to improve feed efficiency (De Jong et al., 2014). More importantly for young pigs, diet form effects feed preference which is influenced by particle size, ingredient composition, and manufacturing processes (Sola-Oriol et al., 2009; De Jong et al., 2014). Regardless if fed as mash or pellets, pigs prefer to consume diets manufactured with coarser (700 microns) ground corn (Bokelman et al., 2015; Gebhardt et al., 2018). Furthermore, coarse ground mash diets may offer GI benefits by lowering stomach pH and reducing the incidence of pathogenic bacteria (Vukmirovic et al., 2017). Similarly, research shows that young pigs prefer pellets with a large diameter (12 mm) compared to smaller pellets (van den Brand et al., 2014). In fact, Clark et al. (2015) observed that feeding a large pellet immediately post-weaning increased FI, regardless of previous creep feed pellet size. In agreement with this data, others have observed irrespective of pellet diameter provided after weaning, pigs exposed to large creep pellets pre-weaning exhibit improved FI and growth post-weaning (van den Brand et al., 2014). These data suggest a relationship between diet form and particle size when offered both pre- and post-weaning on preference and FI.

Palatability

Young pigs are sensitive to palatability, which therefore drives consumption preferences. Undoubtedly, odor and taste play an important role in palatability (Sola-Oriol et al., 2009). Nowicki et al. (2015) observed that objects aromatized with moist soil, grass, and dried mushrooms were more attractive to weanling pigs than synthetic aromas. This study did not investigate the effect of aroma preference on FI but does offer potential opportunities for environmental enrichment strategies to improve exploratory behavior and reduce weaning stress. Furthermore, adding flavor enhancers or sweeteners to starter diets immediately after weaning may encourage solid feed intake (Torrallardona et al., 2001; Langendijk et al., 2007; Sterk et al., 2008). However, the literature is inconsistent, and data are largely dependent on the amount and flavor used, feeding duration, and at what point flavored feed was introduced to pigs. Flavor imprinting is another strategy that could be used to reduce weaning stress and encourage FI after weaning. Oostindjer et al (2010) observed that pigs exposed to flavors in the diet of the sow before birth and during lactation, then subsequently re-exposing to the same flavor at weaning had increased FI and reduced incidence of stress-related behaviors. Figueroa et al. (2013) also observed that brief contact with a demonstrator pig that recently consumed flavored feed was enough to change the feeding behavior of naïve observers, enhancing their preference for flavored feed. These effects may be in response to reduced stress due to the presence of a familiar flavor in the post weaning environment (Oostindjer et al., 2010). As previously discussed, feed preferences are also influenced by diet form and complexity. Sola-Oriol et al. (2009) demonstrated that while particle size characteristics showed only marginal correlations with feed preference, the hardness, fragility, and time spent chewing showed a statistically significant negative correlation with FI. This supports the presumption that feed requiring a shorter chewing time may be preferred in weanling pigs. In a series of experiments investigating a variety of common feed ingredients, Sola-Oriol et al. (2014) determined that cereal grain preference increased as digestible starch increased and crude fiber decreased, with naked or refined oats having the highest preference during the nursery phase. Furthermore, the authors observed fish meal, soybean meal and spray dried porcine blood plasma to have the highest preference of protein sources which was, greater than that for dried skim milk. Specifically, dried porcine solubles has a large mean particle size (Sola-Oriol et al., 2009), which may explain the preference for this ingredient. While palatability of feed ingredients should be taken into account when formulating diets for weanling pigs, it is important to note that preference doesn't always equate to higher FI, especially when pigs are not given a choice between diets.

Diet complexity

Diet complexity in the immediate post-weaning period can mean many different things, including the addition of cooked or heat processed cereal grains, a variety of specialty protein products, and dried milk alternatives. Generally, feeding more complex diets during the first week post-weaning improves pig growth and efficiency (Sulabo et al., 2010; Collins et al., 2017). However, the initial benefits of providing complex diets is quickly diminished as pigs become older. Four experiments conducted by Mahan et al. (2004) demonstrated that pigs had increased initial growth performance when fed complex diets with lactose until 25 kg BW. Others have reported no improvement in performance when complex diets were fed (Steidinger et al., 2002). Because complex diets are often more expensive, Collins et al. (2017) investigated the economic impacts of diet complexity when fed to light, medium, and heavy weight pigs. The authors observed that feeding more complex diets was only cost effective for light weight pigs (<6.5 kg), which was attributed to increased lifetime performance. Douglas et al. (2014) showed that feeding a high-quality starter regime to the low birth weight population improved post-weaning pig performance and increased profitability, whereas there was no effect of starter regime on the average or heavy birth weight population. Similar improvements have been observed with increasing lactose in diets for light weight pigs (Mahan et al., 2004). These data indicate that light weight pigs or those less developmentally mature may be better suited for more complex starter diets.

It is well understood that starter diets are important for providing glucose and other essential nutrients to the newly weaned pig. Regardless of composition though, the challenge becomes getting pigs to actually consume feed following weaning. Under normal circumstances when energy intake is low, the hypothalamus senses diminishing plasma glucose concentrations subsequently inhibiting the mechanistic target of rapamycin complex 1 signaling pathway (mTORC1; Takei et al., 2014). Inhibition of mTORC1 is thought to elicit an increase in FI (Wiczer and Thomas, 2010). Unfortunately, this is often not the case in the immediate post-weaning period. As discussed by Wensley et al. (2020), weaning associated stress may impair normal hypothalamic activation. This suggests a complex relationship between stress and energy homeostasis, which may impact the pig's decision to consume feed. Amino acid levels, growth factors, and insulin signaling also regulate mTORC1 activity, therefore playing a role in a multitude of cellular processes necessary for FI, and subsequent growth and survival (Takei et al., 2014).

Influence of diet complexity on gastrointestinal maturation and post-weaning diarrhea

Diet composition is crucial to the growth and development of the naïve pig's GI system, as well as reducing the occurrence of post-weaning diarrhea. Soybean meal contains anti-nutritional factors and allergenic proteins that reduce nutrient utilization and lower growth performance following first exposure (Li et al., 1990). These effects are often temporary with pigs developing tolerance after 1-2 weeks (Engle, 1994). Consequently, specialty animal proteins are frequently added to nursery starter diets in place of soybean meal because they contain highly digestible AA and are often more palatable than plant protein sources. This helps alleviate the adverse effects of soybean hypersensitivity by slowly acclimating wean pigs to increasing levels of soybean meal in the diet. Furthermore, feeding low crude protein/AA fortified diets, allows nutritionists the opportunity to reduce intact protein sources while concurrently increasing the use of highly digestible crystalline AA (Wang et al., 2018). For these reason, low crude protein diets have gained attention over the last decade because of their ability to effectively lower post-weaning diarrhea (Heo et al., 2009).

Because suckling pigs are consuming high levels of milk lactose, a precursor for lactic acid, stomach acidification by HCl is inhibited (Cranwell et al., 1976). At weaning, consumption of solid feed reduces lactic acid production, thereby stimulating the production of HCl (Yen, 2001). This often leads to an elevation in gastric pH resulting in reduced digestion of feed and a more favorable environment for pathogenic bacteria, which may incite diarrhea (Lawlor et al., 2005; Wang et al., 2018). The addition of organic acids to starter diets is a well-recognized feeding strategy used to manipulate stomach acidity and improve weanling pig buffer capacity (Ravindran and Kornegay, 1993). Likewise, research has demonstrated that diet acidification helps improve protein digestibility (Ravindran and Kornegay, 1993). Similar to organic acids, the inclusion of whey or lactose in starter diets helps lower gastric pH by ensuring continued lactic acid production (Lawlor et al., 2005), thereby reducing the need for diet acidification (Partanen and Mroz, 1999). These responses are found to decrease with age as GI enzymatic activity develops (Yen, 2001). The improvement of weanling pig buffer capacity through a better understanding of feed ingredients is an area of research that still requires further investigation.

Dietary fiber content is another feeding strategy of interest. Providing insoluble fibers in the diet is known to accelerate digesta passage rates and lower intestinal bacterial adhesion, which increases fecal DM, offering an opportunity to reduce post-weaning diarrhea (Montagne et al., 2003). Conversely, providing soluble fibers in the diet slows digesta passage, increasing the production of short-chain fatty acids (SCFA). Specifically, butyrate is a SCFA that can be used as a readily available source of energy for a variety of GI functions (Blaut, 2002), including regulation of epithelial cell growth (Liu et al., 2018), and reduced intestinal inflammation (Liu, 2015). While data is limited, supplementing butyrate may be conditionally important in young pigs undergoing intestinal maturation while also experiencing weaning stress. Research evaluating the effect of fiber sources often observe no performance differences (Menegat et al., 2019). However, gut health tends to be positively impacted, with a more pronounced response observed when insoluble fibers are fed immediately after weaning (Menegat et al., 2019).

Lastly, zinc is commonly added to nursery pig diets at pharmacological levels to reduce post-weaning diarrhea and improve growth performance (Hill et al., 2001). High levels of zinc have also been shown to positively influence intestinal integrity and the immune system of weanling pigs (Liu et al., 2018). While the mechanisms of pharmacological levels of zinc are largely unknown, Ou et al. (2007) observed that added zinc inhibited stem cell factor gene expression, which are responsible for mast cell proliferation and subsequent histamine expression. Mast cell derived histamine has been linked to the pathogenesis of diarrhea, indicating one potential mode of action for added zinc (Ou et al., 2007). Copper is another important trace mineral that offers improved fecal consistency and growth promoting benefits when added at pharmacological levels in nursery pig diets (Menegat et al., 2019). While it's mode of action is also not well defined, the growth promoting effects of copper have been attributed to its bacteriostatic and bactericidal properties (Espinosa and Stein, 2021). Copper supplementation is also recognized to increase lipase activity, stimulate growth hormone secretion, indirectly improve immune responses, and increase mRNA genes involved in post-absorptive metabolism of lipids (Espinosa and Stein, 2021).

Feed ingredients that may impact gastrointestinal health and feed intake

Gastrointestinal health around the time of weaning is often compromised as a result of stress and low FI. Fatty acids and other lipids in sow's milk are a highly digestible energy source frequently not provided in the post-weaning diet (Lauridsen, 2020). The strategic use of FA supplementation may benefit the growth and development of the GI system through energy maintenance, especially while under inflammatory conditions (Liu, 2015). Trials conducted in rats and humans have demonstrated that diets enriched with omega-3 polyunsaturated FA may help downregulate metabolic factors associated with glucose depletion and GI inflammation

(Barber et al., 1999; 2001; Huber et al., 2018). Adding dietary FA post-weaning, may provide opportunities to improve pig health and increase nutrient utilization, particularly in health challenged systems.

Glutamine is a conditionally essential AA that has been also been identified for its role in GI function (Lewis, 2001). Specifically, glutamine is recognized as the primary energy source for intestinal enterocytes (Wu et al., 1996). When supplemented in starter diets at 1%, L-glutamine has been shown to prevent jejunal atrophy during the first week postweaning (Wu et al., 1996), increase intestinal cell proliferation, and reduce the expression of genes associated with oxidative stress (Wang et al., 2008). Similarly, others have demonstrated the importance of glutamine on tight junction protein regulation and CRF expression (Wang et al., 2014). In support of these findings, earlier reports indicate that glutamine may become conditionally essential in times of immune system activation, particularly during stress when the body's glutamine requirement appears to exceed its rate of production (Lacey and Wilmore, 1990). Duttlinger et al. (2019) showed that after a 12 h transport, replacing dietary antibiotics with 0.20% L- glutamine improved pig performance and health during the first 14 d after placement. Under similar transport conditions, L-glutamine supplementation in starter diets increased gut microbial diversity and decreased body lesions in pigs during immediate post-weaning period (Parois et al., 2020). Furthermore, added L-glutamine resulted in decreased tear staining and greater interest in novel objects. An earlier report showed that lying behavior in the first 2 d after simulated transport was increased in groups that did not receive antibiotics compared to antibiotic or L-glutamine fed pigs (Johnson and Lay, 2017). It is well established in humans and rodents that microbial dysbiosis is associated with depressive and anxiety like behaviors (Kelly et al., 2015), which may explain the reduction in aggression, stress, and fear related behaviors observed in pigs fed added glutamine (Johnson and Lay, 2017; Parois et al., 2020). Together, these data suggest that glutamine has an interactive role on GI health, development, and the microbiome-gut-brain axis. While these data suggest a positive response to glutamine when fed in nursery starter diets, widespread adaptation of glutamine supplementation has not been seen. Glutamine has not approved for feeding in all locations globally.

Tryptophan (Trp) is an essential AA that acts as a precursor for the neurotransmitter serotonin, which is associated with mood, sleep and appetite regulation (Le Floc'h and Seve, 2007). It is well established that diets deficient in Trp reduce FI. Furthermore, when pigs are exposed to inflammatory, immune or environmental stressors, serotonin catabolism in the brain increases (Takeda et al., 2004). This mechanism is designed to help prevent mood disturbances and depressive disorders; however, it may lead to a shortage of serotonin as expenditure exceeds synthesis (Takeda et al., 2004). These effects may be intensified when FI is limited (Le Floc'h and Seve, 2007). Supplemental Trp has been reported to reduce stress hormone concentrations, which may be beneficial in the immediate post-weaning period (Koopmans et al., 2005; Liu et al., 2013). Early research has indicated that Trp may also modulate plasma insulin secretion and sensitivity (Cortamira et al., 1991), suggesting a role in glucose metabolism. Increasing dietary Trp also induces high ghrelin levels along the GI tract (Zhang et al., 2007). Ghrelin is a 28-AA peptide hormone secreted from the stomach that is involved in the mTOR signaling pathway and is believed to regulate FI in response to serotonin levels (Zhang et al., 2007; Nørgaard et al., 2015).

Sodium and chloride are also of particular importance for nursery pigs. These minerals, commonly fed in the form of salt, are involved in nutrient absorption, electrolyte balance, and regulation of pH (Menegat et al., 2019). Diets that are deficient in salt result in decreased growth performance due to reduced FI and poor feed efficiency (Shawk et al., 2018a,b). For 5 to 7 kg weanling pigs, providing 0.4% and 0.5% sodium and chloride, respectively is necessary to meet their requirement.

Enzymes are another area commonly studied, with phytases contributing the greatest benefit. While phytase is not known for increasing FI, it is well established that adding exogenous phytase to swine diets helps improve phosphorus availability. Compared to standard doses (< 1,000 FTU), super-dosing phytase (< 2,000 FTU) has been shown to provide additional benefits beyond phosphorus release, which may be attributed to the release of inositol from the phytate complex. Moran et al. (2019) demonstrated that increasing exogenous inositol improved feed efficiency in pigs fed diets without phytase, equivalent to the improvement observed with super-dosing phytase. Following the immediate post-weaning period, FI increased as inositol supplementation increased in the absence of phytase. Though the mode of action is unknown, this suggests that inositol may be conditionally essential in diets of weanling pigs. Croze and Soulage (2013) suggest that myo-inositol has a role in insulin signaling and protein synthesis, possibly improving glucose metabolism and contributing to improved performance.

Gaps in knowledge

Reducing nutrient disruption after weaning can be accomplished through further exploration of multiple post-weaning strategies. Understanding the long-term implications of these strategies is also crucial.

- **Thermoneutral zone:** What environmental temperatures are ideal, in accordance with season, to encourage pen exploration and reduce latency to first feeding?

- **Feed availability:** Mat and gruel feeding are commonly practiced throughout the industry; however, limited data is available to document the value of these feeding strategies.
- **Water availability:** More research in commercial settings with larger group sizes is needed to determine adequate water space. Additionally, how does wet/dry feeding impact water space requirements? And how does feeder arrangement relative to drinker location affect FI and subsequent performance.
- **Liquid feeding/milk replacer:** Liquid feeding strategies do offer opportunities to increase DM intake in the immediate post-weaning period, particularly in lightweight pigs. The implications on death loss and culling rates need to be considered. Does offering liquid feed immediately after weaning require a second weaning period when pigs are transitioned from the liquid diet to solid feed?
- **Delayed feeding:** Does delayed feeding offer an opportunity for pigs to get acclimated with a new environment and pen mates, prior to feed stimuli? Would the sound of feed being dropped into feeders encourage feed behavior? And how long of a delay is too long?
- **Diet form:** Influence of crumble diets on pig feeding preference and growth performance, compared to meal and pellet diets.
- **Diet palatability:** More research is needed on the concept of early flavor experiences. Does perinatal or social interaction flavor learning increase feed acceptance post-weaning as a result of flavor association?

Diet considerations: More research is still needed to determine the effect high fiber and low crude protein, AA fortified diets on post-weaning diarrhea and growth performance.

Conclusion

Weaning older, heavier pigs and encouraging feeding behavior through environmental and nutritional strategies will help improve FI and early growth immediately after weaning. According to a study conducted by Pluske (2013), husbandry and management techniques, including hygiene and education, offer the greatest potential for reducing nutrient disruption at the time of weaning. Several factors are known to influence nutrient intake after weaning including:

- **Feed availability:** Easy access to feed improves immediate post-weaning FI. This is influenced by pen size, group size, feeder design, and location of feeder relative to water.
- **Water quality:** High levels of dissolved minerals in the water do not hinder performance but may influence diarrhea scours and appearance of looseness.
- **Water enrichment:** Water enrichment strategies do provide additional nutrients that have been shown to benefit growth performance and morbidity and mortality when FI is low.
- **Nursery placement:** Sorting pigs into uniform BW groups is beneficial for light weight pigs but not heavy weight pigs.
- **Diet form:** For young pigs the implication of diet form on palatability preference is an important consideration. Pelleted diets increase feed efficiency and nutrient digestibility compared to meal diets. Regardless if fed as a meal or pellet though, weanling pigs prefer diets manufactured with coarse (700 microns) ground corn rather than fine ground corn. When pelleted diets are fed however, young pigs prefer pellets with a larger diameter.
- **Diet complexity:** Feeding more complex diets during the first week post-weaning improves pig growth and efficiency, with the greatest response observed in the

lightweight pig population. The initial benefits observed in performance tend to decrease with increasing time post-weaning.

- **Diet palatability:** Young pigs are sensitive to palatability which is influenced by odor, taste, and texture. Therefore, feed ingredients should be taken into account when formulating diets for newly weaned pigs. Increased preference doesn't always equate to higher FI, especially when pigs are not given a choice between diets.
- **Diet ingredients and nutrients:** Organic acid supplementation, crude protein level, insoluble fiber inclusion, and zinc and copper concentrations alter the occurrence of post-weaning diarrhea. Fatty acids and functional AA such as glutamine and Trp positively influence gut health and subsequent FI. Salt concentrations also play an important role in FI and palatability preferences, with myo-inositol having more recent implications on FI.

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Chapter 3 - Effects of providing sensory attractants to suckling pigs in late lactation and after weaning on post-weaning growth performance

Abstract

Three experiments were conducted to determine the effect of sensory attractants pre- and post-weaning on the growth performance of pigs after weaning. For each experiment, treatments were arranged as a 2 × 2 × 2 factorial with main effects of pre-weaning application (without or with), post-weaning application (without or with), and body weight category (representing the lightest or heaviest 50% of the population). In Exp. 1, 356 nursery pigs (initially 5.7 kg) were used in a 28-d trial with enrichment cubes used as the sensory attractant. A greater percentage of heavy pigs ($P = 0.007$) or pigs offered enrichment cubes pre-weaning ($P = 0.044$) lost BW from weaning to d 3 compared to light pigs or pigs not offered enrichment cubes pre-weaning. From weaning to d 7, a greater percentage of pigs lost weight when not offered cubes post-weaning ($P = 0.002$) compared to pigs offered cubes post-weaning. In Exp. 2, 355 nursery pigs (initially 5.6 kg) were used in a 29-d trial with a powder used as the sensory attractant. Providing a powder attractant both pre- and post-weaning reduced the percentage of pigs that lost weight from weaning to d 3 as compared with providing a powder either pre- or post-weaning only (interaction, $P < 0.05$). In Exp. 3, 355 nursery pigs (initially 5.9 kg) were used in a 24-d trial with a liquid spray used as the sensory attractant. A greater percentage of heavy pigs that did not receive liquid attractant lost weight from weaning to d 3, whereas a greater percentage of light pigs lost weight when they received liquid attractant only pre-weaning (3-way interaction; $P = 0.016$). Across all three experiments, sensory attractant application had limited effects on the

growth performance of pigs after weaning; however, varying responses were observed for the percentage of pigs that lost weight in the first 3 to 7 d immediately post-weaning. In summary, environmental enrichment with cubes (Exp. 1) appears to have the greatest effect when applied post-weaning whereas flavor attractants (Exp. 2 and 3) appear to have the greatest effect when applied both pre- and post-weaning.

Introduction

At the time of weaning, pigs generally have limited experience with solid feed. This often results in low feed intake and body weight (BW) gain post-weaning (Bruininx et al., 2001). Low feed intake has been shown to disrupt the natural development of the gastrointestinal tract, leading to losses in intestinal barrier structure and function (McCracken et al., 1999; Moeser et al., 2017). A review by Wensley et al. (2021a, b) evaluated different feeding and management strategies to minimize the negative consequences of weaning. Among the strategies reported, behavioral development through sensory learning is thought to elicit early feed intake. Sensory learning encourages pigs to use their senses to explore the environment around them. Using sensory learning in combination with feeding may offer an opportunity to ease the weaning transition by training pigs to respond to familiar sensory stimuli. Therefore, it’s suggested that providing flavor, odor, or environmental stimuli both before and after weaning may improve feed intake post-weaning because of sensory association (Oostindjer, 2014). However, little data is available that demonstrates meaningful improvements in performance. Likewise, inconsistent results have been reported when adding flavor enhancers to only starter diets to increase feed acceptance after weaning (Oostindjer et al., 2010a; Blavi et al., 2016). Hence for these experiments, we hypothesized that applying either an enrichment object, powder, or liquid sensory attractant pre- and post-weaning would evoke the greatest post-weaning response as it would provide pigs familiar stimuli, consequently reducing feed neophobia. Likewise, it was hypothesized that administering sensory attractants pre-weaning, but not post-weaning, would be detrimental, resulting in decreased feed intake and increased body weight loss immediately after weaning. Thus, the objective of these studies was to determine the effect of sensory attractants pre- and post-weaning on the growth performance of pigs after weaning.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments. Each experiment was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. In the nursery, each pen (1.2 × 1.2 m) contained a 4-hole, dry self-feeder, and nipple waterer for *ad libitum* access to feed and water. Pigs were weighed and feed disappearance measured on d 3, 7, 14, and 24 or 25 after weaning to determine ADG, ADFI, and G:F. The percentage of pigs that lost weight (pigs that were still below weaning weight) from d 0 to 3 and d 0 to 7 post-weaning was also determined.

Experiment 1

A total of 28 litters (241 × 600, DNA, Columbus, NE) were used. Sows were fed a common lactation diet throughout the experimental period. Four days prior to weaning, pigs were weighed, and litters allotted to 1 of 2 treatment groups in a randomized complete block design based on sow parity and average piglet body weight. Treatments consisted of a negative control (no enrichment cubes) or an enrichment cube treatment, in which approximately 100 g of cubes (7 cubes) were provided to litters once daily (AM) for 4 d pre-weaning. Cubes were placed directly on the floor in the center of farrowing stalls on the opposite side of the heat lamp.

At weaning (approximately 20 d of age), 356 pigs (initially 5.7 kg) were weighed and evenly divided into light or heavy BW categories within pre-weaning treatment (representing the lightest or heaviest 50% of the population) and allotted to nursery pen. Each pen was randomized to 1 of 4 treatments with 4 or 5 pigs per pen and 18 replications per combination of pre- and post-weaning treatment. Body weight category was equally distributed across treatment groups. Treatments were arranged in a 2 × 2 × 2 factorial with main effects of pre-weaning application (without or with enrichment cubes), post-weaning application (without or with enrichment cubes), and BW category [light (2.4 to 5.7 kg) or heavy (5.8 to 9.0 kg)]. Pens of pigs assigned to the enrichment cube treatment group were offered approximately 100 g of cubes (7 cubes) once daily (AM) in the pan of the fence-line feeder for 3 d after weaning.

The enrichment cubes ranged in size from 28 to 51 mm in length and 20 mm in diameter and were manufactured by Form-A-Feed in Stewart, MN (Figure 1). The main ingredients used for cube formulation were soy hulls, soybean meal, wheat midds, digestible sugars, and other palatable ingredients. Cubes were not intended to be a complete diet replacement, but rather to provide a form of sensory enrichment. Therefore, the nutrient profile of cubes was not complete and balanced. In addition to the enrichment cubes, all pigs received 3.5 mm pelleted corn-soybean meal-based starter diets for the 24-d feeding program after weaning, fed in 2 phases with phase 1 fed from d 0 to 7 and phase 2 fed from d 7 to 24.

Experiment 2

A total of 28 litters (241 × 600, DNA, Columbus, NE) were used. Sows were fed a common lactation diet throughout the experimental period. Four days prior to weaning, pigs were weighed and litters were allotted to 1 of 2 treatment groups in a randomized complete block design based on sow parity and average piglet BW. Treatments consisted of a control (without powder) or a treatment with powder, in which approximately 90 g of sensory attractant powder, divided into 2 feedings (AM and PM), were provided in the pan of rotary feeders for 4 d pre-weaning. Litters assigned to the control were not exposed to rotary feeders.

At weaning (approximately 20 d of age), 355 pigs (initially 5.6 kg) were weighed and evenly divided into light or heavy BW categories within pre-weaning treatment (representing the lightest or heaviest 50% of the population) and allotted to nursery pens. Each pen was randomized to 1 of 4 treatments with 5 or 6 pigs per pen and 15 replications per combination of pre- and post-weaning treatment. Body weight category was equally distributed across treatment groups. Treatments were arranged in a 2 × 2 × 2 factorial with main effects of pre-weaning application (without or with powder), post-weaning application (without or with powder), and BW category [light (2.6 to 5.5 kg) or heavy (5.7 to 8.1 kg)]. Pens of pigs assigned to the powder treatment group were offered approximately 45 g of sensory attractant powder per day, divided into 2 feedings (AM and PM) top-dressed on feed in the feeder pan for 2 d post-weaning. On d 3, approximately 45 g of feed (taken from the back of the feeder), divided into 2 feedings (AM and PM), was top-dressed on feed in the feeder pan to mimic powder application. This was done to maximize the behavioral response of top dressing the sensory attractant powder.

Baby Pig Restart APF (TechMix LLC; Stewart, MN) was used as the sensory attractant powder for this experiment. Baby Pig Restart APF is a powdered attractant designed to entice pigs to eat dry feed, while also providing additional nutrients as it is formulated to contain 19.5% crude protein and 2.75% crude fat. Because powder application is not intended to replace complete feed, all pigs received common 3.5 mm pelleted corn soybean-meal-based phase 1 and 2 diets throughout the duration of the 25-d trial. Phase 1 diet was provided from d 0 to 7 and phase 2 diet from d 7 to 25 post-weaning.

Experiment 3

A total of 28 litters (241 × 600, DNA, Columbus, NE) were used. Sows were fed a common lactation diet throughout the experimental period. Within 24 h of farrowing, litters of pigs were weighed and allotted to 1 of 2 treatment groups in a completely randomized design based on farrowing date. Sow parity, average piglet BW, and average litter size were balanced across treatment groups. Treatments consisted of a control (without liquid sensory attractant) or a treatment with liquid sensory attractant, in which approximately 89 ml of liquid sensory attractant per day, divided into 2 applications (AM and PM), was sprayed on the underline of sows for 2 d beginning the morning after farrowing. Treatment application was later resumed for 2 d pre-weaning. In total, pigs received liquid sensory attractant for 4 d pre-weaning.

At weaning (approximately 20 d of age), 355 pigs (initially 5.9 kg) were weighed and evenly divided into light or heavy BW categories within pre-weaning treatment (representing the lightest or heaviest 50% of the population) and allotted to nursery pens. Each pen was randomized to 1 of 4 treatments with 5 or 6 pigs per pen and 15 replications per combination of pre- and post-weaning treatment. Body weight category was equally distributed across treatment groups. Treatments were arranged in a 2 × 2 × 2 factorial with main effect of pre-weaning application (without or with spray), post-weaning application (without or with spray), and BW category [light (2.6 to 5.8 kg) or heavy (6.0 to 8.9 kg)]. Pens of pigs assigned to the liquid attractant treatment group were offered approximately 59 ml of liquid per day, divided into 3 applications (7:00, 12:00, and 17:00), sprayed on the feed in the feeder pan. Treatment application continued for 3 d post-weaning.

BlueLite Pro2Lyte (TechMix LLC; Stewart, MN) was used as the liquid sensory attractant for this experiment. BlueLite Pro2Lyte is a dry powdered electrolyte that when mixed with water according to label instructions creates an isotonic solution. This liquid solution may be used as an attractant to entice pigs to eat dry feed, while also providing additional nutrients. Pigs were fed common 3.5 mm pelleted corn soybean-meal-based phase 1 and 2 diets throughout the duration of the 24-d trial. Phase 1 diet was provided from d 0 to 7, and phase 2 diet from d 7 to 24.

Data analysis

In Exp. 1 and 2, pre-weaning data were analyzed as a randomized complete block design with litter as the experimental unit. Treatment was considered a fixed effect and block was included in the model as a random effect which incorporated both sow parity and average piglet BW. In Exp. 3, pre-weaning data were analyzed as a completely randomized design with litter as the experimental unit. Treatment was considered a fixed effect and parity was included in the model as a random effect. Total born count was analyzed using a poisson model.

Post-weaning data for each experiment were analyzed as a factorial with main effect of: 1) pre-weaning treatment (without or with); 2) post-weaning treatment (without or with); and 3) BW category (light or heavy). Pen was considered the experimental unit. Least square means were applied to estimate the interactive and main effects. A binomial model was used to determine the percentage of pigs within a pen that lost weight from d 0 to 3 and d 0 to 7 post-weaning using a logit link function. All statistical models were fit using the GLIMMIX procedure of SAS v. 9.4 (SAS Institute, Inc., Cary, NC). Results were considered significant at $P \leq 0.05$.

Results

Experiment 1

As expected, providing enrichment cubes to litters pre-weaning did not influence piglet weaning weights (P = 0.976; without = 5.7 kg; with = 5.7 kg). Interestingly, several 3-way interactions were observed after weaning for pre- and post-weaning enrichment cube application and body weight category (Table 1; interactive means are only shown for the significant response variables). Heavy weight pigs that were provided enrichment cubes before weaning, but not after, grew slower and ate less feed from d 7 to 14, 14 to 24, and 0 to 24 post-weaning compared to heavy pigs that were provided enrichment cubes before and after weaning. The opposite effect was observed for light weight pigs (P < 0.05). This led to increased final BW in heavy weight pigs provided enrichment cubes both before and after weaning and decreased final BW (P < 0.05) in light weight pigs provided enrichment cubes before weaning but not after weaning, with all other treatment combinations intermediate. If pigs did not receive enrichment cubes before weaning, providing the cubes after weaning had no impact on performance in either light or heavy pigs. No differences in growth performance (P > 0.10) after weaning were observed for the overall interaction between pre × post-weaning treatment, as well as the overall interaction between post-weaning treatment × BW category (P > 0.05; data not shown). No differences in overall ADG or G:F (P > 0.10) were observed for the interaction between pre-weaning treatment × BW category.

For the main effect of pre-weaning cube application, no overall differences were observed on post-weaning ADG or ADFI (P > 0.10; Table 2). However, pigs offered enrichment cubes prior to weaning had improved overall post-weaning G:F (P = 0.017) compared to pigs not offered enrichment cubes. This response was also observed from d 0 to 7 (P = 0.064) and 14 to

24 (P = 0.009). For the main effect of post-weaning cube application, no effect on the ADG or ADFI (P > 0.10) of pigs after weaning was observed. There was a tendency for pigs offered enrichment cubes post-weaning to have poorer G:F (P = 0.078) compared to pigs not offered enrichment cubes. For the main effect of BW category, heavy weight pigs had improved overall ADG (P < 0.001) and ADFI (P < 0.001) compared to light weight pigs. No evidence for difference in G:F (P > 0.10) were observed.

While limited effects of enrichment cubes were observed on the growth performance of pigs after weaning, the true value of enrichment cubes may be in the percentage of pigs that lost weight 3 or 7 d post-weaning, as measured by the percentage of pigs that were still below weaning weight. No evidence for differences were observed in the 3-way interaction or any of the 2-way interactions for piglet BW loss (P > 0.05). For the main effect of pre-weaning cube application, a greater percentage of pigs lost weight (P = 0.044) from d 0 to 3 post-weaning when offered enrichment cubes prior to weaning compared to no cubes. Conversely, for the main effect of post-weaning cube application, the percentage of pigs that lost weight from d 0 to 7 post-weaning was reduced by 11.7 percentage points (P = 0.002) when pigs were offered enrichment cubes compared to no cubes. There was no evidence for differences for the main effect of BW category (P > 0.10) at d 7 post-weaning; however, the percentage of pigs that lost weight 3 d post-weaning was 15 percentage points greater (P = 0.007) for the heavy weight pig population than the lightweight pig population. This suggests heavy weight pigs have an easier time recovering from the initial weight loss that occurs after weaning.

Experiment 2

Pre-weaning powder application did not influence piglet weaning weight (P = 0.485; without = 5.5 kg; with = 5.6 kg). Post-weaning, no 3-way interactions (P > 0.10) between pre-and post-weaning powder application and BW category were observed (data not shown). Likewise, no overall interactions ($P > 0.10$) between pre × post-weaning treatment were observed, as well as the overall interaction ($P > 0.05$) between post-weaning treatment × BW category. However, several interactions between pre-weaning powder application × BW category were observed (Table 3; interactive means are only shown for the significant response variables). Pre-weaning powder application did not affect post-weaning ADFI in the lightweight pig population, but increased feed intake in the heavy weight pig population ($P = 0.027$). Because ADFI did not impact ADG, differences in G:F ($P = 0.013$) were also observed. Powder application pre-weaning improved overall G:F in the light weight pig population compared to the heavy weight pig population, with the other treatment combinations intermediate. A similar response in ADFI and G:F were also observed from d 14 to 25. No differences were observed in ADG throughout ($P > 0.10$).

For the main effect of pre-weaning powder application, no differences were observed on post-weaning performance ($P > 0.05$; Table 4). Likewise, no differences were observed for the main effect of post-weaning powder application ($P > 0.10$). For the main effect of BW category, no differences were observed in growth performance the first 7 d post-weaning ($P > 0.05$). This suggests that heavy weight and light weight pigs all struggle to make the weaning transition, regardless of starting BW. However, overall (d 0 to 25), heavy weight pigs had increased ADG ($P < 0.001$) and ADFI ($P < 0.001$) compared to light weight pigs, with no evidence for differences observed in G:F ($P > 0.10$).

For the percentage of pigs that were still below weaning weight 3 or 7 d post-weaning, no 3-way interactions were observed ($P > 0.10$). An interaction between pre × post-weaning treatment was observed from weaning to d 3 ($P = 0.015$; Figure 2). Providing powder both pre-and post-weaning reduced the percentage of pigs that lost weight by approximately 20 percentage points compared to the other three treatment combinations. This interaction diminished by d 7 and no other interactions ($P > 0.10$) were observed. The main effects of pre- and post-weaning powder application and BW category are shown in Table 4. Significance was detected on d 3 for the main effect of post-weaning treatment ($P = 0.048$); however, this effect was driven by the interaction between pre × post-weaning treatment as previously described. Numerically, a greater percentage of heavy weight pigs lost weight ($P = 0.091$) during the first 7 days post-weaning compared to the lightweight pigs, which may support the numerically reduced ADG in heavy weight pigs observed from d 0 to 7 post-weaning.

Experiment 3

At the start of the experiment, piglet 24-h birth weight was significantly heavier ($P = 0.026$) for litters assigned to the liquid sensory attractant treatment compared to litters assigned to the control group. This was a result of the randomized allotment procedure over the 5-d farrowing window. However, no differences were observed in total piglet gain pre-weaning ($P > 0.10$). Therefore, litters that received liquid sensory attractant during lactation continued to have numerically heavier BW at weaning compared to litters that did not receive liquid sensory attractant. However, this was not statistically significant ($P > 0.10$).

No 3-way interactions between pre- and post-weaning treatment and BW category ($P > 0.10$) were observed for growth performance after weaning (data not shown). Likewise, no 2-way interactions ($P > 0.10$) between pre × post-weaning treatment were observed, except for BW on d 0 ($P = 0.005$), which reflects the differences in starting BW (24-h birth) as previously discussed. No evidence for treatment differences ($P > 0.05$) were observed for the interaction between post-weaning treatment × BW category; however, interactions between pre-weaning treatment × BW category were observed (Table 5; interactive means are only shown for the significant response variables). Application of a liquid sensory attractant pre-weaning had no effect on the ADG of light weight pigs from d 14 to 24 and 0 to 24, whereas in the heavy weight pig population, pre-weaning application increased gain ($P < 0.01$). This was driven by differences in ADFI ($P < 0.05$). No differences in G:F were observed ($P > 0.10$).

Based on how pigs were then allotted to pens post-weaning, a statistical difference for the main effect of pre-weaning liquid application was observed for d 0 BW ($P < 0.001$). Again, this was a result of lighter weights (24-h birth) at the start of the experiment for pigs that did not receive liquid attractant before weaning. No other differences ($P > 0.05$) were observed for the main effect of pre-weaning attractant thereafter. Likewise, no differences ($P > 0.10$) for the main effect of post-weaning attractant were observed. Treatment differences were observed for the main effect of BW category. Overall (d 0 to 24), heavy weight pigs had increased ADG ($P < 0.001$) and ADFI ($P < 0.001$) compared to light weight pigs. No differences G:F were observed ($P > 0.10$).

For the percentage of pigs that were still below weaning weight 3 or 7 d post-weaning, a 3-way interaction was observed from weaning to d 3 (Figure 3; $P = 0.016$). A greater percentage of heavy weight pigs that did not receive liquid sensory attractant lost weight compared the other three treatment combinations. In contrast, a lower percentage of light weight pigs that received liquid sensory attractant either not at all, only post-weaning, or both pre- and post-weaning lost weight compared to pigs that received liquid sensory attractant only pre-weaning. The interaction observed diminished by d 7 ($P > 0.10$) but does indicate a difference in how light and heavy weight pigs may respond to sensory intervention strategies. The main effects of liquid attractant application can be found in Table 6; however, because the 3-way interaction on d 3 was already discussed, the main effects will not be emphasized. From weaning to d 7 post-weaning, a greater percentage of heavy weight pigs lost weight than light weight pigs (P = 0.051), which agrees with the results of Exp. 1 and 2.

Discussion

The environment in which pigs are reared affects their behavioral development (Lau et al., 2015). Pigs raised outdoors have been identified as calm/passive and spend more time eating post-weaning, whereas pigs raised indoors have been identified as playful/investigative and spend more time exploring their environment (Lau et al., 2015). While investigation is key to getting pigs started on feed, providing indoor reared pigs early opportunities to develop feeding behaviors through sensory enrichment, may lead to early feed intake post-weaning. Oostindjer et al. (2011a) observed that first introducing a novel food type to young pigs in the presence of the sow reduced latency to touching feed and improved feed intake compared to first introducing a novel food type in the absence of the sow. However, if a novel food was first introduced in the absence of the sow, consumption was improved if piglets had environmental enrichment. Because weanling pigs are sensitive to sensory factors including, taste, odor, and texture, and are highly motivated by environmental stimuli (Sola-Oriol et al., 2009; Oostindejer et al., 2011b), it has been suggested that environmental or flavor enrichment during multiple phases of early life may help stimulate behavioral development and reduce post-weaning stress (Oostindjer et al., 2014). Therefore, feed intake may be increased, reducing the post-weaning growth check.

Creep feeding is another strategy that can be used to develop feeding behaviors. Providing creep feed to pigs during lactation encourages exploratory behavior and familiarizes pigs with solid feed before weaning; consequently, improving feed intake and body weight gain in the immediate post-weaning period (Bruininx et al., 2002). More recently, Middelkoop et al.

(2019) observed that providing creep feed in play feeders (conventional rotary feeders with canvas cloth, braided cotton ropes, and PVC spiral tubes attached on the feeder) elicited play behavior, attracting more pigs to creep feed. This response followed pigs through the immediate post-weaning period where increased feed intake and gain were observed. The authors suggested that providing creep feed in play feeders prior to weaning may develop a positive association between solid feed and object play, stimulating greater feed consumption.

Similar learning benefits to creep feeding have also been explored in other forms such as environmental and flavor stimuli. The goal of both strategies is to stimulate investigative activity and help pigs overcome fear of their new environment, therefore leading to increased feed intake. For this reason, we used three strategies to provide pre-weaning enrichment that continued through to the post-weaning period, including large enrichment cubes (Exp. 1), a powder attractant (Exp. 2), and a liquid spray attractant (Exp. 3). Environmental enrichment (straw, wood shavings, peat, and branches) pre-weaning has been shown to increase the floor exploration and play behavior of pigs prior to weaning. However, these behaviors did not follow pigs into the nursery unless environmental enrichment was also offered post-weaning (Oostindjer et al., 2011b). Interestingly, when looking at growth performance effects, Oostindjer et al. (2010b) observed that pre-weaning enrichment alone increased feed intake in the first 48 h after weaning. This response may be related to the development of foraging behaviors or decreased stress. Similar to the pre-weaning behavioral response, post-weaning enrichment alone has been shown to increase pen and floor exploration, play behavior and general activity (Oostindjer et al., 2011b). In contrast to the pre-weaning growth performance response, this led to enriched pigs exhibiting decreased feeder interactions and no differences in feed intake compared to pigs that were not enriched after weaning (Oostindjer et al., 2011b). However, in an earlier experiment, Oostindjer et al. (2010b) observed that post-weaning enrichment alone increased the growth of pigs during the first 14 d in the nursery. While it appears enrichment consistently impacts pig behavior, the growth performance benefits are equivocal.

In Exp. 1, providing large enrichment cubes before weaning, but not after, led to decreased feed intake and BW gain, with the greatest response observed when heavy weight pigs were provided cubes both pre- and post-weaning or not at all. In contrast, light weight pigs provided enrichment cubes before weaning, but not after, exhibited increased feed intake and BW gain. Despite the variation seen in growth performance between light and heavy weight populations, the addition of large enrichment cubes only post-weaning reduced the percentage of pigs that lost weight after weaning. Likewise, a greater percentage of pigs lost weight when offered enrichment cubes only pre-weaning. This response may be related to loss of enrichment at weaning. These data in combination with Oostindjer et al. (2010b; 2011b) suggest that post-weaning environmental enrichment may provide the greatest opportunity to improve the weaning transition.

Pre- and postnatal flavor exposure through the maternal diet has also been suggested to reduce feed neophobia post-weaning (Oostindjer et al. 2010a). However, the data appears to be more consistent for prenatal exposure than postnatal. Figueroa et al. (2013) showed that prenatal exposure to anise or milky cheese through the maternal diet increased pig preference for the previously exposed flavor up to 2 d post-weaning. This may indicate that preferences acquired prenatally can be long-lasting. However, it is important to note that flavor preference in behavioral studies does not always equate to improved growth performance. In two separate studies, prenatal flavor exposure did not increase the feed intake of flavored creep feed during the suckling period compared to unflavored creep feed (Figueroa et al., 2013; Blavi et al., 2016).

Varying responses have also been reported post-weaning. Oostindjer et al. (2010a) showed that prenatal exposure to anise increased pig BW up to 5 d post-weaning compared to pigs that were not exposed prenatally. However, no differences in performance were observed with postnatal exposure alone or the interaction between pre- and postnatal exposure. In contrast, Blavi et al. (2016) showed that feeding sows a flavor compound of anethol, cinnamaldehyde, and eugenol in late gestation through lactation increased piglet feed intake post-weaning, regardless of post-weaning diet. However, this did not lead to improvements in gain. Oostindjer et al. (2011c) also assessed the effect of prenatal flavor exposure on weaning stress. The authors observed a reduction in saliva cortisol levels 4 hours post-weaning when pigs were exposed to flavors prenatally and then re-introduced to that same flavor after weaning. Likewise, latency to eat was decreased, play behavior increased, and both vocalization and manipulation behaviors decreased. Unfortunately, this did not result in increased feed intake or gain. These data may indicate that pigs prefer the scent of previously exposed flavors, rather than taste, which may explain the inconsistent response of postnatal flavor exposure observed throughout the literature (Oostindjer et al., 2011c). Likely, this is a result of a flavor association between olfactory stimuli and positive life experiences, suggesting that flavor learning works by reducing stress due to the presence of a familiar smell, rather than something that tastes good. Unfortunately, this does not consistently translate into improved performance after weaning. Compared to environmental enrichment, it appears that prenatal flavor exposure that continues through lactation is a strategy that may provide opportunities to improve the weaning transition (Oostindjer et al., 2014). Although limited differences in growth performance were observed for Exp. 2 and 3, the percent of pigs that lost BW after weaning agrees with the previous literature. In Exp. 2, sensory attractant powder exposure both pre- and post-weaning reduced the percentage of pigs that lost weight compared to when exposure occurred only pre-weaning, only post-weaning, or not at all. In Exp. 3, sensory attractant liquid exposure only pre-weaning increased the percentage of light weight pigs that lost weight, whereas no exposure increased the percentage of heavy weight pigs that lost weight. The results herein further emphasize the inconsistent responses observed in sensory learning trials, except for prenatal exposure. Prenatal exposure to the sensory attractants used in these studies may have provided added benefits; however, more research is needed to understand the potential implications.

Most behavioral studies that assess flavor or environmental enrichment look at piglet preference rather than body weight loss. Hence, it's challenging to compare the results of these experiments with previous reports. Based on the studies herein, it does appear sensory attractants have the potential to reduce the percentage of pigs that lose weight immediately post-weaning. The effect of sensory attractant application on BW loss post-weaning also seems to be related to piglet BW at weaning, with a greater percentage of heavy weight pigs exhibiting BW loss initially postweaning compared to light weight pigs. While limited differences in ADG and ADFI were observed from d 0 to 7 post-weaning for the main effect of BW category across all 3 experiments, reductions in the percentage of light weight pigs that lost weight may be a result of initial feed intake. Bruininx et al. (2001) showed that feed intake during the first 24-h post-weaning was increased in light weight pigs compared to heavy pigs. This continued for the first 3 d post-weaning, indicating that heavy weight pigs take longer to begin consuming feed, particularly when sorted into pens of all heavy weight pigs (Bruininx et al., 2001), which was the case in these experiments. Because heavy pigs are often more dominant, it is likely that heavy pigs spend more time engaged in aggressive interactions to establish social hierarchy than searching out and consuming feed (Faccin et al., 2019). Despite greater initial BW loss, the overall ADG and feed intake of heavy weight pigs was increased compared to light weight pigs, which agrees with Bruininx et al. (2001). Together, these data emphasize that all pigs, regardless of starting BW, struggle to make the weaning transition.

In summary, sensory attractant application had limited effects on the growth performance of pigs after weaning; however, varying responses were observed for the percentage of pigs that lost weight immediately post-weaning, as measured by the percentage of pigs that were still below weaning weight 3 or 7 d post-weaning. Environmental enrichment with cubes (Exp. 1) appears to have the greatest effect when applied post-weaning whereas flavor attractants (Exp. 2 and 3) appear to have the greatest effect when applied both pre- and post-weaning. Piglet BW at weaning also plays an important role in behavioral development and their subsequent response to sensory attractants. Strategies to reduce the number of pigs that lose weight after weaning warrant further investigation, with an emphasis on understanding how BW loss post-weaning impacts survival and lifetime gain.

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Table 3-1. Body weight category × pre-weaning enrichment cube × post-weaning enrichment cube interaction on nursery pig growth performance, Exp. 1[1]

	BW category:	Light				Heavy					
	Pre-wean cube:	Without		With		Without		With			P =
Item	Post-wean cube:	Without	With	Without	With	Without	With	Without	With	SEM	Interaction[2]
Post-wean BW, kg											
d 14		6.6[c]	6.4[c]	6.8[c]	6.5[c]	9.0[a]	8.9[ab]	8.5[b]	9.0[a]	0.14	0.046
d 24		10.3[cd]	10.2[d]	11.0[c]	10.4[cd]	13.9[ab]	13.5[ab]	13.2[b]	14.0[a]	0.27	0.034
d 7 to 14											
ADG, g		210[cde]	200[de]	229[bcd]	185[e]	282[a]	246[abc]	213[cde]	256[ab]	13.8	0.005
ADFI, g		225[d]	232[cd]	254[cd]	231[cd]	324[a]	312[a]	265[bc]	296[ab]	12.9	0.044
d 14 to 24											
ADG, g		375[d]	374[d]	429[bc]	387[cd]	488[a]	467[ab]	472[ab]	504[a]	16.9	0.047
ADFI, g		512[d]	526[d]	553[cd]	529[d]	662[a]	625[ab]	604[bc]	652[ab]	19.1	0.026
d 0 to 24											
ADG, g		233[de]	228[e]	262[cd]	237[de]	300[ab]	284[abc]	275[bc]	304[a]	10.4	0.028
ADFI, g		310[d]	317[d]	336[cd]	324[d]	409[a]	392[ab]	363[bc]	398[a]	12.2	0.042

[a,b,c] Means lacking common superscript differ, $P < 0.05$.

[1]For the pre-weaning portion of the experiment, a total of 28 litters (241 × 600, DNA, Columbus, NE) were used. Treatments consisted of a negative control (no enrichment cubes) or an enrichment cube treatment, in which approximately 100 g of cubes (7 cubes) were provided to litters once daily (AM) on the floor of farrowing stalls for 4 d prior to weaning. For the post-weaning portion of the experiment, a total of 356 pigs were weaned and used in a 24-d growth trial with 4 or 5 pigs per pen and 18 replicates per treatment. Treatments were arranged in a 2 × 2 × 2 factorial with main effects of pre-weaning treatment (without or with enrichment cubes), post-weaning treatment (without or with enrichment cubes), and BW category (light or heavy). Pens of pigs assigned to the enrichment cube treatment group were offered approximately 100 g of cubes (7 cubes) once daily (AM) in feeder pans for 3 d after weaning. For ease of interpretation, only the significant response variables are shown for the 3-way interactions between BW category and pre- and post-weaning treatment.

[2] In addition to the reported 3-way interaction *P*-values, a BW category × post-weaning enrichment cube interaction was observed in d 14 BW ($P = 0.043$). A BW category × pre-weaning enrichment cube interaction was observed in d 7 to 14 ADFI ($P = 0.006$) and d 0 to 24 ADFI ($P = 0.037$).

Table 3-2. Main effect of pre-weaning enrichment cube, post-weaning enrichment cube, and body weight category on the growth performance of nursery pigs, Exp. 1[1]

	Pre-wean cube				Post-wean cube				BW category			
Item	Without	With	SEM	*P* =	Without	With	SEM	*P* =	Light	Heavy	SEM	*P* =
Post-wean BW, kg												
d 0	5.7	5.7	0.02	0.935	5.7	5.7	0.02	0.688	4.7	6.7	0.02	< 0.001
d 3	5.7	5.7	0.03	0.486	5.6	5.7	0.03	0.138	4.7	6.6	0.03	< 0.001
d 7	6.1	6.1	0.04	0.145	6.1	6.1	0.04	0.257	5.1	7.1	0.04	< 0.001
d 14	7.7	7.7	0.07	0.932	7.7	7.7	0.07	0.891	6.6	8.8	0.07	< 0.001
d 24	12.0	12.1	0.13	0.313	12.1	12.0	0.12	0.699	10.4	13.7	0.13	< 0.001
Pigs that lost BW after weaning, %[2]												
d 3	38.4	49.5	3.91	0.044	48.7	39.1	3.89	0.081	36.5	51.5	3.91	0.007
d 7	8.1	7.7	2.51	0.907	15.5	3.8	2.76	0.002	10.1	6.1	2.43	0.246
d 0 to 7												
ADG, g	54	65	5.4	0.170	54	64	5.4	0.181	59	60	5.4	0.904
ADFI, g	120	122	4.4	0.849	116	126	4.4	0.114	111	131	4.4	0.003
G:F, g/kg	412	511	37.1	0.064	425	498	37.1	0.171	483	441	37.1	0.426
d 7 to 14												
ADG, g	235	221	6.9	0.168	233	222	6.9	0.242	206	249	6.9	< 0.001
ADFI, g	273	262	6.4	0.210	267	268	6.4	0.921	235	299	6.4	< 0.001
G:F, g/kg	869	841	18.3	0.295	880	830	18.3	0.054	877	833	18.3	0.090
d 14 to 24												
ADG, g	425	448	8.4	0.061	441	432	8.4	0.468	391	482	8.4	< 0.001
ADFI, g	581	585	9.5	0.799	583	583	9.5	0.999	530	636	9.5	< 0.001
G:F, g/kg	731	766	9.3	0.009	756	741	9.3	0.279	738	759	9.3	0.110
d 0 to 24												
ADG, g	261	270	5.2	0.257	267	264	5.2	0.604	240	291	5.2	< 0.001
ADFI, g	357	355	6.1	0.839	354	358	6.1	0.697	322	390	6.1	< 0.001
G:F, g/kg	733	759	7.5	0.017	755	736	7.5	0.078	745	746	7.5	0.880

[1]For the pre-weaning portion of the experiment, a total of 28 litters (DNA 241 × 600, Columbus, NE) were used. Treatments consisted of a negative control (no enrichment cubes) or an enrichment cube treatment, in which approximately 100 g of cubes (7 cubes) were provided to litters once daily (AM) on the floor of farrowing stalls for 4 d prior to weaning. For the post-weaning portion of the experiment, a total of 356

pigs were weaned and used in a 24-d growth trial with 4 or 5 pigs per pen and 18 replicates per treatment. Treatments were arranged in a 2 × 2 × 2 factorial with main effects of pre-weaning treatment (without or with enrichment cubes), post-weaning treatment (without or with enrichment cubes), and BW category (light or heavy). Pens of pigs assigned to the enrichment cube treatment group were offered approximately 100 g of cubes (7 cubes) once daily (AM) in feeder pans for 3 d after weaning.

[2] Represents the percentage of pigs that were still below weaning weight 3 or 7 d post-weaning.

Figure 3-1. Enrichment cubes ranged in size from 28 to 51 mm in length and 20 mm diameter and were manufactured by Form-A-Feed (Stewart, MN).

Table 3-3. Body weight category × pre-weaning sensory attractant powder interaction on the growth performance of nursery pigs, Exp. 2[1]

Item	BW category:	Light		Heavy			P =[2]
	Pre-wean powder:	Without	With	Without	With	SEM	Interaction
d 0 to 7							
ADFI, g		71^{b}	68^{b}	68^{b}	87^{a}	4.3	0.014
d 14 to 25							
ADFI, g		430^{b}	397^{b}	510^{a}	551^{a}	16.7	0.030
G:F, g/kg		731^{ab}	783^{a}	768^{ab}	720^{b}	19.2	0.012
d 0 to 25							
ADFI, g		267^{c}	254^{c}	316^{b}	346^{a}	9.3	0.027
G:F, g/kg		677^{ab}	710^{a}	707^{ab}	671^{b}	13.3	0.013

[a,b,c] Means lacking common superscript differ, $P < 0.05$.

[1]For the pre-weaning portion of the experiment, a total of 28 litters (241 × 600, DNA, Columbus, NE) were used during one lactation period. Treatments consisted of a negative control (without powder) or a treatment with powder, in which approximately 45 g of sensory attractant powder were provided to litters of pigs twice daily (AM and PM) in the pan of rotary creep feeders for 4-d prior to weaning. For the post-weaning portion of the experiment, a total of 355 pigs were weaned and used in a 25-d growth trial with 5 or 6 pigs per pen and 15 replicates per treatment. Treatments were arranged in a 2 × 2 × 2 factorial with main effects of pre-weaning treatment (without or with powder); post-weaning treatment (without or with powder); and BW category (light or heavy). Pens of pigs assigned to the powder treatment group were offered approximately 22.5 g of sensory attractant powder twice daily (AM and PM), that was top-dressed on feed in feeder pans for 2 d after weaning. On d 3 approximately 22.5 g of feed (taken from the back of the feeder) was top-dressed on feed in the feeder pans twice daily to mimic powder application.

[2]No 3-way interactions between pre- and post-weaning treatment and BW category were observed for growth performance after weaning ($P > 0.10$). Likewise, no post-weaning treatment × BW category interactions were observed ($P > 0.10$). For ease of interpretation, only the significant response variables are shown for the interaction between pre-weaning treatment × BW category.

Table 3-4. Main effect of pre-weaning sensory attractant powder, post-weaning sensory attractant powder, and body weight category on the growth performance of nursery pigs, Exp. 2[1]

	Pre-wean powder				Post-wean powder				BW category			
Item	Without	With	SEM	*P* =	Without	With	SEM	*P* =	Light	Heavy	SEM	*P* =
Post-wean BW, kg												
d 0	5.6	5.5	0.03	0.593	5.6	5.5	0.03	0.714	4.7	6.4	0.03	<0.001
d 3	5.2	5.3	0.03	0.494	5.2	5.3	0.03	0.415	4.4	6.1	0.03	<0.001
d 7	5.6	5.7	0.04	0.428	5.6	5.7	0.04	0.356	4.8	6.5	0.04	<0.001
d 14	6.8	6.8	0.07	0.880	6.8	6.8	0.07	0.777	5.8	7.8	0.07	<0.001
d 25	10.7	10.7	0.13	0.903	10.7	10.6	0.13	0.562	9.3	12.1	0.13	<0.001
Pigs that lost BW after weaning, %[2]												
d 3	88.9	83.1	3.14	0.148	89.8	81.7	3.22	0.048	83.3	88.8	3.06	0.180
d 7	42.9	37.6	3.75	0.313	41.9	38.6	3.72	0.540	35.8	44.8	3.73	0.091
d 0 to 7												
ADG, g	3.0	15.2	4.70	0.072	6.5	11.7	4.70	0.443	12.4	5.8	4.70	0.322
ADFI, g	69	78	3.1	0.056	72	75	3.1	0.467	70	77	3.1	0.081
G:F, g/kg	-62	140	85.3	0.099	5	73	85.3	0.575	118	-40	85.3	0.195
d 7 to 14												
ADG, g	170	168	7.0	0.753	171	166	7.0	0.552	146	191	7.0	<0.001
ADFI, g	237	249	5.9	0.163	245	241	5.9	0.640	215	271	5.9	<0.001
G:F, g/kg	711	671	22.6	0.216	699	684	22.6	0.634	679	704	22.6	0.430
d 14 to 25												
ADG, g	350	352	8.1	0.831	356	346	8.1	0.374	311	392	8.1	<0.001
ADFI, g	469	474	11.8	0.793	478	465	11.8	0.449	413	530	11.8	<0.001
G:F, g/kg	749	751	13.6	0.928	752	749	13.6	0.865	757	744	13.6	0.498
d 0 to 25												
ADG, g	202	206	4.7	0.508	207	201	4.7	0.413	181	227	4.7	<0.001
ADFI, g	291	300	6.6	0.360	299	292	6.6	0.472	261	331	6.6	<0.001
G:F, g/kg	692	691	9.4	0.897	694	689	9.4	0.703	694	689	9.4	0.752

[1]For the pre-weaning portion of the experiment, a total of 28 litters (241 × 600, DNA, Columbus, NE) were used during one lactation period. Treatments consisted of a negative control (without powder) or a treatment with powder, in which approximately 45 g of sensory attractant powder were provided to litters of pigs twice daily (AM and PM) in the pan of rotary creep feeders for 4 d prior to weaning. For the post-weaning portion of the experiment, a total of 355 pigs were weaned and used in a 25-d growth trial with 5 or 6 pigs per pen and 15

replicates per treatment. Treatments were arranged in a 2 × 2 × 2 factorial with main effects of pre-weaning treatment (without or with powder); post-weaning treatment (without or with powder); and BW category (light or heavy). Pens of pigs assigned to the powder treatment group were offered approximately 22.5 g of sensory attractant powder twice daily (AM and PM), that was top-dressed on feed in feeder pans for 2 d after weaning. On d 3, approximately 22.5 g of feed (taken from the back of the feeder) was top-dressed on feed in the feeder pans twice daily to mimic powder application. \

[2] Represents the percentage of pigs that were still below weaning weight 3 or 7 d post-weaning.

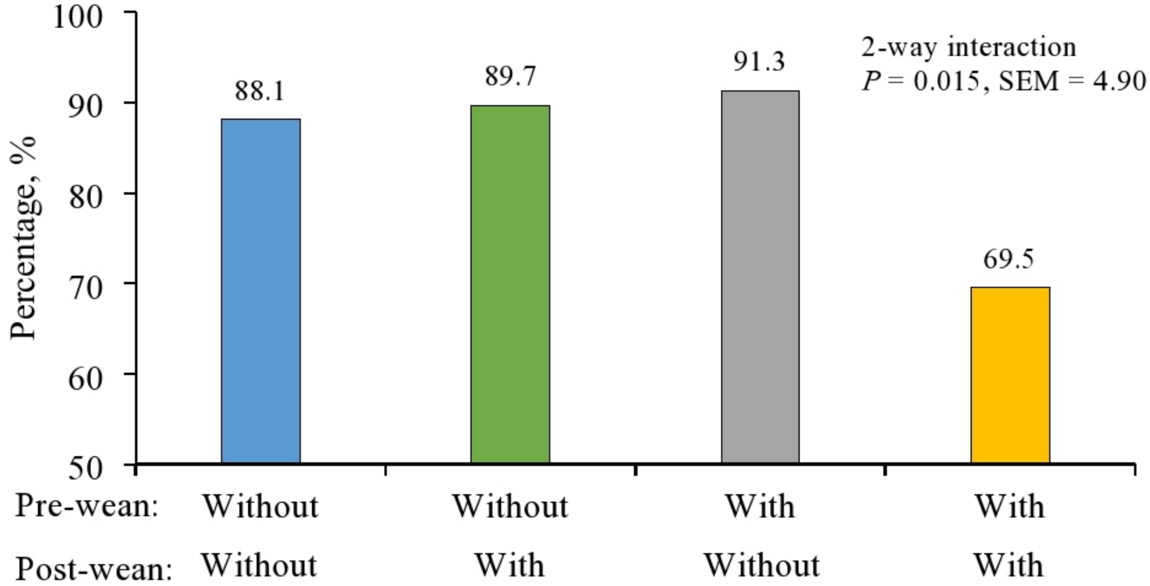

Figure 3-2. Pre-weaning sensory powder × post-weaning sensory powder interaction on the percentage of pigs that lost weight from weaning to d 3. No 2-way interaction from weaning to d 7 was observed (*P* > 0.10).

Table 3-5. Body weight category × pre-weaning sensory attractant liquid interaction on the growth performance of nursery pigs, Exp. 3[1]

	BW category:	Light		Heavy			$P =$[2]
Item	Pre-wean liquid:	Without	With	Without	With	SEM	Interaction
Post-wean BW, kg							
d 24		10.5[c]	10.2[c]	13.1[b]	13.8[a]	0.17	0.008
d 14 to 24							
ADG, g		388[c]	366[c]	436[b]	474[a]	10.1	0.004
ADFI, g		534[c]	515[c]	614[b]	657[a]	12.1	0.013
d 0 to 24							
ADG, g		233[c]	217[c]	260[b]	283[a]	6.7	0.005
ADFI, g		335[b]	314[b]	382[a]	402[a]	8.1	0.013

[a,b,c] Means lacking common superscript differ, $P < 0.05$.

[1]For the pre-weaning portion of the experiment, a total of 28 litters (241 × 600, DNA, Columbus, NE) were used during one lactation period. Treatments consisted of a negative control (without liquid) or a treatment with liquid, in which approximately 3 fluid ounces of liquid sensory attractant per day, divided into 2 applications (AM and PM), were sprayed on the underline of sows for 2 d beginning the morning after farrowing. Treatment application was later resumed for 2 d prior to weaning. In total, pigs received liquid sensory attractant for 4 d pre-weaning. For the post-weaning portion of the experiment, a total of 355 pigs were weaned and used in a 24-d growth trial with 5 or 6 pigs per pen and 15 replicates per liquid attractant treatment. Treatments were arranged in a 2 × 2 × 2 factorial with main effects of pre-weaning treatment (without or with liquid); post-weaning treatment (without or with liquid); and BW category (light or heavy). Pens of pigs assigned to the liquid attractant treatment group were offered approximately 2 fluid ounces of liquid per day, divided into 3 applications (7:00, 12:00, and 17:00), sprayed on the feed. Treatment application continued for 3 d post-weaning.

[2]No 3-way interactions between pre- and post-weaning treatment and BW category were observed for growth performance after weaning ($P > 0.10$). Likewise, no post-weaning treatment × BW category interactions were observed ($P > 0.10$). For ease of interpretation, only the significant response variables are shown for the interactions between pre-weaning treatment × BW category

Table 3-6. Main effect of pre-weaning sensory attractant liquid, post-weaning sensory attractant liquid, and body weight category on the growth performance of nursery pigs, Exp. 3.[1]

	Pre-wean liquid				Post-wean liquid				BW category			
Item	Without	With	SEM	*P* =	Without	With	SEM	*P* =	Light	Heavy	SEM	*P* =
Pre-wean BW, kg												
24-h birth	1.4	1.6	0.05	0.026								
Weaning	5.8	6.0	0.18	0.559								
Total gain, g	4,423	4,403	164.6	0.934								
Average litter size, n	15.4	13.8	0.75	0.151								
Post-wean BW, kg												
d 0	5.8	5.9	0.02	< 0.001	5.9	5.9	0.02	0.141	4.9	6.9	0.02	< 0.001
d 3	5.8	5.9	0.05	0.122	5.8	5.9	0.05	0.126	4.9	6.8	0.05	< 0.001
d 7	6.3	6.3	0.06	0.419	6.3	6.3	0.06	0.493	5.3	7.3	0.06	< 0.001
d 14	7.7	7.8	0.07	0.189	7.7	7.8	0.07	0.549	6.6	8.9	0.07	< 0.001
d 24	11.8	12.0	0.12	0.213	11.9	11.9	0.12	0.992	10.4	13.4	0.12	< 0.001
Pigs that lost BW after weaning, %[2]												
d 3	41.0	41.5	3.91	0.928	45.1	37.6	3.97	0.173	33.9	49.1	3.83	0.007
d 7	9.4	16.3	2.89	0.075	12.2	12.6	2.81	0.909	9.1	16.7	2.87	0.051
d 0 to 7												
ADG, g	62	54	7.6	0.493	58	58	7.6	0.998	63	53	7.6	0.342
ADFI, g	160	151	6.6	0.349	152	159	6.6	0.479	146	165	6.6	0.050
G:F, g/kg	375	305	46.1	0.286	343	338	46.1	0.939	392	289	46.1	0.119
d 7 to 14												
ADG, g	197	206	6.0	0.287	199	203	6.0	0.666	175	228	6.0	< 0.001
ADFI, g	253	245	6.7	0.363	247	251	6.7	0.724	226	272	6.7	< 0.001
G:F, g/kg	783	845	24.1	0.076	809	819	24.1	0.772	784	844	24.1	0.084
d 14 to 24												
ADG, g	412	420	7.2	0.448	419	413	7.2	0.538	377	455	7.2	< 0.001
ADFI, g	574	586	8.6	0.330	580	579	8.6	0.948	524	635	8.6	< 0.001
G:F, g/kg	718	716	6.3	0.820	723	712	6.3	0.231	719	716	6.3	0.789
d 0 to 24												
ADG, g	246	250	4.7	0.622	249	248	4.7	0.882	225	271	4.7	< 0.001

ADFI, g	359	358	5.7	0.946	357	360	5.7	0.677	325	392	5.7	< 0.001
G:F, g/kg	687	695	7.0	0.422	696	687	7.0	0.389	691	691	7.0	0.993

[1]For the pre-weaning portion of the experiment, a total of 28 litters (241 × 600, DNA, Columbus, NE) were used during one lactation period. Treatments consisted of a negative control (without liquid) or a treatment with liquid, in which approximately 3 fluid ounces of liquid sensory attractant per day, divided into 2 applications (AM and PM), were sprayed on the underline of sows for 2 d beginning the morning after farrowing. Treatment application was later resumed for 2 d prior to weaning. In total, pigs received liquid sensory attractant for 4 d pre-weaning. For the post-weaning portion of the experiment, a total of 355 pigs were weaned and used in a 24-d growth trial with 5 or 6 pigs per pen and 15 replicates per liquid attractant treatment. Treatments were arranged in a 2 × 2 × 2 factorial with main effects of pre-weaning treatment (without or with liquid); post-weaning treatment (without or with liquid); and BW category (light or heavy). Pens of pigs assigned to the liquid attractant treatment group were offered approximately 2 fluid ounces of liquid per day, divided into 3 applications (7:00, 12:00, and 17:00), sprayed on the feed. Treatment application continued for 3-d post-weaning.

[2] Represents the percentage of pigs that were still below weaning weight 3 or 7 d post-weaning.

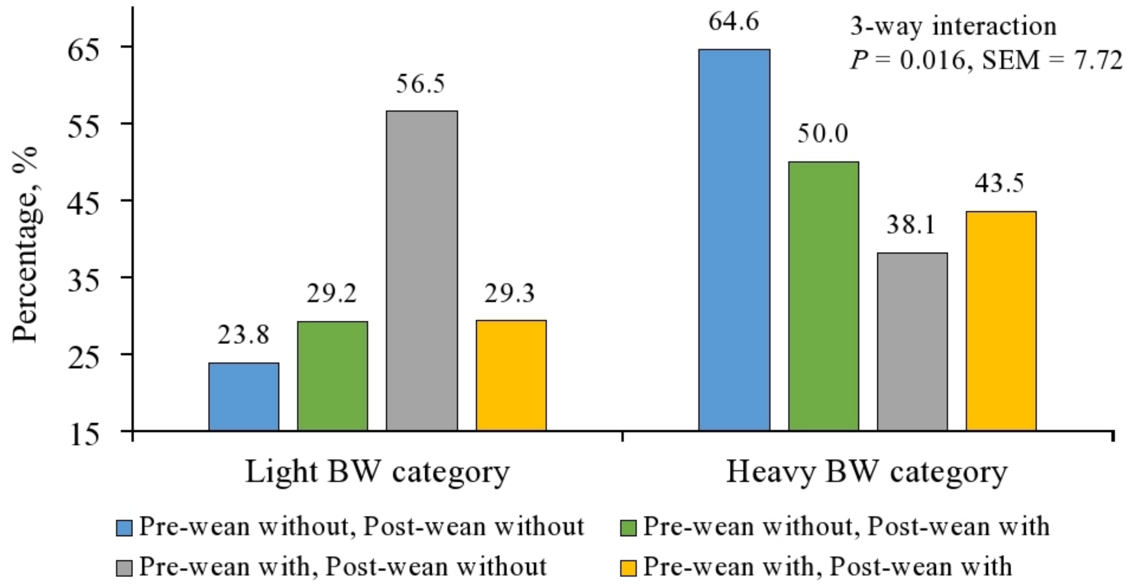

Figure 3-3. Body weight category × pre-weaning sensory liquid × post-weaning sensory liquid interaction on the percentage of pigs that lost weight from weaning to d 3. No 3-way interaction from weaning to d 7 was observed (*P* > 0.10).

Chapter 4 - Effects of mat feeding on the growth performance, removal, and mortality of pigs after weaning

Abstract

Four experiments were conducted to determine the effect of mat feeding strategy on the growth performance, removal, and mortality of pigs after weaning. In Exp. 1, 1,392 weanling pigs (initially 7.0 kg; approximately 24 d of age) were randomly allotted to 1 of 2 mat feeding treatments (mat feed vs. no mat feed). Overall, mat fed pigs had a tendency for improved ADG (P = 0.065) and G:F (P = 0.060) compared to pigs not offered mat feed. Mat fed pigs had fewer removals (P = 0.013) compared to pigs not offered mat feed. In Exp. 2, 2,912 weanling pigs (initially 5.5 kg; approximately 21 d of age) were randomly allotted to 1 of 2 mat feeding treatments (mat feed vs. no mat feed). Overall, no differences in growth performance were observed. However, mat fed pigs had decreased (P = 0.026) final body weights compared to pigs not offered mat feed. This may be related to removal rates as mat fed pigs had fewer removals (P = 0.026). In Exp. 3, 3,264 weanling pigs (initially 5.5 kg; approximately 21 d of age) were randomly allotted to 1 of 4 treatments in a 2 × 2 factorial with main effects of diet form (pellet or crumble) and mat feeding (mat feed vs. no mat feed). No interactions between diet form and mat feeding were observed. No differences were observed in overall growth performance for the main effect of mat feeding. Pigs offered pelleted feed had decreased overall ADFI (feed disappearance from the feeder and feed placed on the mat; P = 0.013) and improved G:F (P < 0.001) compared to pigs offered crumble feed. No differences were observed in removals or mortalities for the main effect of mat feeding or diet form. In Exp. 4, 3,227 weanling pigs (initially 5.1 kg; approximately 21 d of age) were randomly allotted to 1 of 3 treatments consisting of mat feeding small (3.2 mm) pellets, mat feeding large (12.7 mm) pellets, or no mat

feeding. Overall, no differences were observed in ADG or G:F. Mat fed pigs had increased ADFI ($P < 0.001$) compared to pigs not offered mat feed. Given the shorter duration of this experiment, the extra feed provided with mat feeding had a greater impact on overall feed usage than Exp. 1, 2, and 3. No differences were observed in removals or mortalities. When combining the removal and mortality data for the four experiments, mat fed pigs had fewer removals ($P = 0.002$) compared to pigs not offered mat feed. In summary, mat feeding may encourage earlier feeding behavior, therefore reducing the removal rate of pigs post-weaning.

Introduction

Prior to domestication, weaning was a slow process in which young pigs develop new feeding behaviors as they transition from an all milk-based diet to solid feed (Brooks and Tsourgiannis, 2003). The development of these new feeding behaviors over time corresponds with gastrointestinal, immune, and nervous system maturation (Moeser et al., 2017). Consequently, in modern commercial production, weaning is a single, abrupt event marked by a multitude of external and internal stressors. For newly weaned pigs, this can result in low feed intake and body weight gain immediately post-weaning (Bruininx et al., 2001), which can have significant effects on the pig's health status and gastrointestinal system development (Moeser et al., 2017). Therefore, management strategies have become increasingly important to elicit the natural feeding behavior of pigs at weaning. Mat feeding is a strategy in which a small amount of feed is applied onto the floor mats of nursery or wean-to-finish pens immediately after weaning. This feeding strategy is commonly practiced to introduce newly weaned pigs to solid feed by increasing feed accessibility. Similar to suckling, it has also been suggested that mat feeding may help stimulate group feeding behavior, therefore encouraging earlier feed intake after weaning and leading to reduced removal and mortality rates. However, limited research data are available to validate mat feeding protocols and understand their potential benefits. Therefore, the objective of these experiments was to determine the effect of different mat feeding strategies on the growth performance, removal, and mortality of pigs post-weaning.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments. Experiment 1 was conducted in October at a commercial research facility in northeast Kansas. Each pen (3.0 × 5.5 m) was equipped with a single-sided dry, 3-hole, stainless steel feeder, and a dual swinging waterer to allow for *ad libitum* access to feed and water. Likewise, each pen was equipped with a brooder to provide supplemental heat post-weaning. Experiments 2, 3, and 4 were conducted from October to May at a commercial research facility in southeast Minnesota. Each pen (1.8 × 3.4 m) was equipped with a 5-hole stainless steel feeder and cup waterer to allow for *ad libitum* access to feed and water. No supplemental heat post-weaning was provided. Both sites used an automated feeding system (FeedPro; Feedlogic Corp., Willmar, MN) to measure and record daily feed additions to individual pens.

Experiment 1

A total of 1,392 weanling pigs (PIC, Hendersonville, TN; initially 7.0 kg) were used in a 27-d experiment. All pigs were weaned at approximately 24 d of age and transported 1 h to the nursery facility. Upon arrival, pigs were randomized to pens based on sex and then weighed. Pens of pigs were blocked by source farm with each block consisting of 2 barrow and 2 gilt pens, and then randomly allotted to 1 of 2 mat feeding treatments (mat feeding vs. no mat feeding). There were 58 pigs per pen and 12 replications per treatment. Pens of pigs assigned to the mat feeding treatment group were provided approximately 500 g of pelleted feed, three times daily for 6 d post-placement (except for 1 pen which was fed on the mat for only 5 d before the mat disintegrated), for a total of 9.0 kg of feed per pen (155 g per pig). Mat feed was removed from the back of feeders in pens assigned to the mat feeding treatment group and spread across a 1.2 × 2.4 m biodegradable mat.

All pigs were provided the same diets which were fed in 3 different phases (Menegat et al., 2019) according to standard farm protocol. The phase 1 diet was provided at 1.36 kg per head and contained corn, soybean meal, and specialty protein and lactose sources such as spray dried animal plasma, dried whey, and fish meal. The phase 2 diet was provided at 5.90 kg per head, and it contained lower levels of dried whey and fish meal than the phase 1 diet. The phase 3 diet was corn and soybean meal-based and contained no specialty protein or lactose sources. It was formulated for an average pig weight range of 11.3 to 22.7 kg and was fed until the end of the experiment. Phase 1 diets were in pellet form and phase 2 and 3 diets were in meal form.

Pens of pigs were weighed and feed disappearance measured on d 11 and 27 post-weaning to determine ADG, ADFI, and G:F. Average daily feed intake represents feed disappearance from the feeder and feed placed on the mat for mat feeding. Removals and mortalities were recorded throughout the trial; however, mortality was not tracked on pigs after they were removed from the study. Pigs were removed based on animal caretaker discretion for welfare considerations (lameness, sick, or unthrifty) during daily observations

Experiment 2

A total of 2,912 pigs [PIC sow × Duroc sire (PIC 800 or DNA 600), initially 5.5 kg], were used in a 37-d growth trial. All pigs were weaned at approximately 21 d of age and transported 2.5 hours to the nursery facility. Upon arrival to the nursery, pigs were randomized to one of 96 pens (48 feeders). There was one pen of barrows and one pen of gilts per feeder. Thus, feeder (2 pens) was the experimental unit. Feeders were then blocked by group (date of placement) and randomly allotted to 1 of 2 treatments with 60 to 64 pigs per feeder and 24 feeders per treatment. Treatments consisted of mat feeding vs. no mat feeding. Pens of pigs assigned to the mat feeding treatment group were provided one scoop of feed three times daily for 10 d post-placement. Mat feed was provided from a cart (not from the feeder) and the amount of feed applied was used to calculate total feed disappearance. Approximately 318 g of pelleted feed was provided at each feeding, totaling 9.5 kg of feed per feeder (divided amongst 2 pens; 148 to 158 g per pig). A single piece of Dura-Tuff solid flooring (46 × 61 cm; Southwest Agri-Plastics, Inc., Addison, TX) was installed directly into the plastic floor of nursery pens and used as the mat for mat feeding in this experiment.

Like Exp. 1, nursery diets were fed in 3 different phases (Menegat et al., 2019) according to standard farm protocol. The phase 1 diet was provided at 1.8 kg per head and contained spray dried whey and enzymatically treated soybean meal. The phase 2 diet was provided at 5.4 kg per head and phase 3 was provided at 15.9 kg per head. Phase 1 diets were in pellet form and phase 2 and 3 diets were in meal form.

Pens of pigs were weighed and feed disappearance measured every 7 to 14 d to determine ADG, ADFI, and G:F. Like Exp. 1, ADFI represents feed disappearance from the feeder and feed placed on the mat for mat feeding. Removals and mortalities were recorded throughout the trial; however, mortality was not tracked on pigs after they were removed from the study. Pigs were removed based on animal caretaker discretion for welfare considerations (lameness, sick, or unthrifty) during daily observations.

Experiment 3

A total of 3,264 pigs (initially 5.5 kg) were used in a 37-d growth trial. The same genetic composition, weaning age, transportation duration, and allotment procedures were used as in Exp. 2. Treatment structure differed such that feeders were randomly allotted to 1 of 4 treatments with 68 pigs per feeder and 12 feeders per treatment. Treatments were arranged in a 2 × 2 factorial with main effects of diet form [pellet (3.2 mm) or crumble] and mat feeding (mat feeding vs. no mat feeding). Crumble diets were manufactured by processing the pelleted diet through a roller mill, which creates a mixture of mash and smaller pellets compared with strictly pelleted diets (Turner, 2014). Pens of pigs assigned to the mat feeding treatment group were provided one scoop of feed three times daily for 10 d post-placement. Like Exp. 2, mat feed was provided from a cart (not from the feeder) and used to calculate total feed disappearance. An equal volume of pelleted and crumble feed was mat fed rather than an equal weight, resulting in approximately 318 g of pelleted or 372 g of crumble feed provided at each feeding, totaling 9.5 or 11.2 kg of feed per feeder (divided amongst 2 pens; 140 or 165 g per pig). A single piece of Dura-Tuff solid flooring (46 × 61 cm; Southwest Agri-Plastics, Inc., Addison, TX) was installed directly into the plastic floor of nursery pens and used as the mat for mat feeding in this experiment.

Diet composition and feed budgets were the same as in Exp. 2. Diet form for phase 1 and 2 was based on pen treatment assignment where phase 1 diets were either in pellet or crumble form, phase 2 diets were either in meal or crumble form, and phase 3 diets were in meal form. Diet composition was the same regardless of feed form, and data were collected in a similar fashion to Exp. 2.

Experiment 4

A total of 3,227 pigs (initially 5.1 kg) were used in a 14-d growth trial. The same genetic composition, weaning age, transportation duration, and allotment procedures were used as in Exp. 2. Treatment structure differed such that feeders were randomly allotted to 1 of 3 treatments with 63 to 70 pigs per feeder and 16 feeders per treatment. Treatments consisted of mat feeding small (3.2 mm) pellets, mat feeding large (12.7 mm) pellets, or no mat feeding. Pens of pigs assigned to the mat feeding treatment group were provided two scoops of feed three times daily for 10 d post-placement. Like Exp. 2, mat feed was provided from a cart (not from the feeder) and used to calculate total feed disappearance. Approximately 726 g of pelleted feed was provided at each feeding, totaling 21.8 kg of feed per feeder (divided amongst 2 pens; 311 to 346 g per pig). Two pieces of Dura-Tuff solid flooring (92 × 122 cm; Southwest Agri-Plastics, Inc., Addison, TX) were installed directly into the plastic floor of nursery pens. Providing mat feed on two pieces of solid flooring rather than one, as in the previous experiments, created a greater surface area for increased feed allowance.

Diet composition and feed budgets were the same as in Exp. 2; however, only phase 1 diets in pellet form were fed because the trial ended on d 14 due to an outbreak of porcine respiratory and reproductive syndrome virus. Diet composition was the same regardless of pellet size, and data were collected in a similar fashion to Exp. 2.

Data analysis

All data were analyzed on a closeout basis, such that pig removal weights were not used in the calculation for ADG but days prior to removal (pig days) were [(ending pen weight – starting pen weight) ÷ pig days]. Thus, removals and mortalities were assumed to be dependent on treatment.

For each experiment, data were analyzed as a randomized complete block design using the GLIMMIX procedure of SAS version 9.4 (SAS Institute, Inc., Cary, NC) with pen (Exp. 1) or feeder (Exp. 2, 3, and 4) as the experimental unit and treatment as a fixed effect. In Exp. 1, source farm was considered a random effect. In Exp. 2, 3, and 4, pig group (date of placement) was considered a random effect. A binomial model was used to determine removal and mortality rates for each experiment. Following individual analysis, data from all four experiments were combined and a binomial model was used to determine the overall effect of mat feeding on nursery pig removal and mortality rates. For the combined data, the main effect of mat feeding was used as a fixed effect and experiment as a random effect. All results were considered significant at $P \leq 0.05$ and a tendency at $0.05 \leq P \leq 0.10$.

Results

Experiment 1

From d 0 to 11 post-weaning, no differences ($P > 0.10$) in ADG, ADFI, or G:F (Table 1) were observed for the effect of mat feeding. Likewise, no differences in ADG or ADFI were observed from d 11 to 27; however, a tendency for improved G:F ($P = 0.084$) was observed for pigs that received mat feed compared to pigs that did not receive mat feed. Overall (d 0 to 27), mat fed pigs had a tendency for improved ADG ($P = 0.065$) and G:F ($P = 0.060$) compared to those not offered mat feed. No differences ($P > 0.10$) in ADFI were observed. Mat fed pigs had fewer removals ($P = 0.013$) compared to pigs not offered mat feed, but no differences ($P > 0.10$) in mortality were observed.

Experiment 2

From d 0 to 10 post-weaning, no differences ($P > 0.10$) were observed in ADG or G:F (Table 2); however, mat fed pigs had increased ADFI ($P < 0.001$) compared to pigs that did not receive mat feed. These results are likely in response to mat feed wastage. In contrast, from d 10 to 17, mat fed pigs had decreased ADFI (P = 0.010) and improved G:F (P = 0.048) compared to pigs not offered mat feed, with no differences (P > 0.10) in ADG. From d 17 to 39, mat fed pigs had decreased ADG (P = 0.002) and ADFI (P = 0.028) compared to pigs not offered mat feed, with no differences (P > 0.10) in G:F. Overall (d 0 to 39), no differences (P > 0.10) in growth performance were observed. However, mat fed pigs had decreased final body weights (P < 0.026) compared to pigs not offered mat feed, which may be related to removal rates. Mat fed pigs had fewer removals (P = 0.026) compared to pigs not offered mat feed, suggesting a greater percentage of light weight pigs remained on the mat-fed treatment. No differences (P > 0.10) in mortality were observed.

Experiment 3

No significant interactions (P > 0.10) between diet form and mat feeding were observed; hence, only the main effects are provided in Table 3. From d 0 to 7 post-weaning, for the main effect of mat feeding, no differences (P > 0.10) were observed in ADG or G:F. However, mat fed pigs had increased ADFI (P = 0.010) compared to pigs that did not receive mat feed. From d 7 to 14, mat fed pigs had a tendency for improved ADG (P = 0.097) compared to pigs not offered mat feed, but no differences (P > 0.10) in ADFI or G:F were observed. A significant response was observed in ADG (P = 0.020) from d 14 to 21, with mat fed pigs having decreased gain compared to pigs not offered mat feed. No differences (P > 0.10) in ADFI were observed, thus a tendency for poorer G:F (P = 0.068) was observed for mat fed pigs. From d 21 to 28, no differences (P > 0.10) in ADG or ADFI were observed; however, mat fed pigs had improved G:F (P = 0.005) compared to pigs not offered mat feed. From d 28 to 35, mat fed pigs had decreased ADG (P = 0.049) compared to pigs not offered mat feed, with no differences (P > 0.10) observed in ADFI or G:F. Overall (d 0 to 35), no differences ($P > 0.10$) were observed in growth performance for the main effect of mat feeding. Although not statistically significant, a numeric difference was observed for total removals and mortalities, with mat fed pigs having 0.5 percentage points fewer removals and mortalities compared to pigs not offered mat feed.

From d 0 to 7, for the main effect of diet form, pigs that received pelleted feed had improved ADG ($P = 0.001$) and G:F ($P = 0.007$) compared to pigs that received crumble feed, with no differences ($P > 0.10$) observed in ADFI. From d 7 to 14, pigs that received pelleted feed had improved ADG ($P = 0.033$) and G:F ($P < 0.001$). This was driven by decreased ADFI ($P < 0.001$) compared to pigs that received crumble feed. From d 14 to 21, no differences ($P > 0.10$) in ADG were observed; however, pigs that received pelleted feed had decreased ADFI ($P < 0.001$) and improved G:F ($P < 0.001$) compared to pigs that received crumble feed. From d 21 to 35, no differences ($P > 0.10$) in growth performance were observed. Overall (d 0 to 35), no differences ($P > 0.10$) in ADG were observed for the main effect of diet form. However, pigs that received pelleted feed in the first two phases had decreased overall ADFI ($P = 0.013$) and improved G:F ($P < 0.001$) compared to pigs that received crumble feed. No differences ($P > 0.10$) were observed in removals or mortalities.

Experiment 4

From d 0 to 7 post-weaning, ADG and G:F were negative for all treatments (Table 4). Because data were analyzed on a closeout basis, poor performance in the first period was driven by high removal rates that mat feeding and pellet size were not able to overcome. Despite no differences ($P > 0.10$) in ADG and G:F, mat fed pigs, regardless of pellet size, had improved ADFI ($P < 0.001$) in the first period compared to pigs not offered mat feed. This response is likely a result of mat feed wastage, rather than improved feed intake. From d 7 to 14, mat fed pigs continued to have increased ADFI ($P < 0.020$) compared to pigs not offered mat feed. Mat fed pigs also had a tendency for improved ADG ($P = 0.085$). No differences ($P > 0.10$) were observed in G:F. Overall (d 0 to 14), no differences ($P > 0.10$) were observed in ADG or G:F. However, mat fed pigs had increased ADFI ($P < 0.001$), regardless of pellet size, compared to pigs not offered mat feed. Given the shorter duration of this experiment, the extra feed provided with mat feeding had a greater impact on overall feed usage than was found in Exp. 1, 2, and 3. Although not statistically significant ($P > 0.10$), numeric differences were observed in the total removals and mortalities for mat fed pigs compared to those not offered mat feed. Mat feeding small pellets numerically reduced the total removal rate by 2.1 percentage points compared to pigs that did not receive mat feed and 1.2 percentage points compared to mat feeding large pellets.

Experiment 1, 2, 3, and 4

When combining the removal and mortality data for the four experiments, mat fed pigs had fewer removals ($P = 0.002$) compared to pigs that did not receive mat feed (Table 5). No evidence for differences ($P = 0.50$) in mortality were observed.

Discussion

The combination of stressors that occur at weaning often result in compromised intestinal structure and function (Kelly et al., 1991; McCracken et al., 1999; Moeser et al., 2006; Wijtten et al., 2011; Moeser, 2017), which has been shown to suppress the pigs innate immune system (McLamb et al., 2013). Data by Pohl et al. (2017) have also shown that intestinal barrier defects and alterations in immune activity because of weaning can persist into later life. In practice, this may lead to poorer lifetime performance. However, research is needed to understand the potential growth implications of stress post-weaning. Furthermore, chronic or re-occurring stressors have also been linked to a hyperactive gut-brain axis in humans (Kelly et al., 2015), resulting in increased anxiety. If applicable to pigs, this could potentially influence or further delay the pigs' decision to search out and begin consuming feed after weaning, particularly if they have not previously been exposed to solid feed.

Short-term feed deprivation (24 to 72 h) has been shown to alter the endocrine response of weanling pigs, affecting their ability to regulate neuroendocrine hormones associated with feed intake homeostasis (Salfen et al., 2003). While the eating activity of newly weaned pigs increases over the first 3 d post-weaning (Corrigan, 2000), intake in the first 24-h is often less than 100 g (Bruininx et al., 2001). Consequently, there remains a portion of pigs that do not consume feed until 40-h post-weaning (Bruininx et al., 2001). Hence, strategies to minimize stress and improve feed intake after weaning have become increasingly important. Among the available strategies commonly used, mat feeding is thought to stimulate the development of natural feeding behaviors, such as foraging, leading to greater feed consumption.

Mat feeding has been shown to increase the eating behavior of pigs in the first 24-h after weaning (Corrigan, 2000). This may explain the decreased removal rates observed in the experiments reported herein. In agreement, Corrigan et al. (2000) also showed that mat feeding (supplemented feed placed on mat and in feed trough) for 4 d post-weaning decreased morbidity over the first 3 weeks after weaning compared to trough feeding (supplemented feed placed in feed trough only). However, mat fed pigs spent more time eating at the mat and less time eating at the feeder compared to pigs that were not provided mat feed (Corrigan et al., 2000). It may be possible that mat feeding for extended durations (> 3 d) distracts pigs from consuming feed at the feeder. Nonetheless, the 4 to 10 d difference in mat feeding durations between the experiments reported herein and by Corrigan et al. (2000), consistently resulted in decreased removal rates.

Furthermore, with no peer reviewed data available on different mat feeding durations, the optimal duration in which mat feed should be provided cannot be concluded. However, mat feeding for more days will likely increase feed wastage, thus duration should be considered in future experiments.

Similar to the results herein, previous reports by Corrigan et al. (2000) showed that mat feeding had no effect on the ADG of nursery pigs, regardless if gruel or dry pellets were used as the source of mat feed. Corrigan et al. (2000) also observed increased feed disappearance, which commonly resulted in poorer feed efficiency. Hence, the results of these studies indicate that the value of mat feeding is not in improved growth performance, but rather in reduced removal and mortality rates. This response may be less related to mat feeding and more closely related to caretaker activity in the pen. In the process of mat feeding, animal caretakers enter pens and interact with pigs' multiple times a day, therefore, encouraging pigs to get up more frequently.

Although there are limited published data on the effect of crumble diets in pigs post-weaning, the improved feed efficiency observed in Exp. 3 when pigs were provided pelleted diets agrees with previous literature (De Jong et al., 2014; Nemechek et al., 2015; Ulens et al., 2015). Crumble diets are typically manufactured by crumbling pelleted diets, which has the potential to create a disproportionate blend of pellets and mash, therefore making it easier for pigs to sort through the diet. This may explain the poorer feed efficiency response observed in pigs fed crumble diets compared to pellets. Data on pellet quality indicates that minimizing the percentage of fines in pelleted diets is necessary to achieve improved feed efficiency (Nemechek et al., 2015). In addition to diet form and pellet quality, research shows that young pigs prefer pellets with a larger diameter (12 mm) compared to smaller pellets (2 mm; van den Brand et al., 2014). However, it appears that improvements in ADG and feed intake post-weaning are observed only when pigs are exposed to large, pelleted creep feed prior to weaning, rather than post-weaning (van den Brand et al., 2014; Craig et al., 2021). This is likely a result of increased creep feed intake pre-weaning. This also may explain why there was no response to pellet size in Exp. 4, indicating that pellet size is more crucial when creep feeding rather than in nursery starter diets.

In summary, mat feeding had limited effects on the growth performance of pigs; however, mat feeding strategies may encourage natural feeding behaviors, therefore eliciting early feed intake and reducing the removal rate of pigs post-weaning. It is important to note that mat feeding will likely increase feed wastage so care should be taken to determine the appropriate duration of mat feeding and should largely be driven by pig need (i.e. age and health status). Lastly, the results of Exp. 3 indicate that pelleted feed helps improve the feed efficiency of weanling pigs compared to crumble feed. However, it appears that both feed forms can be mat fed and have the same outcome on pig removal and mortality rates.

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Table 4-1. Effect of mat feeding on the growth performance, removal, and mortality of pigs after weaning (Exp. 1)[1]

	Mat feeding[2]			
	No	Yes	SEM	*P* =
Body weight, kg				
d 0	7.0	7.0	0.12	0.846
d 11	9.0	8.9	0.18	0.574
d 27	15.7	15.7	0.23	0.986
d 0 to 11				
ADG, g	114	136	11.4	0.145
ADFI, g[3]	208	211	7.9	0.641
G:F, g/kg	545	641	46.4	0.161
d 11 to 27				
ADG, g	410	418	5.7	0.264
ADFI, g	563	552	10.6	0.477
G:F, g/kg	730	758	11.1	0.084
d 0 to 27				
ADG, g	284	301	7.4	0.065
ADFI, g	413	410	8.5	0.801
G:F, g/kg	691	733	15.1	0.060
Removals, %	9.1	5.3	1.20	0.013
Mortality, %	0.3	0.5	0.29	0.654
Total, %[4]	9.5	5.9	1.20	0.023

[1] A total of 1,392 mixed sex pigs were used with 58 pigs per pen and 12 replicates per treatment.

[2] Treatment consisted of mat feeding vs. no mat feeding. Pens of pigs assigned to the mat feeding group were provided a scoop of feed from the back of the feeder (500 g) on a biodegradable mat three times daily for 6 d post-placement.

[3] Average daily feed intake represents feed disappearance from the feeder and feed placed on the mat for mat feeding. A total of 1,500 g of pelleted feed was applied to mat fed pens daily.

[4] Total = Removals + mortality.

Table 4-2. Effect of mat feeding on the growth performance, removal, and mortality of pigs after weaning (Exp. 2)[1]

	Mat feeding[2]			
	No	Yes	SEM	*P* =
Body weight, kg				
d 0	5.5	5.5	0.30	0.795
d 10	7.3	7.3	0.44	0.476
d 17	9.6	9.4	0.55	0.107
d 39	19.6	19.2	0.84	0.026
d 0 to 10				
ADG, g	139	144	19.0	0.442
ADFI, g[3]	168	181	8.9	< 0.001
G:F, g/kg	812	790	87.4	0.492
d 10 to 17				
ADG, g	296	296	20.7	0.999
ADFI, g	455	434	12.5	0.010
G:F, g/kg	649	681	32.8	0.048
d 17 to 39				
ADG, g	468	457	14.3	0.002
ADFI, g	717	700	52.0	0.028
G:F, g/kg	661	661	36.1	0.999
d 0 to 39				
ADG, g	344	341	15.5	0.433
ADFI, g[3]	515	508	33.2	0.161
G:F, g/kg	672	676	29.4	0.456
Removals, %	5.6	3.8	1.93	0.026
Mortality, %	1.1	0.8	0.27	0.588
Total, %[4]	6.7	4.7	2.12	0.019

[1] A total of 2,912 mixed sex pigs were used with 60 to 64 pigs per feeder (2 pens) and 24 replicates per treatment.

[2] Treatment consisted of mat feeding vs. no mat feeding. Pens of pigs assigned to the mat feeding group were provided a scoop of feed from a feed cart (318 g) on a single 46 × 61 cm piece of DuraTuff solid flooring three times daily for 10 d post-placement.

[3] Average daily feed intake represents feed disappearance from the feeder and feed placed on the mat for mat feeding. A total of 954 g of pelleted feed was applied to mat fed pens daily.

[4] Total = Removals + mortality.

Table 4-3. Main effect of diet form and mat feeding on the growth performance, removal, and mortality of pigs after weaning (Exp. 3)[1]

	Diet form				Mat feeding			
Item	Pellet	Crumble	SEM	*P* =	No	Yes	SEM	*P* =
Body weight, kg								
d 0	5.5	5.5	0.05	0.968	5.5	5.5	0.05	0.905
d 7	6.3	6.1	0.22	0.004	6.2	6.2	0.22	0.703
d 14	8.3	8.0	0.11	< 0.001	8.1	8.2	0.11	0.648
d 21	10.5	10.2	0.20	< 0.001	10.4	10.4	0.20	0.746
d 28	13.4	13.1	0.26	0.004	13.2	13.3	0.26	0.704
d 35	17.1	17.0	0.46	0.157	17.1	17.0	0.46	0.871
d 0 to 7								
ADG, g	107	82	21.4	0.001	92	97	21.4	0.473
ADFI, g[3]	111	104	15.0	0.107	102	113	15.0	0.010
G:F, g/kg	960	753	124.0	0.007	865	848	124.0	0.819
d 7 to 14								
ADG, g	232	217	6.9	0.033	219	230	6.9	0.097
ADFI, g[3]	349	367	8.2	< 0.001	355	361	8.2	0.190
G:F, g/kg	665	593	12.1	< 0.001	618	639	12.1	0.228
d 14 to 21								
ADG, g	309	310	10.0	0.876	316	304	10.0	0.020
ADFI, g	454	477	13.5	< 0.001	469	462	13.5	0.227
G:F, g/kg	682	650	14.5	< 0.001	674	659	14.5	0.068
d 21 to 28								
ADG, g	401	403	28.5	0.809	397	407	28.5	0.153
ADFI, g	588	596	19.2	0.272	596	588	19.2	0.272
G:F, g/kg	682	676	33.9	0.490	665	692	33.9	0.005
d 28 to 35								
ADG, g	526	537	39.3	0.173	540	523	39.3	0.049

ADFI, g	780	794	39.5	0.162	792	783	39.5	0.332
G:F, g/kg	672	676	27.0	0.713	681	667	27.0	0.162
d 0 to 35								
ADG, g	311	306	15.1	0.121	309	309	15.1	0.983
ADFI, g[3]	450	461	18.7	0.013	456	456	18.7	0.855
G:F, g/kg	691	663	8.8	< 0.001	676	678	8.8	0.787
Removals, %	6.7	7.1	1.46	0.627	7.2	6.6	1.47	0.527
Mortality, %	0.7	0.5	0.22	0.468	0.5	0.6	0.21	0.731
Total, %[4]	7.4	7.7	1.34	0.774	7.8	7.3	1.35	0.571

[1] A total of 3,264 mixed sex pigs were used with 68 pigs per feeder (2 pens) and 12 replicates per treatment.

[2] Treatment consisted of a 2 × 2 factorial design with main effect of diet forms (pellet vs. crumble) and mat feeding (mat feeding vs. no mat feeding). Pens of pigs assigned to the mat feeding group were provided a scoop of feed from a feed cart (318 g pellet or 372 g crumble) on a single 46 × 61 cm piece of DuraTuff solid flooring three times daily for 10 d post-placement.

[3] Average daily feed intake represents feed disappearance from the feeder and feed placed on the mat for mat feeding. A total of 954 g of pelleted feed or 1,116 g of crumble feed was applied to mat fed pens daily.

[4] Total = Removals + mortality.

Table 4-4. Effect of mat feeding and pellet size on the growth performance, removal, and mortality of pigs after weaning (Exp. 4)[1]

		Mat feeding[2]			
	Control	3.2 mm pellet	12.7 mm pellet	SEM	*P* =
Body weight, kg					
d 0	5.1	5.2	5.1	0.09	0.822
d 7	5.5	5.5	5.5	0.14	0.623
d 14	6.8	7.0	6.9	0.26	0.313
d 0 to 7					
ADG, g	-9.5	-7.4	-6.7	17.44	0.950
ADFI, g[3]	85[b]	117[a]	121[a]	7.3	< 0.001
G:F, g/kg	-154	-88	-86	182.7	0.736
d 7 to 14					
ADG, g	140	168	176	18.3	0.085
ADFI, g[3]	264[b]	287[a]	294[a]	24.5	0.022
G:F, g/kg	531	567	605	48.9	0.453
d 0 to 14					
ADG, g	58	73	75	16.7	0.186
ADFI, g[3]	166[b]	194[a]	200[a]	17.4	< 0.001
G:F, g/kg	348	354	366	70.7	0.933
Removals, %	14.1	11.8	13.1	2.22	0.267
Mortality, %	0.09	0.28	0.19	0.162	0.720
Total, %[4]	14.2	12.1	13.3	2.19	0.329

[a,b,c] Means lacking common superscript differ by $P < 0.05$.

[1] A total of 3,227 mixed sex pigs were used with 63 to 70 pigs per feeder (2 pens) and 16 replicates per treatment. Trial was cut short due to PRRS outbreak.

[2] Treatment consisted of mat feeding small (3.2 mm) pellets, mat feeding large (12.7 mm) pellets, or no mat feeding. Pens of pigs assigned to the mat feeding group were provided two scoops of feed from a feed cart (726 g) on two 46 × 61 cm pieces of DuraTuff solid flooring three times daily for 10 d post-placement.

[3] Average daily feed intake represents feed disappearance from the feeder and feed placed on the mat for mat feeding. A total of 2,178 g of pelleted feed was applied to mat fed pens daily.

[4] Total = Removals + mortality.

Table 4-5. Overall effect of mat feeding on the removal and mortality of pigs after weaning (Exp. 1 to 4 combined)[1]

	Mat feeding[2]			
	No	Yes	SEM	*P* =
Removals, %	8.6	7.0	1.83	0.002
Mortality, %	0.5	0.5	0.18	0.960
Total, %[3]	9.3	7.7	1.69	0.003

[1] A total of 10,795 mixed sex pigs were used with 58 to 70 pigs per experimental unit and 12 (Exp. 1), 24 (Exp. 2), 12 (Exp. 3), or 16 (Exp. 4) replications per treatment.

[2] In Exp. 1 and 2, treatments consisted mat feeding vs. no mat feeding. In Exp. 3, treatments were arranged in a 2 × 2 factorial with main effects of diet form (pellet or crumble) and mat feeding (mat feeding vs. no mat feeding). In Exp. 4, treatments consisted of mat feeding small (3.2 mm) pellets, mat feeding large (12.7 mm) pellets, and no mat feeding. In Exp. 1, mat feeding was provided 3 times per day for 6 d post-placement. In Exp. 2-4, mat feed was provided 3 times per day for 10 d post-placement.

[3] Total = Removals + mortality.

Chapter 5 - Effects of gruel feeding and oral dextrose on the survivability of pigs after weaning

Abstract

Two experiments were conducted in a 14,400 head nursery using 3,087 (Exp. 1) and 988 (Exp. 2) pigs to determine the effect of gruel feeding (Exp. 1) and supplemental oral dextrose (Exp. 2) on nursery pig survivability after weaning. Upon arrival to the nursery, for Exp. 1, the smallest 10% of pigs were selected and randomly placed in pens with 61 to 108 pigs per pen. Pens of small pigs were assigned to 1 of 2 treatments in a completely randomized design. Treatments consisted of gruel feeding two or four times per day for 14-d post-placement. At each gruel feeding, approximately 1.13 kg of solid feed was added to a round bowl (Rotecna S.A., Agramunt, Spain) located at the front of each pen and water added at a decreasing rate over time. In Exp. 2, every other pig removed for welfare considerations (lameness, sick, or unthrifty) from the general population or pens of small pigs received a single 10 mL oral dose of a 50% dextrose solution (Vet One, MWI Animal Health, Boise, ID), as a source of glucose, before being placed in a removal pen. All removed pigs were tagged and weighed, body temperature recorded, and blood glucose measured prior to and 30 min after entering removal pens. Overall, gruel feeding small pigs two or four times per day for 14-d post-placement did not influence ($P > 0.10$) mortality from weaning to the end of gruel feeding (3.78 vs 4.25%, respectively). Likewise, dextrose administration did not influence ($P > 0.10$) pig mortality after removal to approximately 38 d post-weaning (21.4 vs 23.4% respectively), even though blood glucose levels increased ($P < 0.001$) 30 min after removal for pigs administered dextrose. An interaction was observed for blood glucose and body temperature ($P < 0.001$) where pigs with blood glucose less than 70 mg/dL had increased mortality as body temperature increased. In contrast, pigs with a blood

glucose of 70 mg/dL or greater had decreased mortality as body temperature increased. Pigs weighing less than 4.5 kg also had increased mortality ($P < 0.001$) compared to pigs weighing greater than or equal to 4.5 kg at removal. In summary, gruel feeding four times per day vs two times per day or providing a dextrose supplement to pigs removed from the general population did not improve the survivability of pigs after weaning. Additionally, pigs removed with low bodyweight or with body temperature or blood glucose below or above the normal range had decreased survivability.

Introduction

Pigs reared in modern production systems have limited opportunity to develop natural feeding behaviors that improve the transition from an all milk-based diet to solid feed. Post-weaning, this can lead to feed neophobia resulting in low feed intake and reduced body weight gain (Brooks and Tsourgiannis, 2003). The process of weaning also presents multiple concurrent stressors that lead to a heightened “state of threatened homeostasis” (Nirupama et al., 2018), activating the hypothalamic pituitary adrenal axis. Research in both humans and pigs has shown that activation of the central stress response system can have detrimental effects on intestinal barrier integrity, immune function, and neurodevelopment (McCracken et al., 1999; Hart and Kamm, 2002; Moeser et al., 2007; Kelly et al., 2015), all of which can suppress feed intake, nutrient utilization, and the pigs’ ability to fight pathogens (Pelleymounter et al., 2000; Salfen et al., 2003; McLamb et al., 2013; Li et al., 2017). It is also well established that stress and feed deprivation alter glucose metabolism (Berg et al., 2002; Nirupama et al., 2018).

To minimize weaning stress, the implementation of on-farm feed management strategies has become increasingly important. Gruel feeding is a strategy commonly used where solid feed and water are combined to create a liquid feed, which is added to troughs or bowls located in nursery or wean-to-finish pens. Like suckling, it is believed that gruel feeding may help stimulate group feeding behavior, particularly in populations of small or unthrifty pigs. Despite its practice throughout the industry, there are limited research publications available to validate gruel feeding protocols and the potential impact on pig survivability. Additionally, for pigs that struggle to maintain nutrient intake after weaning or simply fail to thrive, there are few intervention strategies available. Buzzard et al. (2013) observed that pigs characterized as unthrifty had decreased blood glucose compared to pigs categorized as healthy, indicating that unthrifty pigs may be malnourished. Hence, we hypothesized that an oral dextrose supplement (as a source of glucose) would increase circulating glucose when provided to pigs removed from the general population due to welfare considerations, potentially improving pig livability. Limited research is also available examining the physiological differences among pigs removed in a large commercial setting and how their body weight, blood glucose, and body temperature impact survivability. Therefore, the objective of these studies was to determine the effect of gruel feeding and oral dextrose on the survivability of pigs post-weaning.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments.

Pigs were weaned at approximately 21 d of age and transported to a 14,400 head commercial nursery located in the Midwest and placed in rooms based on sow source. A total of 3,087 (Exp. 1) and 988 (Exp. 2) pigs (241 × 600, DNA, Columbus, NE) were used in two trials to measure nursery pig survivability. Each pen was equipped with two 8-hole stainless steel feeders and a nipple bar waterer to allow *ad libitum* access to feed and water. Common corn-soybean meal-based nursery diets were fed in 3 phases and were based on a feed budget. Phase 1 feed budget was provided at 2.5 kg per head, phase 2 feed budget was provided at 5.4 kg per head, and phase 3 feed budget was provided at 16.0 kg per head. In removal and small pig pens, a special early-wean diet was fed at approximately 1.5 kg per head prior to beginning phase 1 feed. All diets were fed in meal form.

Experiment 1

The smallest 10% of pigs were selected upon arrival to the nursery and randomly placed in designated pens. A total of 34 pens across 8 rooms (2 to 5 pens per room) were used for the small pigs with 61 to 108 pigs per pen. Pens of small pigs were assigned to 1 of 2 treatments in a completely randomized design with average pigs per pen balanced across treatment. Treatments consisted of gruel feeding two- or four-times per day. Gruel feeding started when the first group of pigs were placed in each room and continued for 14-d after the last group of pigs were placed in each room. Fill times ranged from 2 to 10 d. At each gruel feeding, approximately 1.13 kg of solid feed from the feeder was added to a single round bowl measuring 40.6 cm in diameter and 7.0 cm deep (Rotecna S.A., Agramunt, Spain) located at the front of each pen. Water was added to feed at a decreasing rate over time such that from d 0 to 5, 6 to 10, and 11 to 14 the ratio of water to feed was 3:1, 1:1, and 1:3, respectively. Pens of pigs were equipped with a heat lamp and two floor mats. One mat was placed under the heat lamp for zone heating and the other was placed near the feeder for mat feeding. Mat feed was provided to all pigs (small pens and general population pens) up to 2 times per day by taking 1 to 2 handfuls (approximately 1.13 kg) of feed from the feeder and spreading it across the mat. Additionally, all small pig pens were monitored daily to track removals and mortalities.

Experiment 2

Pigs removed from the general population or pens of small pigs for welfare considerations (lameness, sick, or unthrifty) over a 4-wk period post-placement were used. At removal, every other pig received a single 10 mL oral dose of a 50% hypertonic dextrose solution (Vet One, MWI Animal Health, Boise, ID) before being placed in a designated removal pen equipped with a heat lamp and floor mats. The 10 mL dextrose solution was used as source of glucose and provided 5 g of dextrose, which delivered 17 kcal of gross energy. All removed pigs were tagged and weighed, blood glucose measured prior to and 30 min after entering removal pens, and body temperature recorded. Blood glucose was measured by puncturing an ear auricular vein with a needle and using a handheld Glucometer (AimStrip Plus, Germaine Laboratories Inc., San Antonio, TX). Mortality was then tracked through the end of the nursery for approximately 38-d post-placement.

Data analysis

Gruel feeding data were analyzed as a completely randomized design with pen as the experimental unit. Treatment was considered a fixed effect and room a random effect. A binomial model was used to determine removal and mortality percentages. Mortalities were calculated by totaling the mortalities out of test pens and the mortalities after removal, and then dividing by initial pen inventory.

Dextrose data were also analyzed as a completely randomized design with room as a random effect and pig as the experimental unit. Least square means was used to assess the effect of dextrose supplementation on blood glucose levels at removal, 30-min post-removal, and the change over time. Pigs were removed from the dextrose dataset when not accounted for at the end of the experiment and not recorded as a mortality. Due to random chance, entry blood glucose levels were statistically different, therefore entry blood glucose was used as a covariate for 30-min post-removal blood glucose and the change over time. A binomial model was used to determine mortality percentages.

The predictor variables of body weight, body temperature, and blood glucose were categorized into biologically significant categories and least squares means were determined using a binary model with mortality as the outcome. A quadratic equation for the continuous predictor variables of body temperature and blood glucose were also tested to determine the predicted probability of mortality based on body temperature and blood glucose. All statistical models were fit using the GLIMMIX procedure of SAS v. 9.4 (SAS Institute, Inc., Cary, NC). Results were considered significant at $P \leq 0.05$.

Results

In Exp. 1, gruel feeding small pigs two or four times per day did not influence removal ($P = 0.239$; Table 1) or mortality ($P = 0.437$) rates from weaning to the end of the gruel feeding period. In Exp. 2, dextrose administration did not influence ($P = 0.443$; Table 2) the survivability of pigs after removal. However, blood glucose concentrations were increased ($P < 0.001$) in pigs administered dextrose compared to no dextrose, which confirms that dextrose supplementation at 10 mL per pig increased circulating blood glucose concentrations.

For the categorical predictor variables in Exp. 2, pigs with a body weight under 4.5 kg at the time of removal had increased mortality compared to pigs with a body weight greater than or equal to 4.5 kg at removal ($P < 0.001$; Figure 1). For blood glucose and body temperature a significant interaction was observed ($P < 0.001$; Figure 2). Pigs with a blood glucose less than 70 mg/dL had increased ($P < 0.05$) mortality when body temperature was greater than 39.7°C compared to pigs with a body temperature within the normal range of 38.6 to 39.7°C. The mortality of pigs with a body temperature less than 38.6°C was intermediate. Additionally, providing an oral dose of dextrose to pigs with a blood glucose less than 70 mg/dL did not improve survivability ($P = 0.101$; Figure 3), regardless of body temperature. Pigs with normal blood glucose ranging from 70 to 120 mg/dL had increased ($P < 0.05$) mortality when body temperature was less than 38.6°C compared to pigs with a body temperature within the normal range of 38.6 to 39.7°C. The mortality of pigs with a body temperature greater than 39.7°C was intermediate. Pigs with a blood glucose greater than 120 mg/dL and a body temperature less than 38.6°C had increased ($P < 0.05$) mortality compared to pigs with a body temperature of 38.6°C or greater. The combination of high blood glucose and low body temperature resulted in substantially greater percent mortality compared to any other combination of blood glucose and body temperature. However, this represented a small proportion of pigs (approximately 2.6%).

The interaction of blood glucose and body temperature can also be interpreted as pigs with a body temperature less than 38.6°C and a blood glucose greater than 120 mg/dL had increased mortality ($P < 0.05$) compared to pigs with a body temperature less than 38.6°C and blood glucose less than 120 mg/dL. Blood glucose level did not influence mortality for pigs with a normal body temperature ranging from 38.6 to 39.7°C ($P > 0.05$). Pigs with a body temperature greater than 39.7°C and a blood glucose less than 70 mg/dL had increased ($P = 0.033$) mortality compared to pigs with a high body temperature and a blood glucose between 70 and 120 mg/dL. Additionally, for pigs with a body temperature greater than 39.7°C, there was no evidence ($P > 0.10$) that blood glucose greater than 120 mg/dL resulted in mortality levels different from pigs with a low blood glucose.

For the continuous predictor variables in Exp. 2, a quadratic relationship was observed for body temperature and probability of mortality ($P < 0.001$; Figure 4). Hence, pigs with a body temperature below or above the normal range had increased predicted mortality. A quadratic relationship was also observed for blood glucose and probability of mortality ($P < 0.001$; Figure 5), such that pigs with low or high blood glucose had increased predicted mortality. Once pigs reached a blood glucose greater than 250 mg/dL their probability of mortality was nearly 100%.

Discussion

Poor feed intake and body weight gain by pigs after weaning is a challenge for commercial swine producers. Numerous studies have assessed dietary approaches to improve feed palatability and nutrient utilization; however, the responses often observed don't fully prevent performance losses. Hence, it has become increasingly important to consider opportunities beyond diet formulation strategies to help pigs transition after weaning. A review by Brooks and Tsourgiannis (2003) indicated that the development of feeding behavior pre-weaning plays an important role in how pigs begin consuming feed post-weaning. Thus, it's important to understanding the feeding behavior of pigs prior to weaning. There are 3 main considerations: 1) at weaning pigs are accustomed to consuming an all-liquid diet, 2) as a species, pigs naturally feed together, and 3) feeding up to this point has been elicited by the sow when she grunts and calls pigs to nurse.

Gruel feeding is practiced throughout the swine industry because it is believed to provoke similar feeding behaviors to suckling (provides liquid mixed with dry feed, several pigs can eat at once, and caretakers entering the pen to gruel feed encourages pigs to get up), while also helping transition pigs from an all milk based diet to solid feed. However, nearly no published literature is available on gruel feeding. Some researchers have evaluated all-liquid diets after weaning, but the responses observed are not consistent. Kim et al. (2001) showed that pigs fed an all-liquid diet the first 14 d post-weaning had improved gain compared to pigs fed an all-dry pelleted diet. Conversely, Lawlor et al. (2002) showed a reduction in ADG and poorer feed efficiency when feeding an all-liquid diet, despite increased dry matter intake. Others have reported no difference in growth performance or morbidity and mortality rates feeding an all-gruel diet (Corrigan et al., 2000). In the current study, no differences in morbidity and mortality were observed when gruel feeding in combination with standard trough feeding. Interestingly, Corrigan et al. (2000) showed that feeding an all-gruel diet decreased eating behavior at the feeder 3 d post-weaning, which may emphasize why gruel feeding in combination with standard trough feeding is a more practical and potentially beneficial strategy than feeding all-liquid diets after weaning. Gruel feeding allows for partial liquid feeding, while also encouraging pigs to start eating solid feed; therefore, preventing pigs from having to undergo a second weaning when an all-liquid diet is stopped, and dry feed is started. Because feed intake and gain were not measured in the study reported herein, and due to the limited number of trials conducted on gruel feeding in combination with standard trough feeding, the effect of gruel feeding on wean pig growth performance, morbidity, and mortality cannot be fully elucidated.

While more research is needed to understand if gruel feeding can minimize morbidity and mortality, it is unlikely that any feed management strategy will fully eliminate the challenges associated with poor health and pigs that simply fail to thrive post-weaning. Hence, in the current study, once challenged pigs were identified, different biological measures were assessed that may influence survivability, including body weight, body temperature, and blood glucose. It is important to note that each of these factors are not the direct cause of mortality but rather indicators of underlying physiological issues that lead to mortality. The results herein showed that pigs removed from the general population with a body weight below 4.5 kg had increased mortality compared to pigs removed with a heavier body weight. This agrees with earlier reports by Larriestra et al. (2006) who identified that weaning pigs ≤ 3.5 kg was a significant predictor of nursery mortality.

Body temperature at removal also appears to be a predictor of nursery mortality. Normal body temperature ranges from approximately 39.0 to 39.6 °C in weaned pigs (Dewey and Straw, 2006), indicating that anything substantially below or above could be considered hypo or hyperthermic, respectively. In humans, hypothermia occurs as core body temperature drops below 35 °C, while hyperthermia occurs as temperature rises above 40 °C (Mayo clinic, 2022a, b). It is expected that these reference values would vary slightly for pigs; however, based on the quadratic response observed for body temperature and predicted probability of mortality, it appears these reference values are suitable. In the current study, removed pigs with a body temperature between approximately 38 and 40 °C had decreased mortality compared to pigs with a body temperature outside of this range. While the direct cause of low or high body temperature was not elucidated in this experiment, thermogenic regulation has been linked to the bodies central stress response pathway. This pathway can be activated by stressors such as pathogen exposure or feed deprivation (Parrott et al., 1995; Inoue and Luheshi, 2010), both of which can occur around the time of weaning.

One of the mechanisms which can result in elevated body temperature is systemic inflammation due to infection, which is a critical component of the host immune system (Almeida et al., 2006). However, when systemic inflammation becomes severe the body responds with a drop in core body temperature (Almeida et al., 2006). Trammell and Toth (2011) showed that low body temperature in mice used to model infectious disease was a valid marker of eventual predicted mortality. Furthermore, recent data in humans showed increased mortality in sepsis patients that presented with body temperature < 36 ˚C (Inghammar and Sunden-

Cullberg, 2020; Baek et al, 2022). If feed deprivation occurs prior to infection, this adds an extra layer of complexity on the body's ability to mount an effective fever response. Feed deprivation in and of itself leads to hypothermia due to decreased leptin concentrations; however, when pathogen exposure occurs in combination with feed deprivation a weakened fever response is observed (Inoue et al., 2008; Krall et al., 2010). Under these circumstances, energy conservation becomes top priority rather than increased body temperature (Inoue and Luheshi, 2010). Likewise, low intake and thus lower heat production through metabolism may be another contributing factor to hypothermia in feed deprived pigs. However, Case et al. (2011) proposed that under ambient temperature conditions, heat produced through digestion contributes minimally to body temperature maintenance. Collectively, these data may explain the increased mortality observed in pigs with low body temperature.

Blood glucose levels can also be affected by pathogen exposure and feed deprivation (Berg et al., 2002; Marik and Bellomo, 2013). In humans, normal blood glucose ranges from approximately 80 to 130 mg/dL, depending on a fasted vs fed state (Centers for Disease Control and Prevention, 2021). We hypothesized that decreased feed intake after weaning would lead to blood glucose levels below normal, therefore increasing mortality rates. Limited research evaluating supplemental glucose has been conducted in wean pigs; however, of the studies available from birth to approximately 30 kg, dosages ranged from 0.30 to 1.75 g per kg body weight (Manell et al., 2016; Kvidera et al., 2017; Engelsmann et al., 2019; Klaaborg and Amdi, 2020). Route of administration (intravenously, subcutaneously, or orally) also varied. Hence, the 10 mL dose used was selected based on an average of the reported literature, ease of application, and an assumed average pig weaning weight of 5.4 kg (approximately 1g/kg body weight). Furthermore, the 30-min blood glucose measure post-dextrose administration was selected based on an oral glucose tolerance test in pigs that showed a peak in blood glucose 10-30 minutes after glucose intake (Manell et al., 2016).

While the results herein showed increased blood glucose concentrations when pigs were administered dextrose compared to no dextrose, no differences in survivability were observed. However, a quadratic response was observed for blood glucose and predicted probability of mortality, with low and high blood glucose levels resulting in greater mortality. Interestingly, in the current study, high blood glucose levels > 250 mg/dL resulted in nearly 100% mortality. While the specific cause of high blood glucose in this population is not known, high levels of glucose in circulation are often associated with the body's adaptive response to acute or chronic illness, known as stress hyperglycemia (Marik and Bellomo, 2013). This is caused by an increased release of cortisol, epinephrine, and norepinephrine in response to hypothalamic pituitary adrenal axis activation, which increases hepatic glucose production. Additionally, cytokines and other inflammatory mediators such as prostaglandins that are released as part of the stress response pathway have been linked to insulin resistance (Parrott et al., 1995; McGuinness, 2005), which is known to elevate blood glucose concentrations. Moderate hyperglycemia in humans ranges from 140 to 220 mg/dL (Marik and Bellomo, 2013). Within this glycemic range, glucose uptake is maximized to provide fuel for the immune system and brain, while also preventing hyperosmolarity (Marik and Bellomo, 2013; Kenny et al., 2016). This is necessary to ensure host survival; however, at blood glucose levels > 220 mg/dL, Marik and Bellomo (2013) suggest that hyperglycemia may become more harmful than protective. Furthermore, as energy reserves become depleted due to severe or prolonged inflammation, hypoglycemia may occur following hyperglycemia (McGuinness, 2005). Collectively, these data indicate that the cause of death in pigs with low or high blood glucose may have been related to feed deprivation, infection, or an underlying metabolic disorder.

Body temperature and blood glucose also appear to interact, although their relationship is not well understood. In the present study, pigs with a blood glucose less than 70 mg/dL had increased mortality as body temperature at removal increased. Throughout the literature hypoglycemia has been observed in combination with both hypo and hyperthermia (Chochinoz and Daughaday, 1975; Tran et al., 2012; Naseerullah and Murthy, 2018), although hypothermia is generally associated with severe hypoglycemia rather than hyperglycemia. Pigs with a blood glucose greater than or equal to 70 mg/dL had decreased mortality as body temperature increased. A retrospective study looking at outcomes in newborn infants showed that 100% of infants with blood glucose levels > 200 mg/dL who were also undergoing therapeutic hypothermia became disabled or did not survive compared to infants with blood glucose levels < 200 mg/dL (Chouthai et al., 2015). These data may support the results observed herein, indicating that pigs within the high blood glucose and low body temperature population first experienced hypothermia, which led to hyperglycemia. We also hypothesize that this group of pigs may have already transitioned into organ failure, whereas pigs with both high blood glucose and body temperature may have been mounting a more normal immune response to infectious pathogens, therefore, decreasing mortality. The interaction between blood glucose and body temperature appears to be dependent on if changes in blood glucose precede body temperature or vice versa, and what the underlying cause (feed deprivation, infection, or metabolic disorder) was that initiated these changes.

In summary, pigs removed from the general population with low bodyweight or with body temperature or blood glucose below or above the normal range had decreased survivability.

While the mechanism by which body temperature and nutrient homeostasis interact is not fully understood, these data suggest a complex relationship between physiological functions and livability. Unfortunately, no differences in livability were observed in the current study when gruel feeding four times per day vs two times per day or providing pigs supplemental oral dextrose.

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Table 5-1. Effect of gruel feeding on the removal and mortality rate of pens of small nursery pigs[1,2]

	Gruel application, times/d			
	Two	Four	SEM	*P* =
Count d 0	1,530	1,557	---	---
Count d 14	1,253	1,262	---	---
Mortality/removal analysis, %				
Removal	14.1	15.6	2.50	0.239
Mortality[3]	3.78	4.25	1.560	0.437

[1] A total of 3,087 mixed sex pigs were used with 61 to 108 pigs per pen and 17 replicates per treatment.

[2] Gruel feed was offered either two-times per day or four-times per day. Gruel feeding started when the first group of pigs were placed in each room and continued for 14-d after the last group of pigs were placed. Fill times ranging from 2 to 10 d. At each feeding, approximately 1.1 kg of solid feed from the back of the feeder was added to a single round bowl measuring 40.6 cm in diameter and 7.0 cm deep, (Rotecna S.A., Agramunt, Spain) located at the front of the pen. Water was added to feed at a decreasing rate over time such that from d 0 to 5, 6 to 10, and 11 to 14 the ratio of water to feed was 3:1, 1:1, and 1:3, respectively. A heat lamp was also provided in each pen.

[3] Mortality = (mortality after removal + mortality in pen) ÷ initial pen inventory.

Table 5-2. Effect of oral dextrose on the mortality rate of nursery pigs removed from general population or small pig pens[1]

	Oral Dextrose		SEM	*P* =
	No	Yes		
Count	476	512	---	---
Blood glucose, mg/dL				
Entry	82.1	74.1	2.03	0.002
30-min[2]	89.8	96.8	1.40	< 0.001
Change[2,3]	11.8	18.7	1.40	< 0.001
Mortality, %	21.4	23.4	4.02	0.443

[1] Every other pig that entered the removal pen received a 10 mL oral dose of a 50% hypertonic dextrose solution. The 10 mL dextrose solution provided 5 g of dextrose, which delivered 17 kcal.

[2] Entry blood glucose used as a covariate.

[3] Represents the average change in blood glucose over a 30-minute period after pigs entered the removal pen.

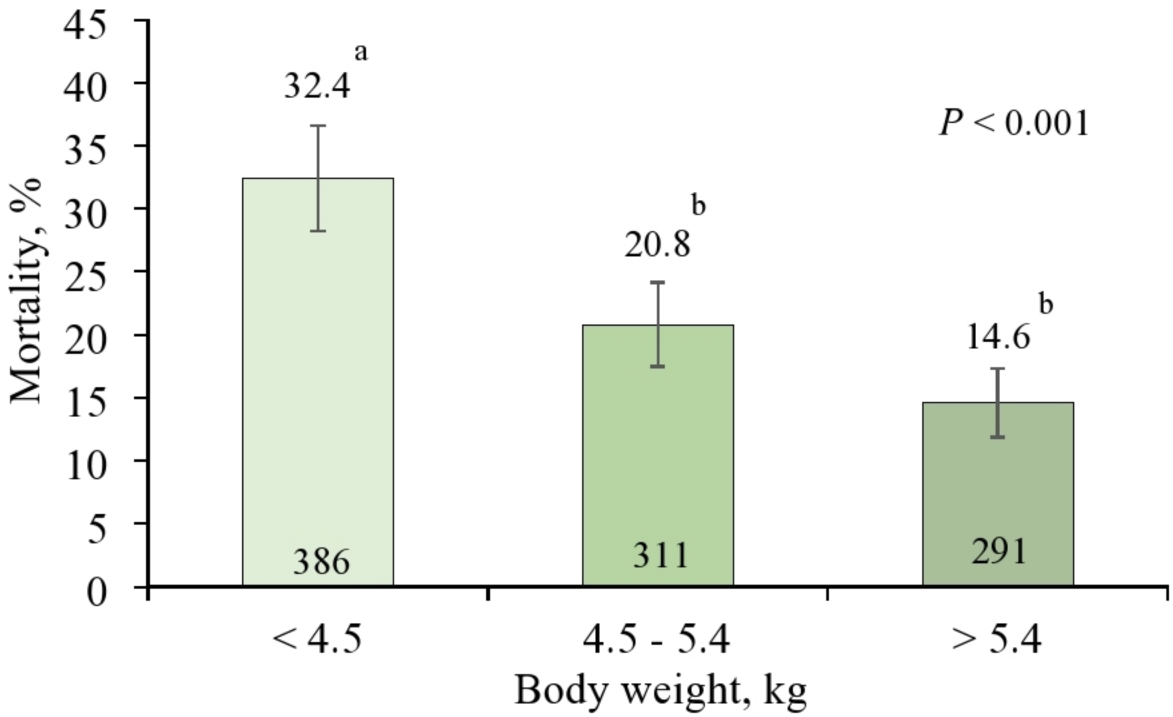

Figure 5-1. Main effect of body weight at removal on the mortality of nursery pigs after removal. Number listed within each bar represents pig count.

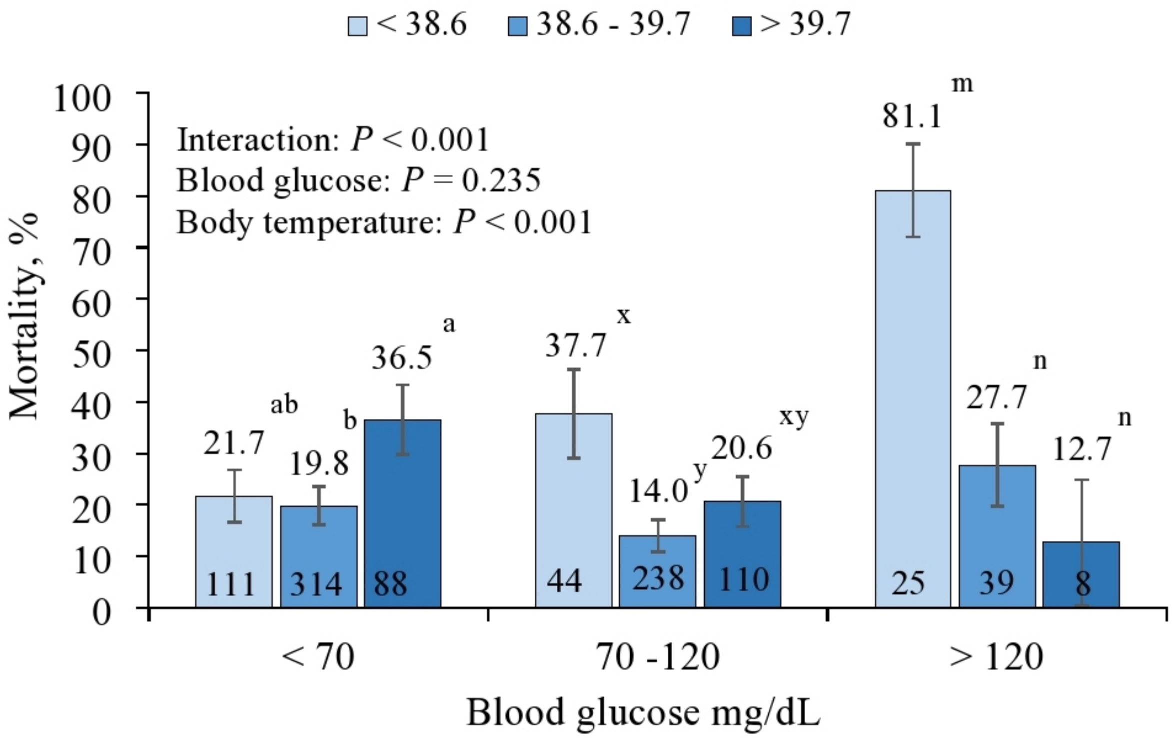

Figure 5-2. Interactive effect of blood glucose and body temperature at removal on the mortality of nursery pigs after removal. Bars within blood glucose category that lack a common superscript differ (*P* < 0.05). Number listed within each bar represents pig count.

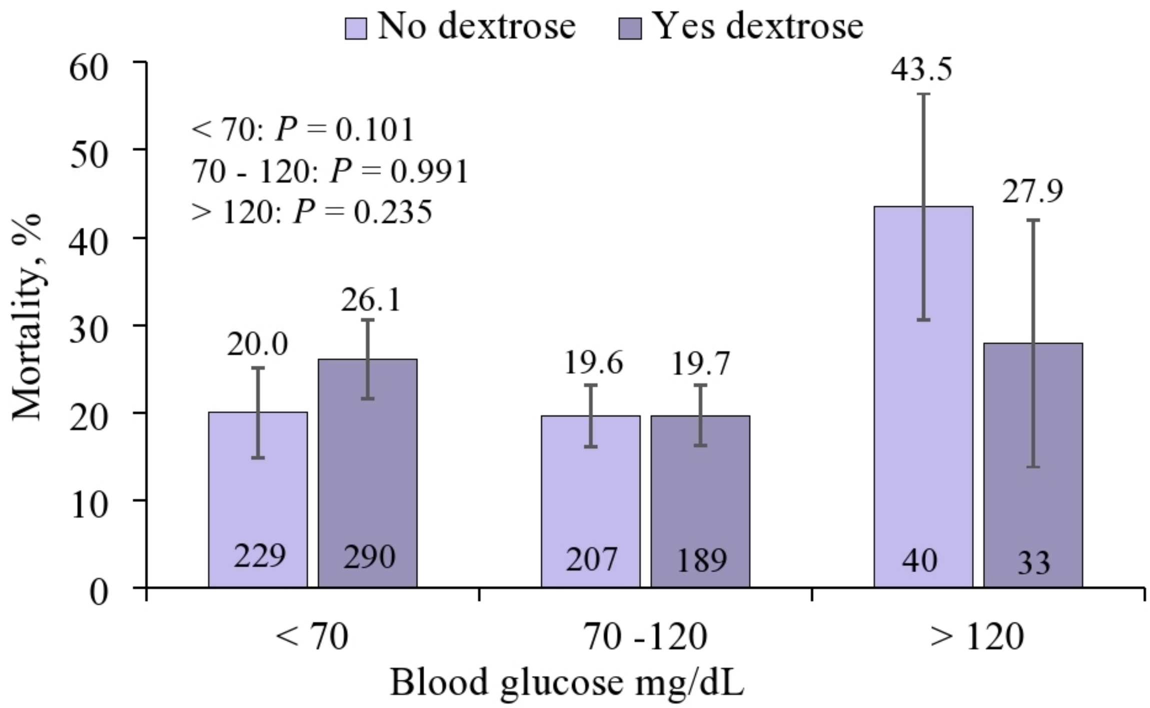

Figure 5-3. Effect of oral dextrose at removal within blood glucose category on the mortality of nursery pigs after removal. Number listed within each bar represents pig count.

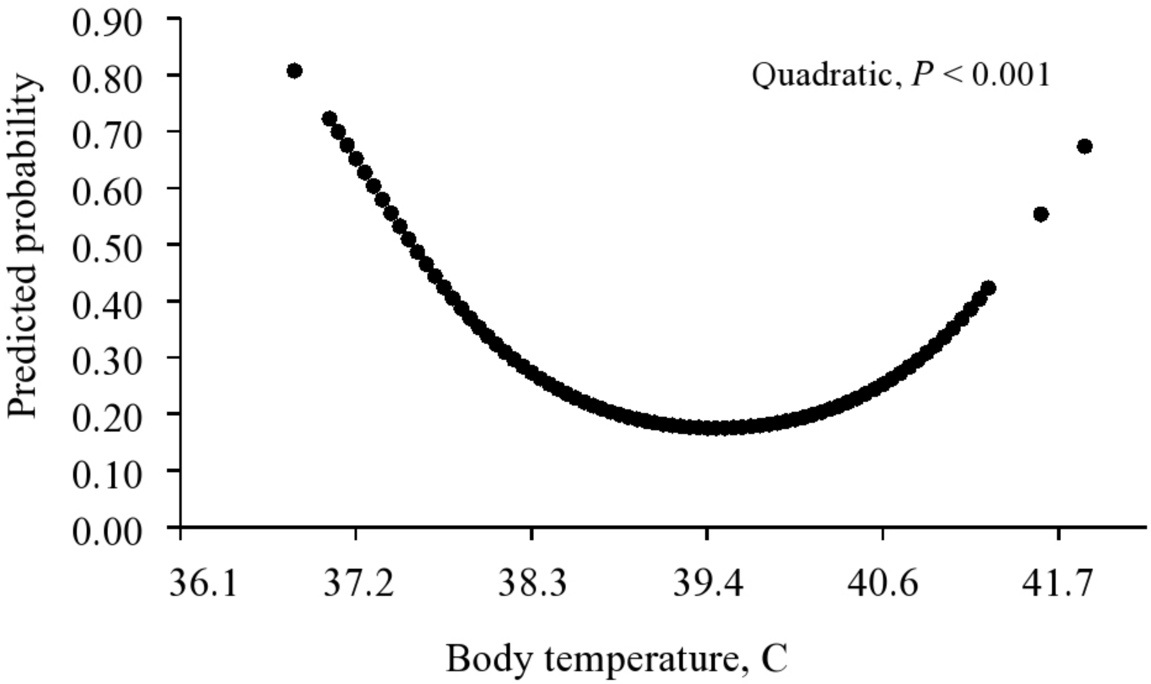

Figure 5-4. Effect of body temperature at removal on the predicted probability of mortality of nursery pigs after removal.

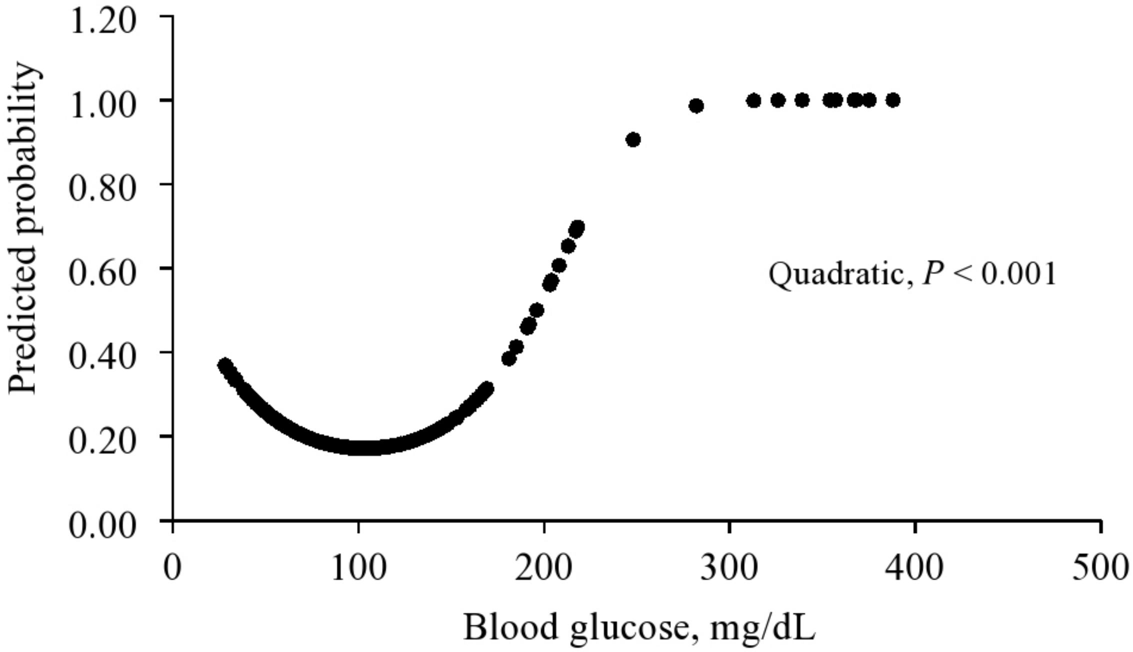

Figure 5-5. Effect of blood glucose at removal on the predicted probability of mortality of nursery pigs after removal.

Chapter 6 - Effect of early vs. late maturing sire lines and creep feeding on the stress response, intestinal permeability, and growth performance of nursery and finishing pigs

Abstract

A total of 21 litters (early or late maturing Duroc × DNA 241) resulting in 247 pigs were used in 170-d trial to determine the effect of sire lines selected for either early or late maturing growth rates and creep feeding on the stress response, intestinal permeability, and growth performance of nursery and finishing pigs. Treatments were arranged in a 2 × 2 factorial with main effect of Duroc sire line (early or late maturing) and creep feeding (with or without). After weaning (initially 6.4 kg), blood cortisol levels were increased ($P < 0.01$) in late maturing pigs compared to early maturing pigs, indicating an increased stress response. A lower percentage ($P < 0.001$) of early maturing pigs had BW less than their weaning weight 3-d post-weaning compared to late maturing pigs. Likewise, early maturing pigs had improved ($P < 0.001$) ADG and ADFI during the first 3 d in the nursery. Early maturing pigs also had increased daily feed intake ($P < 0.001$) from d 2 to 14 in the nursery. Creep feeding had no effect on initial nursery performance. No differences were observed in intestinal permeability. For overall nursery performance, a significant interaction was observed for ADG ($P = 0.007$) and ADFI ($P < 0.001$), with creep feed providing a benefit in late maturing pigs, but not in early maturing pigs. Early maturing pigs had poorer G:F ($P < 0.001$) than late maturing pigs. For overall finishing performance, a significant interaction was observed for ADG ($P = 0.037$), with late maturing pigs that received creep feed having increased ADG ($P \leq 0.024$) compared to the other treatments. A significant interaction was also observed for ADFI ($P = 0.007$), with late maturing

pigs that did not receive creep feed having decreased ADFI ($P \leq 0.002$) compared to late maturing pigs that received creep feed or early maturing pigs whether they received creep feed or not. This resulted in a significant interaction for final BW ($P = 0.005$), with late maturing pigs that did not receive creep feed having decreased market weights ($P \leq 0.003$) compared to the other treatments. In summary, early maturing pigs had lower stress response at weaning and improved ADG and ADFI until approximately 100 kg, at which point late maturing pigs began to exhibit greater ADG. Late maturing pigs had improved feed efficiency throughout much of the experiment. Interestingly, creep feeding late maturing pigs resulted in improved growth performance compared to providing no creep feed, whereas creep feed did not impact early maturing pigs.

Introduction

It is well established that growth potential varies across pig genotypes (Schinckel and De Lange, 1996; Edwards et al., 2006); however, limited published research is available on the potential effects of growing and finishing pig protein deposition on nursery pig performance (< 20 kg BW). As genetic companies have selected for terminal sires with improved lean growth efficiency in late finishing, anecdotal reports from the commercial swine industry suggest that getting pigs started on feed after weaning has become more challenging (Wensley et al., 2021a, b). This might suggest that selecting for performance improvements late in the growth curve may negatively impact performance early in the growth curve. Likewise, pig resiliency may be another contributing factor to poorer performance immediately after weaning (Silalahi, 2017). Colditz and Hine (2015) define resilience as “the capacity of animals to cope with short-term perturbations in their environment and return rapidly to their pre-challenged state.” Others have expanded on this definition indicating that resiliency leads to “minimal changes” in overall growth performance (Harlizius et al., 2020). However, stressors such as weaning, or pathogen exposure appear to have a greater effect on modern Duroc sire lines compared to previous genotypes. While there is limited data investigating the resiliency of varying genotypes, genetic selection is known to affect the pigs stress response (Webb et al., 1982). Likewise, stress is associated with increased intestinal permeability (Moeser et al., 2006, 2007), which can have implications on the pigs innate immune response and subsequent gastrointestinal health (McLamb et al., 2013).

Providing creep feed during lactation familiarizes pigs with solid feed prior to weaning. Research consistently shows that pigs identified as eaters of creep feed during lactation have improved feed intake and body weight gain after weaning (Bruininx et al., 2002). Hence, it's possible that the benefits of creep feed may be greater today than in the past due to sire line selection criteria. Therefore, the primary objective of this study was to determine the effect of Duroc sires selected for early vs. late maturing growth rates and creep feeding on the daily feed intake of pigs the first 14 d after weaning, percentage of pigs that have BW less than or equal to their weaning weight 3 and 7 d post-weaning, and the feed intake and growth performance of pigs from birth to market. The secondary objective of this study was to determine if sire line selection for maturity and creep feeding influence the stress response and intestinal barrier integrity of pigs after weaning.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in this experiment.

Breeding

Sows (DNA 241, Columbus, NE) from the Kansas State University Swine Teaching and Research Center were initially used for this experiment. At breeding, sows were blocked by parity (parity 1 and 2+) and every other sow was inseminated with 1 of 2 sources of semen selected from Duroc sires with the highest indexing early nursery growth or late finishing growth (early or late maturing, respectively). Sows were housed in individual stalls until confirmed pregnant and then moved to group housing. Throughout gestation, a common gestation diet was fed in meal form, and feed allowance was adjusted based on sow body condition. On approximately d 111 of gestation, sows were moved into the farrowing facility.

Farrowing to weaning

A total of 21 litters [early (11 litters) or late (10 litters) maturing Duroc × DNA 241] were selected and used for the remainder of the experiment. Within 24-h post-farrow, litters were cross-fostered to equalize litter size at 10 to 14 pigs per sow within sire line treatment. Pigs were cross-fostered based on average piglet size. Pigs were individually weighed 24-h after birth and at 14 d prior to weaning for creep feed treatment allotment. Litters of pigs were assigned to 1 of 2 creep feeding treatments (with or without creep feed) in a completely randomized design balanced for sow parity, sire line maturity, and average piglet body weight. For litters of pigs assigned to the creep feed treatment, a phase 1 nursery diet containing 1.0% chromic oxide was offered ad libitum until weaning. The creep diet was pelleted (0.48 × 1.27 cm) and fed using a commercial rotary creep feeder starting 14 d prior to weaning. A common lactation diet was fed to sows throughout lactation in meal form.

On the day prior to weaning (morning and afternoon), rectal swabs were taken from all pigs provided creep feed using a cotton-tipped applicator. The color of each swab was visually assessed, and pigs were categorized as eaters or non-eaters of creep feed when swab color was green.

Post-weaning

At weaning (approximately 21 d of age), a total of 247 pigs (initially 6.4 kg) were weighed and assigned to 51 pens in a completely randomized design based on Duroc sire line [early (130 pigs) or late (117 pigs) maturing] and creep feeding treatment [with (130 pigs) or without (117 pigs)]. There were 4 or 5 pigs per pen and 12 or 13 replications per treatment. Each pen (1.2 × 1.2 m) contained a 4-hole, dry self-feeder, and nipple waterer for *ad libitum* access to feed and water. Pigs were individually weighed on d 3 and 10 post-weaning to determine initial changes in body weight. Feeders were also weighed daily for the first 14 d post-weaning to determine daily feed disappearance over time. After 14 d, pigs were weighed and feed disappearance measured weekly to determine ADG, ADFI and G:F. Common diets were fed throughout the nursery based on a 4-phase feeding program with phases fed from d 21 to 31, 31 to 46, 46 to 67, and 67 to 76 of age, respectively. Phase 1, 2, and 4 diets were provided in pellet form and phase 3 diets were in meal form.

At the end of the nursery period, 241 pigs were transported to the finisher facility and randomly distributed into 32 pens based on Duroc sire line (early or late maturing) and creep feeding treatment (with or without). There were 7 or 8 pigs per pen and 7 or 8 replications per treatment. Each pen was equipped with a 2-hole, single-sided, dry self-feeder (Farmweld, Teutopolis, IL) and a cup waterer. Floor space allowance was maintained at 0.93 m^2 per pig. Pens were located over a completely slatted concrete floor with a 1.2 m pit underneath for manure storage. A robotic feeding system (FeedPro; Feedlogic Corp., Wahpeton, ND) was used to deliver and record daily feed additions to each pen. Pens of pigs were weighed every other week and feed disappearance measured to determine ADG, ADFI, and G:F until market. Common corn-soybean-meal-based diets were fed over a 3-phase feeding program throughout the finisher. All diets were in meal form. At the end of the experiment, 36 barrows (1 or 2 pigs per pen) of average BW were selected and sent to the Kansas State University meat lab for muscle metabolism analysis (data not reported). The remaining 200 pigs were tattooed and tagged before being shipped to Triumph Foods in Saint Joseph, MO for hot carcass weight, percent yield, backfat, loin depth, and percent lean. Percentage lean was calculated from a plant proprietary equation. Carcass yield was calculated by dividing individual pig HCW by individual pig live weight at loadout from the finishing barn.

Blood cortisol and intestinal permeability

Cortisol concentrations in blood serum were used to determine if sire line maturity and creep feeding influenced the short-term stress response of pigs immediately after weaning. The day prior to weaning, 1 or 2 gilts per litter (28 gilts total) were randomly selected to determine baseline cortisol levels. The following day, pigs were weaned from sows, loaded on a trailer, and transported to an on-site nursery (approximately 10 meters from the farrowing facility). The same subset of gilts used to establish baseline cortisol levels were identified by writing the time they were removed from the sow on their back, such that 30 min post-weaning changes in serum cortisol due to weaning stress could be determined. On each collection day, one blood sample of approximately 6 mL was collected from the external jugular vein using a silicone coated red stopper tube with no additive. Serum was then separated by centrifugation (20 min at 10,000 × g) and stored at -20C until analysis using a commercial ELISA kit (Cortisol Parameter Assay Kit, R&D Systems, Minneapolis, MN).

On d 7 post-weaning, the same subset of gilts used for serum cortisol were bled for complete blood count (CBC) and serum chemistry analysis. Two blood samples of approximately 6 mL were collected from the external jugular vein using a lavender stopper tube with EDTA (CBC) or a silicone coated red stopper tube with no additive (serum chemistry). Following collection, one sample of whole blood was immediately sent to the Kansas State University Veterinary Diagnostics Laboratory for CBC analysis. For the other sample, serum was separated by centrifugation (20 min at 10,000 g) and then sent to the Kansas State University Veterinary Diagnostics Laboratory for serum chemistry analysis.

After blood was collected for CBC and serum chemistry analysis, a lactulose:mannitol dual sugar test was conducted to assess intestinal permeability. Gilts were individually weighed and moved to empty pens with access to ad libitum water, but no feed. After a 2 h fast, each gilt was administered an oral gavage solution of lactulose (500 mg/kg body weight; Fisher Scientific, Pittsburgh, PA) and mannitol (50 mg/kg body weight; Sigma-Aldrich, St. Louis, MO), dissolved in distilled water. Sixty minutes following sugar administration, a blood sample of approximately 6 mL was collected from the external jugular vein from each gilt using a silicone coated red stopper tube with no additive. Following collection, serum was separated as previously described and stored at -20C until samples were sent to the University of Illinois for analysis of lactulose and mannitol concentrations based on modifications of procedures described by Bao et al. (1996) and Smiricky et al. (2002). The lactulose:mannitol ratio (LMR) was calculated by converting lactulose and mannitol concentrations to umol/L using the molecular weight of each sugar, and then calculating their ratio.

Data analysis

Average piglet BW pre-weaning were analyzed as a 2 × 2 factorial with main effect of Duroc sire line (early or late maturing) and creep feeding (with or without). Total born count was analyzed using a Poisson model, and the percent of pigs that were categorized as eaters of creep feed were analyzed using a binomial model. In each analysis, sow was considered the experimental unit. Parity (parity 1 vs parity 2+) was included as a random effect in average piglet BW and total born count.

Nursery and finishing pig growth performance were analyzed as a 2 × 2 factorial to test the interactive and main effects of Duroc sire line (early or late maturing) and creep feeding (with or without). A binomial model was used to determine the percent of pigs that did not gain weight from d 0 to 3 and d 0 to 10 post-weaning. Daily feed intakes were analyzed in a first-order ante-dependence covariance matrix for repeated measures using a 3-way interaction with main effect of Duroc sire line (early or late maturing), creep feeding (with or without), and day post-weaning. Pen was considered the experimental unit for each analysis. Carcass measurements were analyzed as a 2 × 2 factorial similar to growth performance. Pig was considered the observational unit and pen was included in the model as a random effect to account for subsampling to define pen as the experimental unit. Hot carcass weight was used as a covariate for backfat, loin depth, and percent lean.

Blood cortisol levels were analyzed in an unstructured covariance matrix for repeated measures using a 3-way interaction with main effect of Duroc sire line (early or late maturing), creep feeding (with or without), and collection day. A random intercept of ELISA plate was used. Serum chemistry, CBC, and intestinal permeability was analyzed as a 2 × 2 factorial similar to growth performance. In each analysis, pig was considered the experimental unit. All statistical models were fit using the GLIMMIX procedure of SAS v. 9.4 (SAS Institute, Inc., Cary, NC). Results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 \leq P \leq 0.10$.

A growth curve from birth to market was developed by fitting cumulative BW and days of age to a nonlinear Gompertz growth model using the nlsfit function from the easynls package in R (version 3.5.1 (2018-07-02), R Foundation for Statistical Computing, Vienna, Austria). Average daily gain was modeled in Excel from cumulative BW by taking the first-order derivative of the Gompertz equation with respect to age. A similar approach was taken for cumulative feed intake and ADFI using a cubic model and it's first-order derivative with respect to age. Feed efficiency was modeled by fitting a cubic function to the G:F LS-means from each period. All feed intake and efficiency curves were modeled using Excel.

Results

Growth performance

Sows bred to an early maturing Duroc sire had fewer total born (14.0 pigs/litter) compared to sows bred to a late maturing Duroc sire (15.3 pigs/litter). This may explain the numeric differences observed in 24 h birth weights. However, neither response was statistically significant ($P > 0.10$; Table 1), which is likely a result of the low replication for litter data.

At weaning, early maturing pigs had increased BW ($P < 0.001$) compared to late maturing pigs. Likewise, pigs that received creep feed had increased BW ($P < 0.001$) compared to pigs that did not receive creep feed. This was primarily driven by early maturing pigs and may be related to a greater percentage of early maturing pigs (41.5%) being categorized as eaters of creep feed compared to late maturing pigs (15.2%; $P = 0.010$). Early maturing or creep fed pigs continued to have heavier BW ($P < 0.05$) throughout the nursery. No interactions were observed for BW until 67 and 76 d of age ($P < 0.05$). Creep feeding late maturing pigs resulted in increased BW ($P < 0.001$) but did not affect early maturing pigs ($P = 0.700$).

In the first 3 d post-weaning (21 to 24 d of age), no differences ($P > 0.10$) were observed for the interaction between sire line maturity and creep feed or for the main effect of creep feed. However, late maturing pigs had poorer ADG ($P < 0.001$), ADFI ($P < 0.001$), and feed efficiency ($P = 0.001$). This may explain why a greater percentage ($P < 0.001$) of late maturing pigs did not gain weight during the first 3 d in the nursery compared to early maturing pigs. It is important to note that of the pigs that did gain weight, early maturing pigs gained approximately 141 g/d and late maturing pigs gained approximately 104 g/d. Interestingly, creep feed did not affect gain or feed intake during the first 3 d in the nursery ($P > 0.10$). From 21 to 31 d of age, early maturing pigs or pigs provided creep feed prior to weaning had improved ADG (P < 0.05) compared to late maturing pigs or pigs not provided creep feed prior to weaning. Early maturing pigs also had improved ADFI ($P < 0.001$) and G:F ($P < 0.001$) compared to late maturing pigs, whereas creep feed only tended to improve ADFI ($P = 0.067$). By 31 d of age or 10 d post-placement, no evidence for treatment differences were observed in the percentage of pigs that had not gained weight since weaning ($P > 0.10$). For daily feed intake, early maturing pigs continued to have increased daily feed intake (sire maturity × day, $P < 0.001$) from d 2 to 14 in the nursery compared to late maturing pigs, after almost no feed consumption by either group on d 1 post-weaning (Figure 1). From 31 to 76 d of age, a similar response in growth performance was observed; therefore, overall nursery performance will be discussed. Overall (21 to 76 d of age), a significant interaction was observed for ADG ($P = 0.007$) and ADFI ($P < 0.001$). Creep feeding did not impact the ADG ($P = 0.639$) or ADFI ($P = 0.230$) of early maturing pigs; however, late maturing pigs that received creep feed had greater ADG ($P = 0.001$) and ADFI (P

< 0.001) compared to late maturing pigs that did not receive creep feed. For overall feed efficiency, no interaction between sire line maturity and creep feed or main effect of creep feed was observed ($P > 0.10$); however, early maturing pigs had poorer G:F ($P < 0.001$) than late maturing pigs.

During the growing-finishing period, from 76 to 94 d of age, no interaction between sire line maturity and creep feed or main effect of creep feed was observed for ADG or G:F ($P > 0.10$; Table 2). However, for the main effect of sire line, early maturing pigs continued to have increased ADG ($P = 0.002$) and poorer feed efficiency ($P < 0.001$) compared to late maturing pigs. For ADFI, a significant 2-way interaction was observed ($P = 0.014$), with creep feed providing a benefit in late maturing pigs ($P = 0.003$), but not early maturing pigs ($P = 0.689$). From 94 to 108 d of age, no 2-way interactions were observed for any of the response criteria ($P > 0.10$). Likewise, no differences in ADG ($P > 0.10$) were observed for the main effect of sire line maturity or creep feed. However, early maturing pigs had increased ADFI ($P < 0.001$) and poorer G:F ($P < 0.001$) compared to late maturing pigs. A creep feeding response was also observed, with pigs that received creep feed prior to weaning having poorer G:F ($P = 0.006$). Similarly, from 108 to 122 d of age, no differences in ADG ($P > 0.10$) were observed, yet early maturing pigs continued to have increased ADFI ($P = 0.003$). Hence, a significant interaction between sire line maturity and creep feed was observed ($P = 0.025$) for G:F, with late maturing pigs that did not receive creep feed prior to weaning having improved G:F ($P \leq 0.020$) compared to the other treatments. No differences in growth performance ($P > 0.10$) were observed from 122 to 136 d of age. Beginning at 136 d of age or approximately 100 kg, late maturing pigs exhibited improved ADG ($P = 0.001$) and G:F ($P < 0.001$), which continued through the end of the experiment. For overall finishing performance, a significant interaction was observed for

ADG ($P = 0.037$), with late maturing pigs that received creep feed having increased ADG ($P \leq 0.024$) compared to the other treatments. A significant interaction was also observed for ADFI ($P = 0.007$), with late maturing pigs that did not receive creep feed having decreased ADFI ($P \leq 0.002$) compared to late maturing pigs that received creep feed or early maturing pigs whether they received creep feed or not. This resulted in a significant interaction for final BW ($P = 0.005$), with late maturing pigs that did not receive creep feed having decreased market weights ($P \leq 0.003$) compared to the other treatments. Lastly, late maturing pigs had improved G:F ($P < 0.001$) compared to early maturing pigs.

The shape of growth, intake, and feed efficiency curves are depicted in figures 2 to 6. When plotting days of age from birth to market against cumulative body weight using a Gompertz model, early maturing pigs had heavier body weights throughout the experiment compared to late maturing pigs. Using the derivative of the Gompertz model, ADG was modeled and showed early maturing pigs having greater ADG until approximately 125 d of age at which point late maturing pigs began to exhibit greater ADG. When plotting days of age from approximately 40 d of age to market against cumulative feed intake using a cubic model, early maturing pigs had increased feed intake throughout the experiment compared to late maturing pigs. Using the derivative of the cubic model, ADFI was modeled and showed early maturing pigs having greater ADFI until approximately 160 d of age at which point late maturing pigs began to exhibit greater ADFI. When plotting days of age from approximately 30 d of age to market against feed efficiency using LS-means, early maturing pigs had improved feed efficiency until approximately 50 d of age at which point late maturing pigs began to exhibit improved feed efficiency.

Carcass characteristics

For carcass characteristics, a tendency for increased hot carcass weight ($P = 0.057$) was observed for early maturing pigs compared to late maturing pigs. A tendency for increased hot carcass weight ($P = 0.067$) was also observed for pigs that received creep feed compared to not. No interaction between sire line maturity and creep feed or the main effect of sire line was observed for yield ($P > 0.10$); however, increased yield ($P = 0.049$) was observed for pigs that received creep feed compared to pigs that did not receive creep feed. No differences in backfat were observed ($P > 0.10$). For loin depth, an interaction between sire line maturity and creep feed was observed ($P = 0.011$), with early maturing sires that did not receive creep feed having decreased loin depth compared to the other treatments. A similar response was observed for percent lean ($P = 0.066$). For the main effect of sire line, late maturing pigs had increased loin depth ($P = 0.010$) and percent lean ($P = 0.032$) compared to early maturing pigs.

Blood cortisol and intestinal permeability

For blood cortisol, no 3-way interaction between sire line maturity, creep feed, and collection day were observed. Likewise, no 2-way interaction between creep feed and collection day, or the main effect of creep feed were observed. However, a significant 2-way interaction between sire line maturity and collection day were observed ($P = 0.004$; Figure 7). Baseline (pre-wean) cortisol levels were approximately 30 ng/mL for both sire lines ($P = 0.590$), but 30-minutes after weaning a greater increase in blood cortisol was observed in late maturing pigs compared to early maturing pigs ($P < 0.01$).

For CBC and serum chemistry, no 2-way interactions between sire line maturity and creep feed were observed ($P > 0.10$; data not shown) for any response criteria. For the main effect of sire line maturity, early maturing pigs had increased concentrations of monocytes ($P =$

0.041; Table 3), plasma protein (*P* = 0.049), and fibrinogen (*P* = 0.022) compared to late maturing pigs. In contrast, late maturing pigs had increased creatinine levels (*P* = 0.041; Table 4) compared to late maturing pigs. For the main effect of creep feed, pigs that received creep feed prior to weaning had increased concentrations of monocytes (*P* = 0.050) compared to pigs that did not receive creep feed. No other differences were observed (*P* > 0.05).

For intestinal permeability, no 2-way interactions or main effects were observed for lactulose, mannitol, or the LMR (Table 5). However, numeric differences did exist, with late maturing pigs that did not receive creep feed prior to weaning having the highest LMR.

Discussion

Duroc pigs are commonly used in swine breeding programs because of their lean growth rate and meat quality attributes. While these traits are highly heritable, significant differences in growth performance have been observed between Duroc lines (Chen et al., 2002; Lonergan et al., 2018; Li et al., 2021). This was observed in the present study during both the nursery and finishing phase of production where early maturing Duroc pigs had improved ADG until approximately 94 d of age and late maturing Duroc pigs had improved gain from approximately 136 d of age until market (170 d of age). Maximum ADG occurred at approximately 88 and 119 kg in early and late maturing pigs, respectively, illustrating that late maturing pigs reached a maximum inflection point later in life than early maturing pigs. Additionally, late maturing pigs had improved G:F throughout the experiment. These differences in growth performance may be related to the protein deposition curve for early versus late maturing Duroc pigs and may also explain the reduction in carcass lean observed for early maturing pigs compared to late maturing pigs.

Selecting two Duroc sire lines with different growth patterns from birth to market created progeny with drastic differences in lifetime growth performance. Interestingly, improved performance in late finishing for late maturing pigs was accompanied by a poorer start in the nursery. Compared to early maturing pigs, late maturing pigs had an increased stress response immediately after weaning and decreased daily feed intake the first 2-weeks post-weaning. For both sire lines, feed intake on d 1 post-weaning was lower than previously reported (Brooks and Tsourgiannis, 2003), with greater increases in feed intake observed thereafter for early maturing pigs compared to late maturing pigs. Feed intake in both sire lines was relatively constant from d 3 to 6 post-weaning within line, before increasing again. This response is consistent throughout the literature (Brooks and Tsourgiannis, 2003) and is likely related to gastrointestinal development as pigs begin to consume solid feed (Montagne et al., 2007). Increased stress and low feed intake immediately after weaning in late maturing pigs is likely responsible for the greater percentage of late maturing pigs that did not gain BW in the first 3 d after weaning compared to early maturing pigs. These data may suggest that selecting for performance improvements late in the growth curve adversely effects other traits such stress and early nursery performance. Research evaluating the growth performance of different sire lines post-weaning often begins in the growing or finishing period, rather than at weaning. To our knowledge, this is the first study reporting growth and feed intake differences from birth to market in early versus late maturing Duroc sire lines.

Differences in growth performance were also observed in response to creep feed. Pigs offered creep feed for 14 d prior to weaning had increased weaning weights compared to pigs not offered creep feed. This response contradicts previously reported data evaluating the effect of creep feed on weaning BW (Bruininx et al., 2002; Kuller et al., 2007; Sulabo et al., 2010a;

Huting et al., 2017; Middelkoop et al., 2020). Improvements in ADG and ADFI were also observed after weaning; however, these differences did not occur until 3-d post-weaning and only lasted until the end of phase 1, at which point a significant interaction was observed. Several studies have observed similar improvement in feed intake and BW gain early after weaning in response to creep feeding (Bruininx et al., 2002; Kuller et al., 2007; Sulabo et al., 2010); however, the length of time in which improvements continue after weaning varies. The greatest response to creep feeding often occurs in the first 3-weeks post-weaning, but like the results reported herein, may not occur until after approximately 4-d post-weaning (Muns and Magowan, 2018; Middelkoop et al., 2020).

After phase 1 in the nursery, a significant interaction was observed between sire line and creep feed that continued throughout the remainder of the experiment. Creep feed did not elicit growth performance differences in early maturing pigs; however, late maturing pigs that were offered creep feed had improved ADG and ADFI compared to late maturing pigs not offered creep feed. This response was observed in the nursery and finishing phases of production. In contrast, previous studies reporting the effect of creep feed on lifetime pig performance have not found lasting differences (Kuller et al., 2007; Muns and Magowan, 2018). To our knowledge this is the first experiment that has evaluated the effect of creep feeding on different pig genotypes. Hence, it appears that creep feeding provided greater benefit to late maturing pigs compared to early maturing pigs, despite the limited number of creep feed eaters that were identified in the late maturing pig population prior to weaning. The increased number of eaters in the early maturing population may explain the improved feed intake and BW gain immediately after weaning compared to late maturing pigs. This would agree with previous reports, where eaters of creep exhibit greater feed intake and BW gain post-weaning compared to non-eaters (Bruininx et al., 2002; Kuller et al., 2007; Sulabo et al., 2010).

While genetic selection generally focuses on traits related to improved production performance, selection for host defense and/or pathogen tolerance may be an opportunity to improve the immunity of pigs (Guy et al., 2012; Ballester et al., 2020). Likewise, stress hormones such as cortisol measured in hair are reported to have medium to high heritability, indicating that genetic selection may also influence chronic stress (Ballester et al., 2020). Both immune health and chronic stress have the potential to further impact growth performance; and hence are important traits to also consider in genetic selection programs. In the current study, chronic stress was not assessed; however, cortisol measured 30-min post-weaning was higher than that measured prior to weaning, indicating an increased stress response. The response observed was significantly increased in late maturing pigs compared to early maturing pigs. Because stress has also been shown to alter pig behavior (Worsaae and Schmidt, 1980), increased serum cortisol concentrations in response to weaning may have contributed to the low feed intake and reductions in body weight gain observed in late maturing pigs compared to early maturing pigs immediately post-weaning.

Moeser et al. (2006) observed elevated serum cortisol concentrations during the first 7 d post-weaning compared to unweaned, age-matched pigs. Weaned pigs averaged a cortisol of approximately 40 ng/mL, while unweaned pigs averaged < 30 ng/mL. In a later study, Moeser et al. (2007) observed serum cortisol ranging from 40 to 65 ng/ml in weaned pigs compared to 20 to 30 ng/mL for unweaned pigs. The unweaned cortisol levels observed in both Moeser et al. (2006, 2007) studies agree with the results observed herein. However, the post-weaning cortisol levels in the present study were increased compared to Moeser et al. (2006, 2007). This is likely a result of timing because Moeser et al. (2006, 2007) bled pigs 24-h post-weaning compared to 30-min post-weaning. In pigs exposed to multiple different stressors, cortisol levels are shown to peak within 4 h of exposure, depending on the duration of exposure (Becker et al., 1985). The wean pig cortisol levels observed by Moeser et al. (2006, 2007) may suggest that cortisol levels remain elevated 24-h after stress exposure.

Activation of the bodies central stress response system can have significant effects on intestinal barrier and immune function. Moeser et al. (2006, 2007) observed that weaning increased intestinal permeability; however, changes in cortisol were not correlated with intestinal function. In the present study, changes in blood cortisol were observed, but no differences in intestinal permeability were seen. However, numeric differences did exist, with late maturing pigs that did not receive creep feed prior to weaning having the highest LMR. An increased LMR indicates increased intestinal permeability and may be related to the poorer growth performance observed in late maturing pigs that did not receive creep feed. This response occurred in combination with increased serum cortisol concentrations and decreased feed intake post-weaning in late maturing pigs. Additionally, late maturing pigs that were not provided creep feed had the poorest performance throughout the nursery and finishing phase of production, resulting in a significantly lighter pig BW at market. Hence, late maturing pigs that did not receive creep feed may have been displaying some degree of intestinal dysfunction. More research is needed to better understand this potential effect. The significant response observed in intestinal permeability by Moeser et al. (2006, 2007) compared to the lack of response herein may be a result of method used to assess permeability.

Dual sugar tests are conducted by administering oral markers such as lactulose and mannitol (Wijtten et al., 2011). Lactulose is a disaccharide with high molecular weight (342 Da), while mannitol is a monosaccharide with a low molecular weight (182 Da). Both sugars are not metabolized by the body and are affected similarly through the digestion process. Lactulose moves in small quantities across the intestinal wall via paracellular transport, whereas mannitol moves more readily across the epithelium via transcellular transport. Thus, the lactulose to mannitol ratio has been used in human medicine to determine intestinal permeability.

Lactulose and mannitol recovery can be measured in blood or urine. However, of the available pig studies, urine has been assessed most frequently, despite blood being an easier collection method. Using the same lactulose and mannitol dosage as the present study, Zhang and Guo (2009) and Li et al. (2018) measured the concentration of lactulose and mannitol in pigs approximately 40 d of age by collecting urine over a 6-h or 12-h period, respectively. The LMR in both studies ranged from 0.087 to 0.135 or 0.046 to 0.068, respectively. In the current study, the concentration of lactulose and mannitol in pigs approximately 28 d of age was measured by collecting a single blood sample. The LMR ranged from 0.18 to 0.50. Differences in LMR may be related to pig age, collection medium (blood versus urine), or duration of fasting prior to sugar administration. A series of experiments conducted in chickens assessed intestinal permeability by measuring lactulose and mannitol concentrations in blood. Gilani et al. (2017a) reported that lactulose and mannitol sugars could be detected in blood up to 90 min post sugar gavage. However, the greatest increase in lactulose and mannitol concentrations was observed from between 30 and 60 min, with minimal changes observed thereafter. Because fasting has been shown to increase IP (Gilani et al., 2018), a 2-h fast was used in the present study rather than an overnight fast. The experiments conducted by Gilani et al. (2017a, 2017b, 2018) showed LMR's ranging from 0.08 to 0.43, depending on fasting duration. These data more closely align with the LMR observed herein compared to the studies where urine was collected.

Limited differences in CBC and serum chemistry were observed. Of the differences detected between sire lines, early maturing pigs had increased monocytes, plasma proteins, and fibrinogen concentrations compared to late maturing pigs. In contrast, late maturing pigs had increased creatinine concentrations. Creep fed pigs also had increased monocyte concentrations compared to pigs that did not receive creep feed. Despite these differences, the reported values for all treatments were in normal ranges, except for creatinine which was slightly below reference values. Likewise, for the response criteria where no differences were observed, the values reported fell within normal reference ranges.

Activation of the stress response system stimulates corticotropin releasing hormone and the subsequent secretion of glucocorticoids, epinephrin, and norepinephrine. It is well established that glucocorticoids have immunosuppressive and anti-inflammatory properties (Elenkov et al., 1999). When released in response to stress induced signals from the hypothalamus, glucocorticoids such as cortisol, decrease circulating monocytes (Booth, 1998; van Furth and Beekhuizen, 1998). Monocytes are responsible for the secretion of pro-inflammatory cytokines; hence, lower levels of pro-inflammatory cytokines result in decreased inflammation. Tissue inflammation in the body has been linked to fibrinogen concentrations, such that an increased inflammatory response results in increased circulating fibrinogen (Esmon, 2005). Fibrinogen is an acute phase protein responsible for protecting the body against vascular injury by activating coagulation, therefore, leading to increased risk of blood clots. In addition to fibrinogen, albumin and globulin are other proteins found in blood circulation. However, because no differences were detected in these proteins between treatments, the increased level of plasma proteins observed in early maturing pigs compared to late maturing pigs was driven by increased fibrinogen concentrations. Glucocorticoids are also responsible for mobilizing energy reserves in response to stress (Braun and Marks, 2015). Consequently, excessive mobilization of body proteins can lead to energy store depletion and subsequent reductions in muscle mass. Administration of synthetic corticosteroids have been shown to increase plasma creatinine, which is a product of muscle tissue degradation (Andreev et al., 1999). Increased creatinine levels are also linked to dehydration (Bongers et al., 2018). Hence, weaning appears to have caused an increased stress response and subsequent shift in immune function in late maturing pigs compared to early maturing pigs, resulting in increased cortisol levels, decreased concentrations of monocytes and fibrinogen, and increased creatinine. Collectively, these physiological responses may have driven the reductions in feed intake and subsequent body weight loss observed in late maturing pigs immediately post-weaning.

In summary, early maturing pigs exhibited decreased stress and improved feed intake and BW gain immediately after weaning. Improved ADG and ADFI persisted until approximately 100 kg or 136 d of age, at which point late maturing pigs began to exhibit greater ADG. Late maturing pigs also had improved feed efficiency throughout much of the experiment. Interestingly, it appears that creep feeding late maturing pigs resulted in improved growth performance compared to providing no creep feed, whereas creep feed had little impact on early maturing pigs.

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Table 6-1. Interactive effect of early or late maturing sire line and creep feed on nursery pig growth perforamnce[1]

Item	Sire line maturity:	Early		Late			*P* =		
	Creep feed:	No	Yes	No	Yes	SEM	Sire maturity	Creep feed	Interaction
Litter, n		6	6	4	5	-	-	-	-
Nursery pens, n		13	13	12	13	-	-	-	-
Body weight, kg									
24 h[2]		1.6	1.6	1.5	1.4	0.21	0.244	0.758	0.845
d 4[2,3]		2.4	2.4	2.2	2.2	0.30	0.265	0.975	0.975
d 21 (weaning)[4]		6.4	6.7	6.1	6.2	0.07	< 0.001	< 0.001	0.083
d 24		6.8	7.1	6.2	6.3	0.08	< 0.001	0.005	0.070
d 31		8.3	8.8	7.0	7.3	0.14	< 0.001	0.002	0.429
d 46		15.7	16.4	12.1	13.9	0.31	< 0.001	< 0.001	0.198
d 67		30.4[a]	30.5[a]	24.7[c]	27.1[b]	0.51	< 0.001	0.012	0.024
d 76		39.8[a]	39.5[a]	33.0[c]	36.1[b]	1.36	< 0.001	0.022	0.006
Percentage of pigs without weight gain after weaning, %[5]									
d 24		7.7	3.1	40.4	38.5	6.80	< 0.001	0.270	0.350
d 31		0.0	0.0	9.6	9.4	4.09	0.967	0.999	0.999
Phase 1 (d 21 to 24)									
ADG, g		127	139	40	29	15.9	< 0.001	0.957	0.452
ADFI, g		124	133	72	78	7.6	< 0.001	0.340	0.815
G:F, g/kg		1,001	1,038	103	21	289.1	0.001	0.936	0.832
Phase 1 (d 21 to 31)									
ADG, g		185	211	90	111	11.2	< 0.001	0.036	0.820
ADFI, g		236	261	151	165	10.4	< 0.001	0.067	0.585
G:F, g/kg		780	802	581	655	32.0	< 0.001	0.131	0.408
Phase 2 (d 31 to 46)									
ADG, g		492[a]	503[a]	341[c]	416[b]	0.033	< 0.001	0.005	0.030
ADFI, g		654[a]	651[a]	460[c]	534[b]	16.2	< 0.001	0.026	0.018
G:F, g/kg		752	772	742	779	12.8	0.923	0.028	0.491
Phase 3 (d 46 to 67)									
ADG, g		701[a]	674[ab]	600[c]	646[b]	14.0	< 0.001	0.488	0.010
ADFI, g		1,125[a]	1,072[a]	856[c]	792[b]	20.5	< 0.001	0.122	< 0.001
G:F, g/kg		624[c]	629[c]	701[a]	664[b]	8.5	< 0.001	0.063	0.015
Phase 4 (d 67 to 76)									
ADG, g		1023[a]	991[a]	924[b]	999[a]	20.5	0.027	0.286	0.009

ADFI, g	1793[a]	1719[a]	1483[c]	1598[b]	31.9	< 0.001	0.514	0.004
G:F, g/kg	571	577	625	626	9.0	< 0.001	0.662	0.751
Overall (d 21 to 76)								
ADG, g	602[a]	595[a]	489[c]	541[b]	10.9	< 0.001	0.036	0.007
ADFI, g	942[a]	916[a]	721[c]	805[b]	16.1	< 0.001	0.073	< 0.001
G:F, g/kg	639	650	679	672	6.5	< 0.001	0.727	0.186

[1] A total of 247 mixed sex pigs (early or late maturing Duroc × DNA 241) were used with 4 or 5 pigs per pen and 12 or 13 replications per treatment. Treatments were arranged in a 2 × 2 factorial with main effect of Duroc sire line (early vs. late maturing) and creep feeding (with or without).

[2] Analyzed using litter as the experimental unit.

[3] All pigs were weighed 14 d prior to weaning to allot litters to creep feed. Therefore, d of age ranged from 4 to 7.

[4] Weaning ranged from 18 to 21 d of age.

[5] Percentage of pigs that gained ≤ 0 kg from d 0 to 3 or 0 to 10 post-weaning.

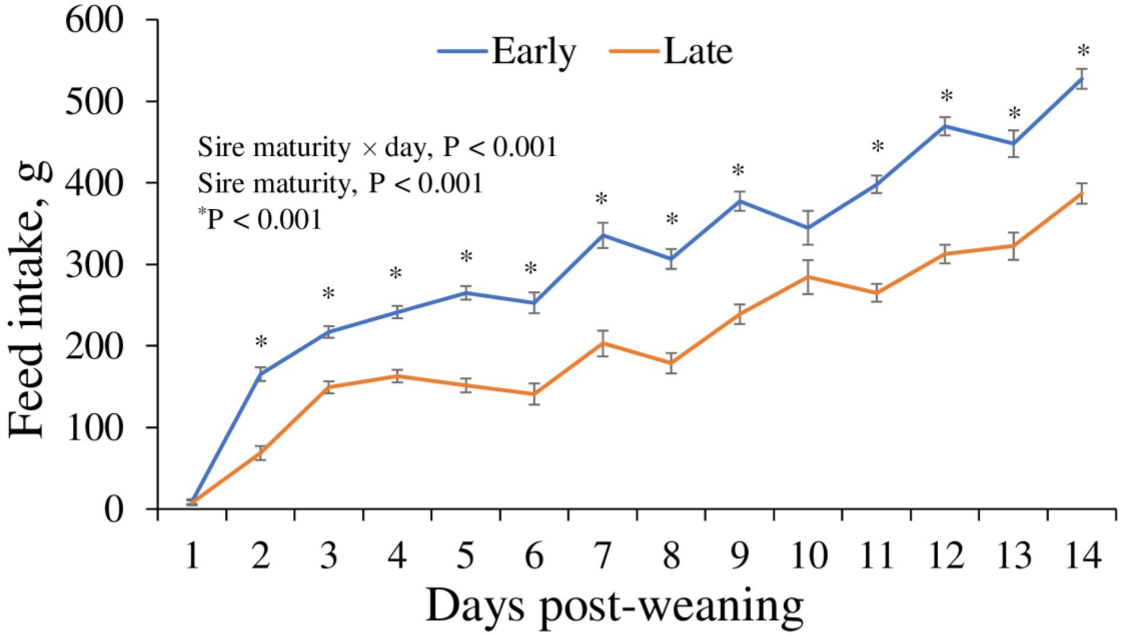

Figure 6-1. Interactive effect of sire line (early or late maturing Duroc sire) and day on daily feed intake the first 14 d in the nursery. Error bars represent +/- 1 standard error from the mean.

Table 6-2. Interactive effect of early or late maturing sire line and creep feed on finishing pig growth performance and carcass characteristics[1]

Sire line maturity:	Early		Late			*P* =		
Item Creep feed:	No	Yes	No	Yes	SEM	Sire maturity	Creep feed	Interaction
Pens, n	8	9	7	8	-	-		-
Body weight, kg								
d 76	39.8^{a}	39.5^{a}	32.9^{c}	36.2^{b}	0.78	< 0.001	0.052	0.022
d 94	57.1^{a}	56.7^{a}	48.5^{c}	52.7^{b}	0.97	< 0.001	0.042	0.017
d 108	72.2^{a}	71.2^{a}	63.2^{c}	67.5^{b}	1.20	< 0.001	0.156	0.029
d 122	88.3	87.6	79.4	83.7	1.37	< 0.001	0.167	0.062
d 136	104.7	104.0	95.2	100.3	1.57	< 0.001	0.149	0.063
d 154	125.5^{a}	124.4^{a}	116.3^{b}	122.5^{a}	1.59	0.001	0.099	0.022
d 170	143.0^{a}	141.4^{a}	134.7^{b}	142.0^{a}	1.55	0.015	0.059	0.005
d 76 to 94								
ADG, g	960	955	874	921	18.6	0.002	0.239	0.148
ADFI, g	2,021^{a}	2,005^{a}	1,699^{c}	1,841^{b}	32.1	< 0.001	0.046	0.014
G:F, g/kg	475	477	514	500	7.30	< 0.001	0.364	0.267
d 94 to 108								
ADG, g	1,077	1,036	1,053	1,052	24.2	0.868	0.364	0.392
ADFI, g	2,553	2,527	2,273	2,373	57.0	< 0.001	0.493	0.250
G:F, g/kg	422	411	463	443	5.67	< 0.001	0.006	0.431
d 108 to 122								
ADG, g	1,153	1,173	1,152	1,157	19.8	0.645	0.510	0.705
ADFI, g	3,053	3,060	2,814	2,957	54.7	0.003	0.155	0.194
G:F, g/kg	378^{b}	384^{b}	410^{a}	392^{b}	5.3	< 0.001	0.230	0.025
d 122 to 136								
ADG, g	1,165	1,166	1,161	1,184	33.7	0.829	0.700	0.729
ADFI, g	3,262	3,297	3,153	3,269	59.4	0.229	0.184	0.477
G:F, g/kg	358	354	368	362	8.9	0.274	0.587	0.946
d 136 to 154								
ADG, g	1,155	1,133	1,186	1,235	19.7	0.001	0.481	0.067
ADFI, g	3,679^{a}	3,553^{a}	3,394^{b}	3,605^{a}	49.2	0.017	0.361	0.001
G:F, g/kg	314	319	350	343	5.45	< 0.001	0.835	0.236
d 154 to 170								
ADG, g	1,180	1,245	1,078	1,068	28.8	< 0.001	0.315	0.176

ADFI, g	3,704[ab]	3,612[bc]	3,557[c]	3,792[a]	47.9	0.717	0.124	0.001
G:F, g/kg	291	295	332	329	7.0	< 0.001	0.938	0.591
Overall (d 76 to 170)								
ADG, g	1,094[b]	1,084[b]	1,093[b]	1,129[a]	11.0	0.042	0.209	0.037
ADFI, g	3,031[a]	2,999[a]	2,785[b]	2,963[a]	38.6	< 0.001	0.054	0.007
G:F, g/kg	361	362	393	381	3.7	< 0.001	0.130	0.093
Carcass characteristics								
HCW, kg	102.4	102.7	96.9	102.3	1.69	0.057	0.067	0.100
Yield, %	72.1	72.9	72.4	72.6	0.28	0.945	0.049	0.280
Backfat, mm	16.6	16.3	15.8	15.9	0.49	0.181	0.818	0.573
Loin depth, mm	61.2[b]	63.9[a]	65.8[a]	64.0[a]	0.97	0.010	0.586	0.011
Lean, %	53.5	54.0	54.5	54.1	0.27	0.032	0.684	0.066

[1] A total of 241 mixed sex pigs (early or late maturing Duroc × DNA 241) were used with 7 or 8 pigs per pen and 7 or 8 replications per treatment. Treatments were arranged in a 2 × 2 factorial with main effect of Duroc sire line (early vs. late maturing) and creep feeding (with or without).

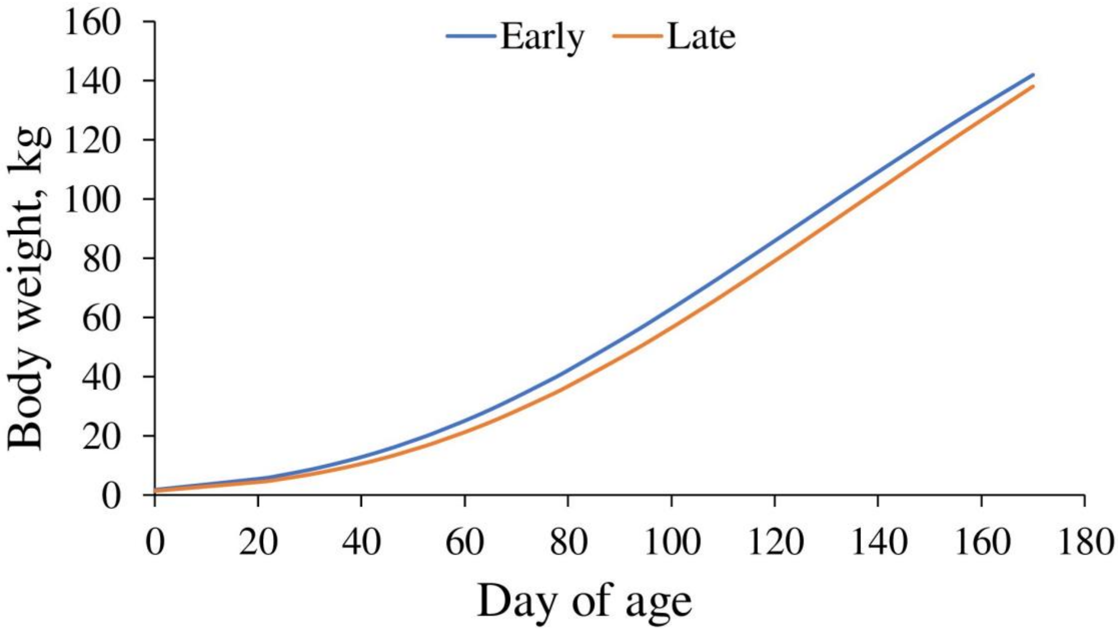

Figure 6-2. Effect of sire line (early or late maturing Duroc sire) on the cumulative growth curve (Gompertz model) of pigs from birth to market.

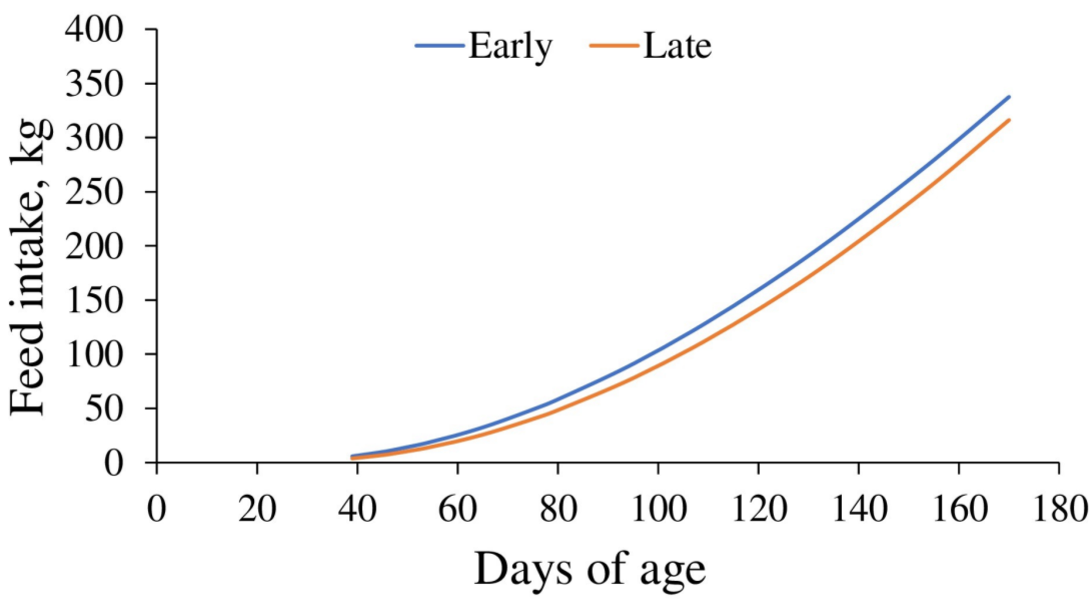

Figure 6-3. Effect of sire line (early or late maturing Duroc sire) on the cumulative feed intake curve (cubic model) of nursery and finishing pigs.

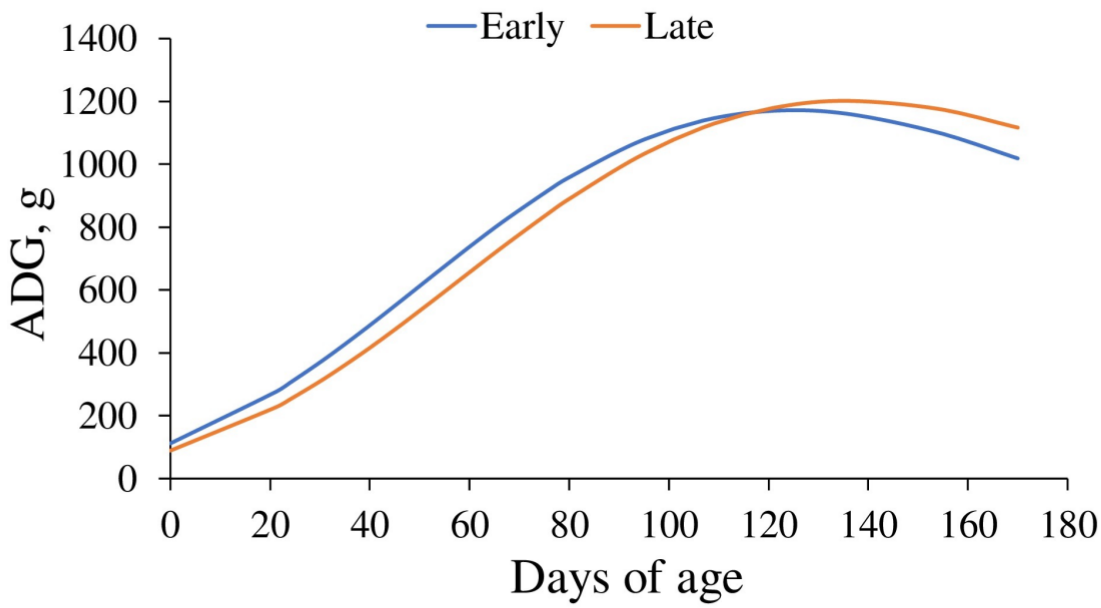

Figure 6-4. **Effect of sire line (early or late maturing Duroc sire) on the modeled average daily gain (derivative of cumulative body weight from Gompertz model) of pigs from birth to market.**

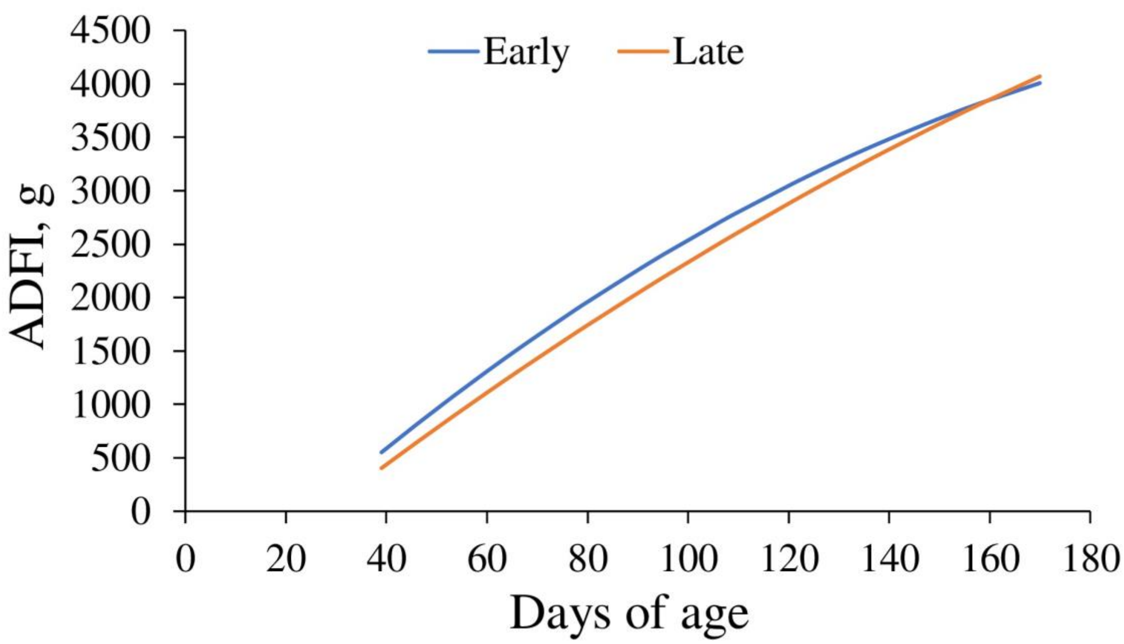

Figure 6-5. **Effect of sire line (early or late maturing Duroc sire) on the modeled average daily feed intake (derivative of cumulative feed intake from cubic model) of nursery and finishing pigs.**

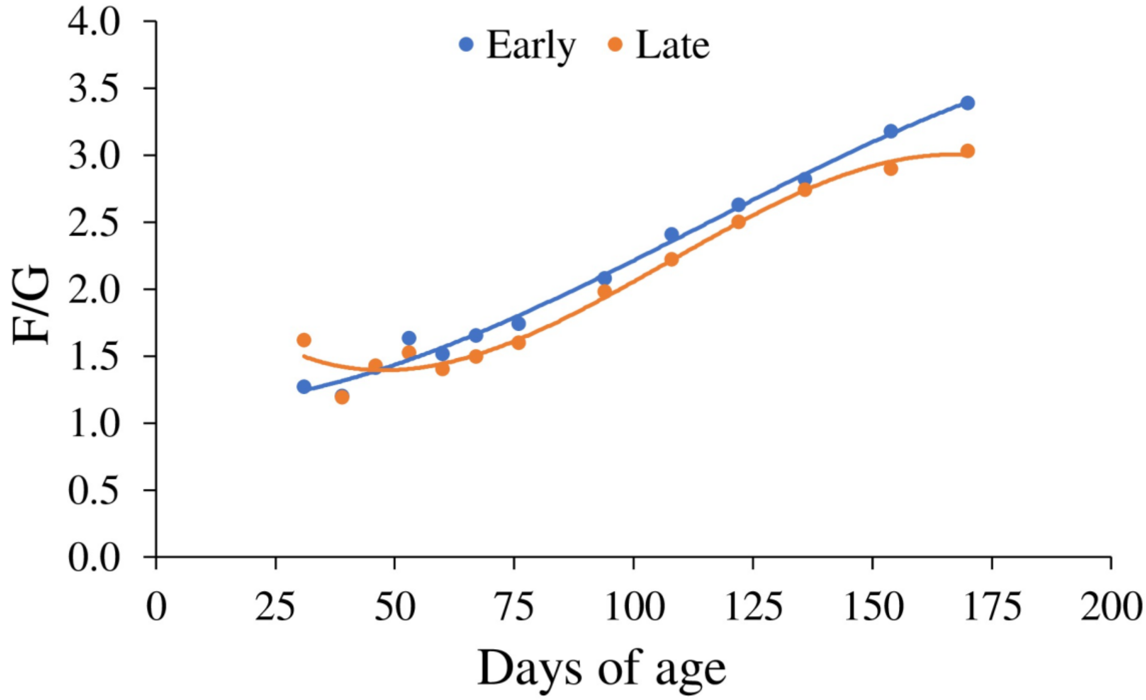

Figure 6-6. **Effect of sire line (early or late maturing Duroc sire) on the feed efficiency (using LS-means) of nursery and finishing pigs.**

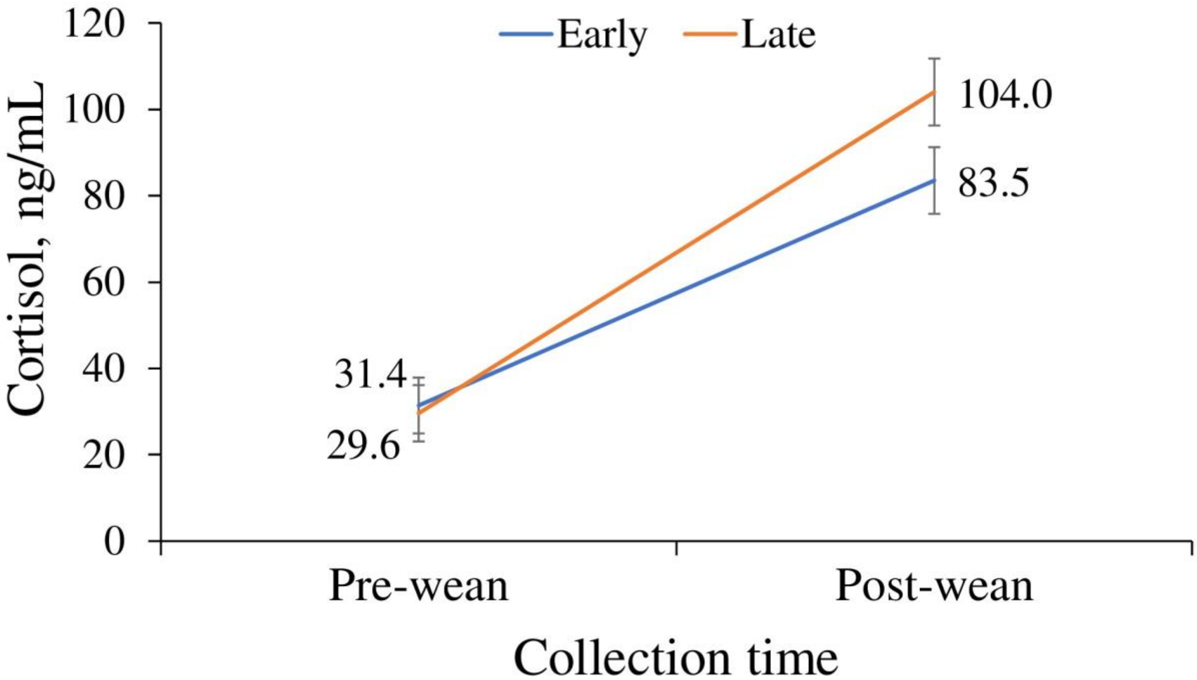

Figure 6-7. Interactive effect of sire line (early or late maturing Duroc sire) and collection time on the cortisol level of pigs around weaning. No differences were observed between sire line maturity pre-weaning (*P* = 0.590), but differences were observed post-weaning (*P* = 0.002). Pre-wean cortisol was collected the day prior to weaning and post-wean cortisol was collected 30-minutes after weaning. Error bars represent +/- 1 standard error from the mean.

Table 6-3. Main effect of early or late maturing sire line and creep feed on the complete blood count of nursery pigs[1]

	Sire maturity				Creep feed			
Item	Early	Late	SEM	*P* =	No	Yes	SEM	*P* =
Pigs, n	14	13	-	-	13	14	-	-
Leukocyte, K/uL	15.1	13.2	0.99	0.175	13.3	15.0	0.99	0.234
Erythrocyte, M/uL	6.65	6.47	0.12	0.284	6.66	6.46	0.18	0.232
Hemoglobin, g/dL	12.9	12.8	0.242	0.737	12.9	12.8	0.242	0.706
Cellular hemoglobin, g/dL	11.8	11.6	0.24	0.578	11.8	11.6	0.24	0.626
Cell volume, fL	62.5	64.1	0.84	0.186	62.6	63.9	0.84	0.251
Cell hemoglobin, pg	19.4	19.8	0.28	0.385	19.4	19.8	0.28	0.327
Mean cell hemoglobin, g/dL	28.4	28.1	0.26	0.325	28.3	28.2	0.26	0.689
Red blood cell distribution, %	18.7	19.0	0.65	0.779	18.7	19.1	0.65	0.647
Segmented neutrophil, K/uL	6.3	5.3	0.83	0.361	5.3	6.3	0.83	0.414
Lymphocyte, K/uL	7.5	6.9	0.49	0.440	7.0	7.4	0.49	0.572
Monocyte, K/uL	1.14	0.80	0.111	0.041	0.81	1.13	0.111	0.050
Eosinophil, K/uL	0.19	0.18	0.035	0.825	0.19	0.19	0.03	0.941
Basophil, K/uL	0.04	0.07	0.023	0.442	0.05	0.06	0.023	0.582
Hematocrit, %	40.1	39.9	0.97	0.916	39.9	40.1	0.97	0.834
Plasma protein, g/dL	5.8	5.5	0.08	0.049	5.5	5.7	0.08	0.126
Fibrinogen, mg/dL	336	207	37.9	0.022	243	300	37.8	0.288

[1] A total of 27 gilts (early or late maturing Duroc × DNA 241) were used to assess complete blood count 7 d post-weaning. Treatments were arranged in a 2 × 2 factorial with main effect of sire line (early vs. late maturing) and creep feeding (with or without). One blood sample of approximately 6 mL was collected from the external jugular vein using a lavender stopper tube with EDTA. Whole blood was immediately sent to the Kansas State University Veterinary Diagnostics Laboratory for analysis.

Table 6-4. Main effect of early or late maturing sire line and creep feed on the serum chemistry of nursery pigs[1]

	Sire maturity				Creep feed			
Item	Early	Late	SEM	*P* =	No	Yes	SEM	*P* =
Pigs, n	14	14	-	-	14	14	-	-
Glucose, mg/dL	106	103	2.8	0.356	105	103	2.8	0.642
Urea nitrogen, mg/dL	8.1	9.4	0.93	0.366	8.57	8.93	0.93	0.789
Creatinine, mg/dL	0.83	0.96	0.042	0.041	0.88	0.91	0.042	0.635
Total protein, g/dL	4.8	4.6	0.08	0.218	4.6	4.7	0.08	0.266
Albumin, g/dL	3.5	3.4	0.10	0.505	3.4	3.5	0.10	0.959
Globulin, g/dL	1.3	1.2	0.06	0.584	1.2	1.3	0.06	0.190
Total calcium, mg/dL	10.7	10.7	0.18	0.800	10.8	10.7	0.18	0.633
Phosphorus, mg/dL	8.9	8.7	0.29	0.567	8.9	8.7	0.29	0.614
Sodium, mmol/L	137	138	0.5	0.167	138	138	0.5	0.424
Potassium, mmol/L	6.0	6.3	0.15	0.271	6.0	6.3	0.15	0.271
Chloride, mmol/L	99	100	0.5	0.087	99	99	0.5	0.917
Bicarbonate, mmol/L	25.6	26.3	0.70	0.432	26.4	25.5	0.70	0.354
Anion gap, mmol/L	19.9	19.5	0.68	0.658	19.5	19.9	0.68	0.658
Sodium potassium ratio	23.0	22.3	0.62	0.420	23.2	22.1	0.62	0.202
Aspartate transaminase P5P, U/L	71.6	76.1	15.06	0.837	70.3	77.4	15.06	0.740
Alkaline phophatase, U/L	407	394	22.3	0.678	398	403	22.3	0.879
Gamma glutamyl transferase, U/L	35.2	32.8	3.48	0.626	34.9	33.1	3.48	0.731
Sorbitol dehydrogenase, U/L	0.31	0.32	0.016	0.533	0.33	0.30	0.016	0.218
Creatine kinase, U/L	2,219	1,914	643.8	0.741	2,006	2,128	643.8	0.895
Total bilirubin, mg/dL	0.20	0.25	0.031	0.261	0.24	0.21	0.031	0.419

[1] A total of 28 gilts (early or late maturing Duroc × DNA 241) were used to assess serum chemistry 7 d post-weaning. Treatments were arranged in a 2 × 2 factorial with main effect of sire line (early vs. late maturing) and creep feeding (with or without). One blood sample of approximately 6 mL was collected from the external jugular vein using a silicone coated red stopper tube with no additive. Serum was separated by centrifugation (20 min at 10,000 g) and then sent to the Kansas State University Veterinary Diagnostics Laboratory for analysis.

Table 6-5. Interactive effect of early or late maturing sire line and creep feed on the intestinal permeability of nursery pigs[1]

Item	Sire maturity:	Early		Late			P =		
	Creep feed:	No	Yes	No	Yes	SEM	Sire maturity	Creep feed	Interaction
Pigs, n		6	6	7	7	-	-		-
Serum Lactulose, umol/L		5.3	8.2	7.3	8.6	3.70	0.740	0.565	0.815
Serum Mannitol, umol/L		31.4	32.7	14.1	44.8	9.38	0.775	0.092	0.119
LMR[2]		0.18	0.37	0.50	0.36	0.170	0.400	0.892	0.362

[1] A total of 26 gilts (early or late maturing Duroc × DNA 241) were used to assess intestinal permeability 7 d post-weaning. Treatments were arranged in a 2 × 2 factorial with main effect of sire line (early vs. late maturing) and creep feeding (with or without). After a 2 h fast, each gilt was administered an oral gavage solution of lactulose (500 mg/kg body weight; Fisher Scientific, Pittsburgh, PA) and mannitol (50 mg/kg body weight; Sigma-Aldrich, St. Louis, MO), dissolved in distilled water. Sixty minutes following sugar administration, a blood sample of approximately 6 mL was collected from the external jugular vein from each gilt using a silicone coated red stopper tube with no additive. Serum was separated by centrifugation (20 min at 10,000 × g) and stored at -20C until samples were sent to the University of Illinois for high performance liquid chromatography analysis of lactulose and mannitol concentrations.

[2] Lactulose: mannitol ratio (LMR) was calculated by converting lactulose and mannitol concentrations to umol/L using the molecular weight of each sugar, and then calculating their ratio.