Maintaining continuity of nutrient intake after weaning. II. Review of post-weaning strategies

Madie R. Wensley,[†,1] **Mike D. Tokach,**[†] **Jason C. Woodworth,**[†] **Robert D. Goodband,**[†] **Jordan T. Gebhardt,**[‡] **Joel M. DeRouchey,**[†] **and Denny McKilligan**[‖]

[†]Department of Animal Sciences and Industry, College of Agriculture, Manhattan, KS 66506-0201, USA; [‡]Department of Diagnostic Medicine/Pathobiology, College of Veterinary Medicine, Kansas State University, Manhattan, KS 66506-0201, USA; and [‖]TechMix Inc., Stewart, MN 55385, USA

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 µm) 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.

Key words: feed intake, nutrient disruption, pig, post-weaning

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[1]Corresponding author: wensleym@ksu.edu
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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 feed intake (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 FI

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 FI.

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, 2006). Consequently, feed deprivation (72 h) 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 FI 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 °C 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 h 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 FI. 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 FI. 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 FI 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 h, 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 FI 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 versus 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 μm is known to improve feed efficiency, whereas for pelleted diets, a particle size as fine as 350 μm 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 μm) 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 FI (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 GI 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., 2019a). 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., 2019a).

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., 2019b). 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 GI health and FI. 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., 2015). 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., 2019b). 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 5–7 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 µm) 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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