Invited Review: Management and feeding strategies to ameliorate the impact of removing antibiotic growth promoters from diets fed to weanling pigs

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Kil, D. Y. and Stein, H. H. 2010. **Board Invited Review: Management and feeding strategies to ameliorate the impact of removing antibiotic growth promoters from diets fed to weanling pigs**. Can. J. Anim. Sci. **90**: 447–460. A review of the literature was conducted with the objective of identifying management and feeding strategies for weanling pigs that are effective in reducing the negative impacts of discontinued use of antibiotic growth promoters (AGP) in diets fed to weanling pigs. If no AGP are used, dietary crude protein concentrations should be reduced to less than 18% in diets fed to pigs during the immediate post-weaning period. Diets should be fed in a liquid form if possible, preferably as fermented liquid feed. Feed intake should be restricted to 75% of ad libitum intake during the initial 2 wk post-weaning to reduce the amount of substrates available to pathogens in the hind gut. The profit from pig production will be maximized if pigs are weaned between 21 and 28 d of age. All-in all-out production should be practiced and pigs should always be weaned into an empty, clean, and disinfected room, preferably at a location separated from the sow farm. Disease pressure and mortality do not necessarily have to increase if no AGP are used, but profits will likely be reduced because costs of preventing diseases in pigs fed diets containing no AGP often are greater than the cost of AGP.

Key words: Alternatives, antibiotics, management strategies, pigs, weaning

Kil, D. Y. et Stein, H. H. 2010. **Revue commandée par la rédaction: stratégies d'élevage et d'engraissement pour compenser l'impact du retrait des antibiotiques employés comme facteur de croissance dans la ration des porcelets sevrés**. Can. J. Anim. Sci. **90**: 447–460. Les auteurs ont compulsé la documentation scientifique afin d'identifier les stratégies d'élevage et d'engraissement susceptibles d'atténuer les répercussions de l'abandon des antibiotiques en tant que stimulateur de croissance dans la ration des porcelets sevrés. Lorsqu'on n'utilise pas d'antibiotique comme facteur de croissance, la concentration de protéines brutes dans la ration devrait être inférieure à 18% immédiatement après le sevrage. Dans la mesure du possible, les aliments seront liquides et, de préférence, fermentés. Au cours des deux semaines suivant le sevrage, l'ingestion des aliments ne dépassera pas 75% de la quantité ingurgitée à satiété, afin de diminuer le volume de substrats à la disposition des microorganismes pathogènes dans l'intestin postérieur. On maximisera les profits de l'entreprise si les animaux sont sevrés entre 21 et 28 jours. On privilégiera aussi la technique de production du tout-plein tout-vide et le sevrage se fera dans une salle vide, propre et désinfectée, de préférence à l'écart de l'endroit où sont gardées les truies. Les maladies et le taux de mortalité n'augmenteront pas nécessairement si on retire les antibiotiques des rations, mais on assistera sans doute à une baisse des bénéfices, car prévenir la maladie chez les porcelets ne recevant pas d'antibiotiques coûtera plus cher que l'achat des antibiotiques eux-mêmes.

Mots clés: Solutions de rechange, antibiotiques, stratégies d'élevage, porcs, sevrage

Antibiotics have been used in animal production for more than 50 yr, and the practice of feeding antibiotics as growth promoters has become an integral part of developing nutritional strategies for swine (Close 2000). It is well documented that antibiotic growth promoters (AGP) improve growth performance and reduce diarrhea and mortality (Cromwell et al. 1996; Weber et al. 2001; Kyriakis et al. 2002). On average, growth rate is improved by 16.4% in weanling pigs, 10.6% in growing pigs, and 4.2% in growing-finishing pigs if AGP are used (Cromwell 2001). Likewise, feed efficiency is improved by an average of 6.9% in weanling pigs, 4.5% in growing pigs, and 2.2% in growing-finishing pigs if AGP are included in the diet. Inclusion of AGP in diets fed to pigs also reduces mortality and morbidity by approximately 50% (from 4.3 to 2.0%). The reduction in mortality is more prominent under high disease conditions in young pigs than under high health conditions (Cromwell 2001). It is generally accepted that the beneficial effects of AGP are a consequence of suppression of some pathogenic bacteria within the animal's digestive tract, increased feed utilization, and stimulation of metabolic processes throughout the animal, although the exact mechanisms by which AGP influence pig performance are not completely understood (Doyle 2001). It has been estimated that AGP are

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Abbreviation: **AGP**, antibiotic growth promoters included in 80 to 90% of pig starter feeds, 70 to 80% of grower feeds, 50 to 60% of finisher feeds, and 40 to 50% of sow feeds in the United States (Cromwell 2001). Seventeen antimicrobial agents (12 antibiotics and 5 chemotherapeutics) are currently approved by FDA for use in swine feeds in the United States.

Despite the positive impact on pig performance of AGP, there are concerns that the use of AGP in animal feeds can result in the development of antibiotic-resistant bacterial strains and antibiotic residue problems in animal products (Bager et al. 2000; Gallois et al. 2009). It is also perceived that these antibiotic-resistant strains can be transferred to humans, which may impair the effectiveness of certain antibiotics in the treatment of human diseases (den Bogaard and Stobberingh 1999; Bager et al. 2000; Carroll 2003). As a result of these concerns, the use of AGP in swine diets has been discontinued in the European Union and a similar approach has been suggested for the United States. However, the discontinuation of using AGP may reduce performance and increase the therapeutic use of antibiotics because enteric diseases in particular are difficult to control with no use of in-feed antibiotics (Casewell et al. 2003). In Sweden, where AGP in feed have not been used since 1986, the discontinuation of using AGP resulted in an increase in the amount of prescription medication used in swine production (Mudd et al. 1998). In Denmark, discontinuation of the use of AGP resulted in increased problems with post-weaning diarrhea and chronic infections of weanling pigs due to *Lawsonia intracellularis*, which caused reduced weight gain and increased mortality (Callesen 2002; Kjeldsen 2002). As a result of these problems, the therapeutic use of antibiotics in Denmark increased after the removal of AGP from swine diets (Larsen 2002; Casewell et al. 2003). It is, therefore, likely that if the usage of AGP is discontinued in North America, an increase in the usage of therapeutic antibiotics may be the result. Reduced pig performance and increased mortality can also be expected due to reduced health of pigs. The consequences of discontinued use of AGP for human health are unclear as the removal of AGP from Danish livestock production resulted in increased incidences of salmonellosis and campylobacter problems in humans (Casewell et al. 2003).

Because AGP have the most beneficial effect in diets fed to newly weaned pigs, the adverse effects associated with not using AGP are greatest in weanling pigs (Kjeldsen 2002). It is, therefore, important that procedures to alleviate these problems be identified. Alternative dietary tools have been described and recent reviews have summarized the research that has been conducted in this area (Pettigrew 2006; Stein and Kil 2006; Gallois et al. 2009; Lallès et al. 2009). However, it is recognized that it is also important to consider many aspects of swine management if pigs are to be successfully produced without AGP (Doyle 2001), but experiences using different management and feeding strategies have not been summarized. The objective of this review, therefore, is to summarize published reports on management and feeding strategies that are used to improve performance of weanling pigs. Some of these strategies will be equally effective in situations with or without AGP, but others may be needed only if AGP are not included in the feed.

WEANING AGE

Early weaning to reduce the transfer of diseases from the sow to the offspring has been used in the North American swine industry for many years. This production system can shorten the farrowing interval and increase the number of litters farrowed per sow per year and the number of pigs weaned per sow per year (Levis 1990). Early weaning (i.e., weaning before pigs are 21 d old) is, however, more likely to contribute to increased mortality (Losinger et al. 1998), decreased growth performance (Leibbrandt et al. 1975), and abnormal behaviors of piglets (Metz and Gonyou 1990). It has been speculated that poor performance of early-weaned pigs compared with pigs weaned at an older age may be attributed to gastrointestinal underdevelopment (Pluske et al. 2003), reduced nutrient utilization (Leibbrandt et al. 1975), reduced disease resistance and an immature immune system (Blecha et al. 1983; Niekamp et al. 2007), reduced intestinal barrier function (Moeser et al. 2007), undesirable morphological changes in the small intestine (Cera et al. 1988), and increased susceptibility to environmental stress. Pigs weaned at 21 d also have a greater ileal pH and a reduced number of *lactobacilli* compared with pigs weaned at 28 d (Mathew et al. 1995). A greater intestinal pH may favor growth of pathogens such as *Escherichia coli*. Weaning pigs at 7 or 14 d of age rather than at 28 d of age markedly increases abnormal behavior including belly nosing and chewing on penmates (Worobec et al. 1999), which may lead to reduced growth performance. It is, therefore, not surprising that improvements in growth performance of weanling pigs has been reported as weaning age was increased (Bonnette et al. 1990; Fangman et al. 1996a; Dunshea et al. 2002; Main et al. 2004; Callesen et al. 2007), although there also are reports of no differences in performance between early- and late-weaned pigs (Shields et al. 1980; Geary and Brooks 1998) or of greater performance for early-weaned pigs than for late-weaned pigs (Hohenshell et al. 2000). However, in most of these experiments, the effects of weaning age on growth performance of weanling pigs were determined in diets containing AGP. In experiments where weanling pigs were fed diets containing no AGP, improved daily gain, feed intake, and feed efficiency during the initial 6 wk post-weaning of pigs weaned at 16 to 21 d compared with pigs weaned at an age of 11 to 16 d was reported (Fangman et al. 1998). Increasing weaning age (6 wk vs. 4 wk) prevented growth reduction and improved enteric health when weanling pigs were challenged with enterotoxigenic *E. coli* (Wellock et al. 2007, 2008a,b). This observation is consistent with the fact that early-weaned pigs have an immature immune system. Ball and Aherne (1987a,b) reported that pigs weaned at 4 wk of age had better growth performance and nutrient digestibility than pigs weaned at 3 wk. However, the incidence of diarrhea was greater in pigs weaned at 4 wk, possibly due to a greater nutrient intake, but the diarrhea disappeared more rapidly in pigs weaned at 4 wk than in pigs weaned at 3 wk.

In experiments with weanling pigs fed diets containing AGP, Cho et al. (2007) reported a linear increase in performance and nutrient digestibility as weaning age increased from 14 to 28 d. Pigs weaned at 20 d also have greater daily gain and feed intake, but reduced morbidity, compared with pigs weaned at 15 d (Smith et al. 2008). The reason for these observations may be that pigs increase their production of digestive enzymes as they get older (Lindemann et al. 1986), which enables them to absorb more nutrients, and therefore, gain more weight.

In Danish experiments with pigs fed diets containing no AGP, pigs weaned at 33 d of age had a greater BW at 81 d of age, reduced mortality, and reduced treatment for diarrhea compared with pigs weaned at 26 d of age (Callesen and Thorup 2004). Treatments for diarrhea were also reduced in pigs weaned at 35 d of age compared with pigs weaned at 29 d (Callesen and Thorup 2005). However, in subsequent experiments, pigs weaned at 33 d of age required the same number or more treatments against diarrhea as pigs weaned at 27 or 28 d of age (Callesen and Thorup 2006; Callesen et al. 2006). The combined conclusions from these experiments are that although weaning weight is greater if pigs are weaned at an older age, there are no subsequent improvements in performance or reductions in treatments against diseases if the weaning age is increased from approximately 26 d to approximately 33 d. This conclusion is in agreement with a Canadian report suggesting that weaning age does not influence the BW of pigs at 53 d of age (Beaulieu and Patience 2005).

Based on economic analyses of all production parameters, it was concluded that under Danish conditions, increasing weaning age from 4 to 5 wk will reduce profits because of fewer pigs farrowed per sow per year (Thorup et al. 2006). From experiments in the United States, it was reported that profits increase if pig weaning age increases from 12 to 21 d (Main et al. 2005). Feed cost per kilogram gain is also reduced if pigs are weaned at 20 d rather than at 15 d (Smith et al. 2008). It is, therefore, likely that profits are maximized if pigs are weaned between 3 and 4 wk of age and there seems to be no technical or economic advantage of weaning later than at 4 wk or earlier than at 3 wk. Based on the conclusions from the Danish experiments it may also be hypothesized that if no AGP are included in the diet fed to weanling pigs, it is likely that profits are maximized if weaning age is close to 4 wk.

SEGREGATED EARLY WEANING

Site-segregated early weaning, or off-site weaning, means that weanling pigs are moved to a nursery that is located on a site that is separated from the breeding herd (Patience et al. 2000), which may eradicate diseases caused by indigenous pathogens that can be transferred from sows to pigs within the herd (Harris 2000). If pigs are weaned at the same age into either on-site or off-site facilities, pigs weaned into off-site facilities have improved body weight gain compared with pigs weaned to on-site facilities (Fangman et al. 1996b; Patience et al. 2000; Levesque et al. 2001; Brown et al. 2002; Beaulieu et al. 2006). Likewise, off-site weaned pigs (average 10 to 14 d at weaning) had improved daily gain and feed intake compared with pigs weaned on-site at an age of 20 to 28 d (Richert et al. 1996; Frank et al. 1998; Kendall et al. 1999), and pigs weaned at days 7 to 10 at off-site facilities were 6.3 and 11.2 kg heavier when pigs were 28 and 50 d of age, respectively, compared with pigs weaned on-site at days 14 to 17 (Dritz et al. 1996). These results indicate that the positive effects of off-site weaning are independent of the weaning age of pigs.

The improved growth performance of pigs weaned off-site compared with pigs weaned on-site is likely due to less antigenic exposure of the pigs' immune system (Richert et al. 1996; Harris 2000) because antigenic challenges in young pigs are often associated with a reduction of growth and feed intake (van Heugten et al. 1994; Dong and Pluske 2007). This hypothesis is consistent with the fact that a stimulation of the immune system will reduce pig performance (Williams et al. 1997).

Site segregation cannot prevent all pathogen-transmission from the sow herd to the weaned pigs (Fangman et al. 1996b; Fangman and Tubbs 1997). In fact, site segregation at an early age may result in pigs being more susceptible to diseases than pigs weaned into traditional on-site systems because pigs weaned into an off-site facility may have a reduced potential of herd immunity due to reduced antigenic exposure (Harris 2000). An immune challenge induced by vaccination also induced slower growth rates in pigs weaned off-site compared with pigs weaned on-site (Drum et al. 1998) indicating that pigs weaned to off-site facilities are more challenged if they are exposed to antigens. Improved growth performance in pigs weaned to off-site facilities is, therefore, obtained only if the health status of the pigs is maintained.

Weaning pigs into a clean environment improves growth performance compared with weaning pigs into a dirty environment (Bassaganya-Riera et al. 2001; Le Floch'h et al. 2006, 2009). It is, therefore, possible that the positive responses observed for pigs weaned to off-site facilities can be explained by the fact that these facilities are operated on an all-in-all-out basis with proper cleaning and disinfection between groups of pigs. If on-site facilities are operated the same way as off-site facilities, performance of pigs weaned on-site may be similar to that of pigs weaned off-site (Fangman et al. 1998), and it is recommended that regardless of whether pigs are weaned to on-site or to off-site facilities, they should always be weaned into clean facilities that are operated on an all-in-all-out basis (Johansen et al. 2004). Pigs weaned into all-in-all-out systems have improved health status and growth performance and decreased activation of the immune system compared with pigs weaned into continuous flow systems (Damgaard and Jensen 2009). Systems based on all-in-all-out pig flow should, therefore, be used for pigs that are weaned off-site as well as for pigs that are weaned on-site (Fangman and Tubbs 1997).

A special form of segregation to improve the health of pigs is to segregate sows by parity. Using this management system, all parity 1 sows are kept in a separate unit while all other sows are kept together. Parity 1 sows are introduced into the unit with the older sows after the first litter has been weaned. The advantage of this system is that parity 1 sows may be handled together and treated according to their needs, which are perceived to be different from the needs of older sows (Boyd et al. 2002). The pigs weaned from parity 1 sows are kept together after weaning and not mixed with pigs from older sows, which is believed to reduce the overall disease level of the pigs from both the parity 1 sows and the older sows (Boyd et al. 2002). The practice of segregating parity 1 sows from older sows, therefore, can be implemented only in relatively large production systems where the flow of gilts is sufficient to produce enough pigs to fill entire barns.

In situations where AGP cannot be used in diets fed to weanling pigs, the importance of controlling pathogens that can affect weanling pig performance is increased and a means to reduce the pathogenic load becomes more important. Therefore, off-site weaning and all-in-all-out management systems will help reduce the impact of discontinued use of AGP on weanling pigs.

PHYSICAL FORM OF THE DIET

Feeding high-quality diets to weanling pigs is critical for a successful transition from the highly digestible sow milk to less digestible cereal-based diets. The greater the digestibility of nutrients in the weaning diet is, the less substrate will be available to pathogens in the hindgut, and diets containing highly digestible nutrients are, therefore, usually fed during the immediate post-weaning period. Nutrient digestibility in weaning diets may be improved by changing the physical form of the diet. Pelleting, liquid feeding, and fermented liquid feeding are the most common feed processing methods used in diets fed to weanling pigs. Nutrient digestibility is also improved if the grain in the diet is ground to an average particle size of less than 600 μm (Kim et al. 2002). Weanling pigs fed diets containing ingredients that are hammer-milled also have improved growth performance compared with pigs fed diets containing ingredients that are roller-milled (Choct et al. 2004a). Feed texture characteristics such as hardness, fragility, chewing work, and adhesiveness may also influence the palatability of diets fed to young pigs (Solà-Oriol et al. 2009b).

Pelleting will reduce diet dustiness, feed wastage, feed segregation, and increase bulk density (Skotch et al. 1983). Pigs fed a pelleted diet have greater daily gain (Hancock et al. 1994; Laitat et al. 1999; Sawyer et al. 1999; Ohh et al. 2002; Xing et al. 2004) and improved feed efficiency (Patterson 1983; Hancock et al. 1991, 1994; Sawyer et al. 1999; Ohh et al. 2002; Xing et al. 2004) compared with pigs fed a mash diet. The improvement in performance of pigs fed pelleted diets rather than mash diets may be a result of improved nutrient digestibility (Medel et al. 2004; Xing et al. 2004), improved palatability (Skotch et al. 1983; Chae and Han 1998; Solà-Oriol et al. 2009a), and reduced time to consume the feed (Laitat et al. 1999). Smaller pellet size may result in improved performance of weanling pigs compared with larger pellet size (Dong and Pluske 2007), but that is not always the case (Edge et al. 2005). It has, however, been reported that a pellet size of 4 mm improves feed utilization of weaned pigs compared with either smaller or larger pellets, whereas growth rate is not influenced by pellet size (Traylor et al. 1996). In a case study involving 50 herds in southern Ontario, it was observed that feeding pelleted diets to weanling pigs may increase the risk of post-weaning diarrhea because pelleting generally increases feed intake. Pelleted feed may, therefore, move faster through the intestinal tract, which may result in more undigested nutrients reaching the large intestine and increasing proliferation of pathogens (Amezcua et al. 2002).

Extrusion and expansion of diets fed to weanling pigs may also improve feed efficiency (Chae et al. 2000; O'Doherty and Keady 2001; Owusu-Asiedu et al. 2002), although that is not always the case (Hongtrakul et al. 1998; Johnston et al. 1999). The effect of thermal processing on growth performance of pigs largely depends on feed ingredient characteristics, and nutrient digestibility is usually not improved by thermal treatment in diets that contain mainly highly digestible feed ingredients (Chae and Han 1998). Pelleting may, therefore, be more beneficial than extrusion and expansion for diets fed to pigs during the immediate post-weaning period because these diets often contain large quantities of milk products or animal protein sources (Chae et al. 1997). In fact, thermal treatment may have a negative impact on weanling pig performance if diets containing milk products or special protein sources that are susceptible to Maillard reactions are heated (Hongtrakul et al.1998; Johnston et al. 1999; Dong and Pluske 2007). However, if diets used during the initial week post-weaning are only pelleted, average daily gain and feed efficiency may be improved by 10 and 14%, respectively, compared with the performance of pigs fed a mash diet (Steidinger et al. 2000). Because of improved nutrient digestibility in pelleted diets compared with mash diets, feed efficiency may be improved by as much as 24% in certain types of diets (Medel et al. 2004).

Feeding diets in a liquid form rather than as a dry feed may help weanling pigs adapt more easily to the transition from sows milk to solid feed because a liquid diet is more fitting to the immature digestive system of weanling pigs than a dry diet (Choct et al. 2004b). Liquid feeding is usually prepared by mixing feed and water in a certain ratio and an acidifier is sometimes added to the diet to maintain a pH at 3.5 to 4.5 (Plumed-Ferrer and Wright 2009). Liquid feeding may benefit weanling pigs by increasing villous height (Deprez et al. 1987; Yang et al. 2001; Scholten et al. 2002) and the concentration of lactic-acid-producing bacteria (Geary et al. 1996; van Winsen et al. 2001), decreasing weaning stress (Lecce et al. 1979), and improving the nutritive value of cereal grains due to increased activity of inherent endogenous enzyme activity in grains (Choct et al. 2004b). Pigs fed diets in a liquid form usually have improved daily gain and feed efficiency compared with pigs fed diets in a meal form (Braude and Newport 1977; Lecce et al. 1979; Partridge et al. 1992; Choct et al. 2004b; Han et al. 2006). In 10 experiments conducted in Denmark, daily weight gain was improved by 12.3% on average for pigs fed a liquid diet compared with pigs fed the same diet in a dry form (Jensen and Mikkelsen 1998). Results from experiments in the United States indicate that the positive response of liquid feeding to weanling pigs is up to two times greater than observed in the Danish experiments (Zijlstra et al. 1996; Odle and Harrel 1998; Kim et al. 2001). Pigs fed a liquid diet during the initial 14 d post-weaning reached marked weight 3.7 d sooner than littermates that were fed the same diet in a dry form (Kim et al. 2001). The main reason for these observations is believed to be that liquid diets result in increased feed intake, which subsequently induces a healthier and more intact villi-structure in the small intestine (Dong and Pluske 2007). Pigs fed liquid diets are, therefore, less susceptible to *E. coli* infections. Increased synthesis of short-chain fatty acids and reduced pathogenic activity in the intestines of pigs fed liquid diets may also contribute to an improved growth performance (Scholten et al. 1999).

Liquid feed may be fermented before feeding to increase the concentration of lactic acid bacteria (Brooks et al. 2001; Plumed-Ferrer and Wright 2009). Protein digestion may also be improved because of a reduced pH in the stomach of pigs fed fermented liquid feed (Brooks et al. 2003) and fermented liquid feed may also improve the fermentation activity in the gastrointestinal tract (Mikkelsen and Jensen 1997; Højberg et al. 2003). Thus, fermented liquid feed may have characteristics similar to probiotics and organic acidifiers, which may explain why pigs fed fermented liquid diets have better performance than pigs fed dry diets (Russell et al. 1996). In Danish experiments, fermented liquid feeding of weanling pigs improved daily gain by 13.4% compared with non-fermented liquid feed, and by 22.3% compared with dry feed (Jensen and Mikkelsen 1998). However, in other experiments, no positive effects of fermented liquid feed were observed (Lawlor et al. 2002). The possible reason for this discrepancy may be that fermented liquid feed increases degradation of amino acids, especially lysine, in the diet and the concentration of fermentation metabolites (e.g., bio-amines) may also negatively influence diet palatability ('Canibe et al. 2007). To prevent amino acids from being fermented during diet fermentation, it has been suggested that only the cereal grain portion of the diet should be fermented (Brooks et al. 2003; Canibe et al. 2007).

Supplementation of a fermented co-product to the diet may also improve growth performance and health of pigs in a way that is similar to feeding fermented liquid feed (Scholten et al. 1999, 2002; Ginting-Moenthe et al. 2002). Co-feeding of fermented liquid and dry feed may, however, be more beneficial than feeding either dry or fermented diets (Dunshea et al. 2000). By providing only a portion of the feed as liquid feed and at the same time supplying dry feed to pigs on an ad libitum basis, the risk of spoiling of the liquid feed is reduced because all liquid feeds will be consumed relatively quickly after feeding (Dunshea et al. 2000). Co-feeding of fermented liquid feed and dry feed containing no AGP may also result in growth performance of pigs that is similar to that obtained by pigs fed a diet containing AGP in a dry form (Amezcua et al. 2007).

In conclusion, although there are relatively few experiments that investigated the effect of the physical form of the diet on the performance of weanling pigs in the absence of AGP, manipulation of the physical form may have beneficial effects on pig performance. In particular, feeding fermented feed may have a prophylactic effect on gastrointestinal disorders and improve growth performance to the same extend as AGP. If liquid diets cannot be used, it is recommended that diets be pelleted and that the grain in the diets be ground to a particle size around 600 μm.

RESTRICTED FEEDING

Non-digested dietary nutrients will enter the large intestine and provide substrates for microbial fermentation, which may facilitate development of an inappropriate gut microflora and undesirable fermentation, resulting in enteric diseases such as diarrhea. One possible method to minimize post-weaning diarrhea is, therefore, to restrict feed intake during the immediate post-weaning period. Restricted feeding decreases the incidence of post-weaning diarrhea and the proliferation of haemolytic *E. coli*. compared with providing feed on an ad libitum basis (Thomlinson 1969; Lecce et al. 1983; Göransson et al. 1995). Pigs that were fed only 85% of the amount of the feed consumed by pigs that were allowed free access to feed had a reduction of 40% in the incidence of diarrhea and 33% in the severity of diarrhea (Ball and Aherne 1987a,b). Pigs that were on the restricted feeding schedule also recovered faster from diarrhea than pigs allowed free access to feed. Similarly, restricted feeding from day 3 to 8 post-weaning reduced the incidence of diarrhea, proliferation of haemolytic *E. coli.*, and mortality (Rantzer et al. 1996). When ad libitum feeding was resumed on day 9 post-weaning, incidence and severity of diarrhea and proliferation of *E. coli* continued to be less in pigs that were previously restricted in their feed intake compared with pigs that were allowed ad libitum feeding during the entire post-weaning period (Rantzer et al. 1996). In a Danish experiment, it was observed that restricting feed intake to 75% of ad libitum during the initial 14 d post-weaning reduced mortality due to diarrhea by 50% and lowered therapeutic treatments for diarrhea by 56% compared with feeding ad libitum (Jørgensen et al. 2000).

There is, therefore, ample evidence that restricted feeding during the immediate post-weaning period will reduce the incidence of diarrhea, but restricted feeding is often associated with decreased growth rate when compared with ad libitum feeding (English et al. 1978; Ball and Aherne 1982; Bark et al. 1986). However, if pigs are allowed ad libitum access to feed after the initial post-weaning period, this growth retardation may be ameliorated by compensatory growth (Wilson and Osbourn 1960). This hypothesis is consistent with Ball and Aherne (1982) who reported that the age at 90 kg was the same for pigs that had been fed restricted during the immediate post-weaning period, and pigs that were given free access to feed during this period. Negative effects of restricted feeding may also be reduced if feed is provided in four to eight small meals per day rather than in one or two meals (Ball and Aherne 1982; Lecce et al. 1983; Bark et al. 1986). Restricted feeding usually also results in improved feed efficiency and improved nutrient digestibility (Ball and Aherne 1987a). If AGP can no longer be used to control post-weaning diarrhea, restricted feeding may, therefore, be used as an alternative, although pig growth performance may be reduced during this period.

USE OF LOW-PROTEIN DIETS

The most important nutrient associated with digestive disorders in weanling pigs is crude protein. Weanling pigs generally produce relatively low quantities of hydrochloric acid in the stomach and, therefore, the pH in the stomach is increased when pigs consume a meal. Feed ingredients that are used as protein sources in weanling pig diets, such as soybean meal, fish meal, and milk powder, also have a high buffering capacity, which will further contribute to an increase in stomach pH (Bolduan et al. 1988), which is unfavorable for pepsin activity (Manners 1976). Therefore, excessive crude protein intake by pigs weaned at 21 d of age may result in microbial fermentation, and pigs fed a high-protein diet without AGP have increased protein fermentation in the intestinal tract compared with pigs fed a low-protein diet (Heo et al. 2008, 2009). Undigested feeds that contain nitrogen may also accelerate the production of toxic nitrogenous compounds including ammonia, which is harmful to intestinal health (Bolduan et al. 1988; Pluske et al. 2002; Nyachoti et al. 2006; Htoo et al. 2007). Pigs fed low-protein diets, therefore, have greater resistance to infections than pigs fed diets containing greater concentrations of protein (Houdijk et al. 2007; Opapeju et al. 2009) and infections in pigs fed a high-protein diet result in a greater decrease in growth rate than infections in pigs fed a low-protein diet (Wellock et al. 2008a). Pigs fed low-protein diets also have a reduced incidence and severity of diarrhea and improved fecal consistency compared with pigs fed high-protein diets (Göransson et al. 1995; Göransson 1997; Kendall et al. 2004; Heo et al. 2008, 2009; Opapeju et al. 2008; Yue and Qiao 2008). Results of a Danish experiment using pigs in commercial facilities indicate that the incidence of diarrhea can be reduced by 25% if crude protein concentration is reduced from 21 to 18% in diets containing no AGP (Callesen and Johansen 2006). It is, therefore, evident that problems with scouring and reduced disease resistance, which are often observed if AGP are removed from the diets, may be ameliorated if low-protein diets are fed during the immediate post-weaning period.

A low concentration of crude protein in diets fed to weanling pigs may, however, result in reduced growth performance because one or more of the indispensable amino acids may be present in concentrations below the requirement for maximum growth. Low-protein diets, therefore, have to be supplemented with crystalline sources of amino acids to maintain the balance and concentration of indispensable amino acids (Cinq-Mars et al. 1988; Hansen et al. 1993; Han et al. 1995; Le Bellego and Noblet 2002; Heo et al. 2008, 2009; Opapeju et al. 2009). By using this approach, it is possible to reduce dietary crude protein from 21.2 to 18.4% without sacrificing pig performance, but with a significant reduction in the incidence of diarrhea (Reynoso et al. 2004).

If no AGP are included in the diets, it may be necessary to formulate diets containing less than 18% crude protein during the immediate post-weaning period to avoid scouring and intestinal malfunctions. In such diets, it may be required that six crystalline amino acids, (lysine, methionine, threonine, tryptophan, isoleucine, and valine) are included to meet the requirement for all amino acids (Heo et al. 2008, 2009). Crystalline sources of lysine, methione, and threonine are available at relatively inexpensive prices and are commonly used in the feed industry. Crystalline sources of tryptophan, isoleucine, and valine are, however, so expensive that they are cost prohibitive under commercial conditions. An alternative strategy is to reduce the concentration of all amino acids in the diets to approximately 80% of the requirement, which can usually be accomplished by the addition of no crystalline amino acids other than lysine, methionine, and threonine. By using this approach, it is possible to produce diets that contain only 15.0 to 15.5% crude protein. Feeding such a diet during the immediate post-weaning period will usually result in greatly reduced problems with diarrhea, and, if such a diet is used, it is usually possible to wean pigs without the use of AGP. Average daily gain of the pigs, however, will be reduced by 60 to 80 g d^{-1} if a diet containing only 15% crude protein is used without inclusion of all indispensable amino acids at required levels (Stein and Kil 2006). However, if pigs suffer from diarrhea, they will also have reduced performance (Göransson 1997) and because the time period that the low-protein, amino acid deficient diet is fed is usually relatively short (i.e., 2 to 4 wk), it is of little or no practical consequence that growth performance is slightly reduced during this period. When pigs are allowed to consume a diet with a normal crude protein level, they will compensate for the reduced growth rate during the immediate post-weaning period (Kyriazakis et al. 1991; Wellock et al. 2009) and pigs fed a low-protein diet for 2 wk post-weaning quickly catch up when they are allowed to consume a diet containing adequate levels of crude protein (Stein and Kil 2006).

The origin of the protein in diets fed to weanling pigs is also important as excessive levels of soy proteins may cause allergenic reactions (Li et al. 1990; Friesen et al. 1993). Use of animal proteins during the immediate post-weaning period is, therefore, widely recommended. In particular, use of spray-dried plasma protein in diets fed to newly weaned pigs appears to offer some protection against enteric diseases and diarrhea as recently reviewed (van Dijk et al. 2001; Pettigrew 2006; Torrallardona 2010).

In conclusion, excess crude protein in diets fed to weanling pigs will result in diarrhea and digestive disorders of pigs, but if a low-protein diet is fed during the immediate post-weaning period, these problems may be ameliorated. If no AGP are used, it may be necessary to reduce dietary amino acids concentrations during the initial 2 to 4 wk post-weaning to levels that are below the pig's requirement for maximal growth. This may result in reduced growth performance during the immediate post-weaning period, but pigs will compensate during the following period if they are allowed access to a diet that is adequate in amino acids.

ENVIRONMENT FOR POST-WEANING PIGS

At weaning, the pig is exposed to various stressors and pathogenic infections by restricted space allowance, co-mingling with unfamiliar animals, unfavorable ambient temperature, contaminated air, and low bio-security. The combined and additive effects of these stressors and pathogenic threats accelerate the detrimental effects on the growth performance of pigs (Hyun et al. 1998). The health of the pig will, therefore, be improved if the number of stressors in the pigs environment is reduced (Ekkel et al. 1995).

Crowding increases social stress and negatively influences feed intake and growth rate of weanling pigs (Brumm et al. 2001; Turner et al. 2003; Wolter et al. 2003; Smith et al. 2004). It is currently recommended that weanling pigs are allowed at least 0.34 m^2 per pig in slatted pens (Holden and Kliebenstein 2002), but it is possible that if no AGP are used, more space could be required (Varley 2004). Co-mingling of weanling pigs originating from different farms should always be avoided, because some pigs may bring specific pathogens that others do not have immune protection against, which will result in a disease outbreak (Gray et al. 1996). Mixing with non-littermates within the same farm should be restricted as much as possible to minimize stress of weanling pigs (Ekkel et al. 1995; Puppe et al. 1997). Mixing litters decreases growth rate and increases agonistic behavior, which may result in wounds that can increase disease susceptibility (Friend et al. 1983; Hessing and Tielen 1994). If mixing of unfamiliar pigs at weaning is unavoidable, grouping pigs by sex may reduce fighting and aggressive behavior among pigs after mixing (Colson et al. 2006). It is also possible that modified farrowing crates that allow for mixing of pigs prior to weaning may reduce aggressive behavior among pigs after weaning.

Control of ambient temperature is also critical because weanling pigs experiencing low feed intake and a stressful environment become highly sensitive to cold stress. Cold stress and drafts predispose weanling pigs to diarrhea (Armstrong and Cline 1977; Scheepens et al. 1991; Hessing and Tielen 1994), but high temperature can also reduce feed intake and growth rate of weanling pigs. The recommended ambient temperature during the initial 2 to 3 wk post-weaning is 26 to 28°C and the temperature should be adjusted according to feed intake of weanling pigs (Le Divedich and Herpin 1994).

The concentration of air contaminants within a swine building is highly correlated with the productivity and health of pigs. However, most ventilation systems in swine buildings are only able to control air moisture and temperature (Donham 1991). Therefore, a high-performing ventilation system may be needed to reduce the risk of respiratory disease and to improve health status by removing contaminants, noxious gases, odor, and airborne pathogens. Weanling pigs that are reared in a building with a low level of ammonia, CO_2, and dust have greater feed intake and growth rate, but lower plasma stress hormone concentrations compared with pigs reared in a building with high levels of those contaminants (Lee et al. 2005).

A continuous supply of clean drinking water is also essential (Thacker 1999, 2001; Dong and Pluske 2007) and the flow rate of water should be maintained between 0.5 and 0.7 L min^{-1} (Barber et al. 1989; Thacker 2001). Use of bowl drinkers may increase feed intake and reduce belly-nosing during the initial post-weaning period compared with nipple drinkers (Torrey and Widowski 2004), although the type of drinker does not always affect feed intake of pigs (Torrey et al. 2008).

A strict bio-security program should be implemented when AGP are removed, because farms using no AGP become more susceptible to pathogenic transmission (Holden and Kliebenstein 2002). Introduction of new pigs and entry of livestock trucks to the farm area are two of the most common sources of entry of pathogens to the farm (Holden and Kliebenstein 2002); therefore, livestock transporting trucks should be cleaned and disinfected before entering the farm. Site segregation at the farm level will keep similar aged animals, which are isolated from other age groups, and will reduce cross contamination of pathogens (Owsley 2002).

In conclusion, a health-enhancing environment can improve the health and productivity of weanling pigs by reducing the effects of possible stressors and pathogenic challenges. The main points to observe are strict bio-security for people and livestock trucks and control of rodents and flies. Co-mingling of pigs among farms should be avoided and co-mingling within a farm should be reduced as much as possible. Inside the barns, pigs should be allowed adequate space, and a warm, clean, and draft-free environment should be provided.

CONCLUSIONS

Although the exact mechanisms for AGP have never been established, there is no doubt that the use of AGP in diets fed to weanling pigs results in improved growth performance as well as in reductions in enteric diseases and mortality. As a consequence, problems with enteric diseases and increased mortality have been observed when AGP have been removed from the diet. To prevent this, several management and feeding strategies may be implemented. It will be beneficial to increase weaning age to close to 4 wk because older pigs have better immunity and are easier to get started on solid feed than early-weaned pigs. It is also beneficial to wean pigs to off-site facilities because the disease pressure is reduced in these facilities compared with on-site weaning, where disease transmission from older to younger animals can take place. Pigs should always be weaned into clean and disinfected facilities and ventilation and heating systems should be operated to allow for a warm and draft-free environment for the pigs. All facilities for weanling pigs should be operated on an all-in-all-out basis.

Diets for weanling pigs should be formulated using high-quality feed ingredients and, if possible, all or some of the feed should be provided in a liquid or a fermented liquid form. However, to prevent degradation of dietary amino acids during fermentation it is recommended that only the grain portion of the diet is fermented. If dry diets are provided, it may be beneficial to pellet the diets using a 4-mm dye prior to feeding to reduce dustiness and increase palatability. Feed intake of the pigs should be restricted during the initial 2 wk post-weaning to reduce the risk of pigs getting diarrhea, and the daily feed allowance should be provided in as many meals as possible.

The concentration of crude protein in diets fed to pigs during the initial 2 to 4 wk post-weaning needs to be around or less than 18%. If problems with diarrhea persist at this level of crude protein, it may be necessary to reduce crude protein to 15%. This will usually result in slight reductions in growth rate, but pigs will compensate when they are later provided with adequate levels of protein.

By using management and feeding strategies that focus on preventing diarrhea and reducing mortality during the post-weaning period, it will be possible to produce pigs without the use of AGP. Some of these strategies may, however, add cost to the system, and profits may, therefore, be reduced if no AGP are used.

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