DIFFERENTIAL GESTATION FEEDING LEVELS ON SOW AND LITTER PERFORMANCE, NUTRIENT DIGESTIBILITY AND ENERGY HOMEOSTASIS

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Chapter 1. Literature review

Introduction

Two thirds of sows' lifetime are spent in gestation, indicating that a better understanding of energy and nutrient utilization would be critical for improvement of reproductive performance and better economic returns. Additionally, lactation in swine is of a relatively short duration, with a potentially larger nutritional demand upon the animal, as compared with pregnancy. The high energy and nutrients demand during lactation generally renders the feed intake during lactation not enough to meet the requirement for milk production, which causes the sows to mobilize body reserves to compensate for the deficit. Therefore, maximization of feed intake during lactation is the common practice in the management of lactation sows.

Among the nutritional strategies, modification of energy and protein intake and feeding levels during gestation and/or lactation has been widely used in sow management. In the past several decades, numerous studies have been conducted to investigate the effect of energy intake during gestation and/or lactation on sow and litter performance (Frobish et al., 1973; Buitrago et al., 1974; Libal and Wahlstrom, 1977; Okai et al., 1977; Young et al., 1990; Dourmad et al., 1996; Xue et al., 1997). Additionally, effect of protein intake during gestation and/or lactation on sow and litter performance has also been evaluated (Rippel et al., 1965; Holden et al., 1968; Baker et al., 1970; Mahan and Mangan, 1975; Shields et al., 1985; Mahan, 1998). Furthermore, numerous studies have been conducted to evaluate the effects of feeding levels during certain period of gestation (Cromwell et

al., 1989; Heo et al., 2008; Hoving et al., 2011) or whole gestation (Dourmad, 1991; Mahan, 1998) on sow and litter performance in one or several reproductive cycles.

Presently in North America, gestation sows are generally housed in two systems: individual stall and group pen housing. In the recent years, the subject of conventional housing system for gestation sows in stalls has become the point of debate driven by societal concern about animal welfare, even though the scientific evidence remains equivocal with regards to which housing system is best for gestation sows. Currently, more than a quarter of pork producers have committed to phase out individual crates for gestation sows (CAST, 2009). In particular, Smithfield Foods has reached 83% of sows housed in group pens during gestation in their company owned farms by December, 2015, and it is estimated that all individual stalls for gestation sows will be phased out by 2017. Generally, sows housed in group pens have similar reproductive performance compared with sows housed in individual stalls. However, mixing sows in group pens before embryo implantation could impair reproductive performance (Hopgood et al., 2011; Li et al., 2014). Additionally, sows housed in group pens have higher injury scores, higher risk of lameness and thus higher culling rate compared with sows housed in individual stalls (Anil et al., 2005; Anil et al., 2009; Calderón Díaz et al., 2014). However, management of group formation, group size and feeding strategies may minimize the negative effects of group pen housing system on culling rate.

Numerous factors have been shown to influence the apparent digestibility of energy and nutrients. The digestibility of energy and nutrients are generally improved with increased body weight (**BW**) (Noblet and Shi, 1994; Morel et al., 2006; Noblet et al., 2013). The

positive effect of BW on the apparent digestibility of energy and nutrients is maximized when mature sows fed at maintenance are compared with growing pigs fed *ad libitum* (Noblet and Shi, 1993). Inconsistent results have been found concerning the effect of gestation periods on digestibility of energy and nutrients (Nuzback et al., 1984; Noblet and Etienne, 1987; Olesen et al., 2001). Numerous studies have shown that traditional local breeds, such as Chinese Meishan pigs, have higher apparent digestibility of energy and nutrients, especially dietary fiber, compared with modern genotypes (Fevrier et al.,1988; Kemp et al., 1991; Morel et al., 2006; Urriola and Stein, 2012). Furthermore, increasing feeding levels can decrease digestibility of energy and nutrients in pigs at different stages (Haydon et al., 1984; Ball and Ahernet, 1987; Everts and Smits, 1987; Smits et al., 1994; Goerke et al., 2014), while increasing feeding frequency may improve the apparent digestibility of energy and nutrients (Shabi et al., 1999).

Feed ingestion is a necessary behavior that provides the energy and nutrients for maintenance requirement and/or other specific requirements, such as growth, pregnancy and lactation. Feed intake regulation consists of complex systems, in which peripheral gastrointestinal hormones, peripheral adipose signals and central nervous system integrate together and play a critical role. Among the gastrointestinal hormones, ghrelin is believed to serve as "meal initiator", which concentrations rise before feeding and decline after feeding (Tschöp et al., 2000; Cummings, 2001; Tschop et al., 2001; Sánchez et al., 2004; Liu et al., 2008). Numerous studies have shown that ghrelin may serve as both a short-term and long-term indicator of energy homeostasis. It was well-documented that ghrelin secretion was up-regulated in the condition of negative energy balance, such as

fasting and anorexia nervosa, and down-regulated in the case of positive energy balance, such as feeding and obesity (Ariyasu et al., 2001; Toshinai et al., 2001; M. Tschop et al., 2001; Wren et al., 2001). Besides ghrelin, cholecystokinin, glucagon-like peptide 1 and oxyntomodulin function as short-term factors to inhibit feed intake. In contrast, insulin and leptin, recognized as "adiposity signals" which are proportional to body fat mass (Maffei et al., 1995), play a important role in the long-term regulation of food intake and body weight, thus achieving energy homeostasis.

The objectives of this dissertation were to evaluate the effect of different feeding levels during several short periods of gestation and housing systems on sow and litter performance, and the effect of feeding levels during several short periods of gestation on apparent digestibility of energy and nutrients. Additionally, effect of different feeding levels during several short periods of gestation on plasma hormones and metabolites related to feed intake regulation and energy homeostasis was assessed. Furthermore, best physiological indicators were proposed to predict the hunger status or energy homeostasis in pregnant gilts.

Maternal nutrition on reproductive performance

The knowledge of the requirements of nutrients and energy for gestation and lactation sows has accumulated rapidly and abundantly in the past several decades, which resulted in the publication of nutrient and energy requirements for reproductive sows recommended by National Research Council (NRC, 2012). Relatively little, however, is

known about long-term maternal nutrition on sow lifetime productivity and progeny development, as well as its impact on cost effectiveness and environmental sustainability.

Similar to other mammals, sows appear to be able to effectively buffer against nutritional deficiency by mobilization of their own body reserves to meet the requirement for fetal survival and growth (Pond, 1973). In the case of severe energy and protein restriction, the birth weight of piglets and litter are reduced, and litter size is adversely affected mostly when the feed intake or energy intake is restricted to a greater extent. Additionally, protein deprivation throughout gestation, but not energy restriction during this period, seems to exert a permanent stunting effect on the development of the progeny. Therefore, different mechanisms may be involved in the influence of maternal energy and protein supply on reproduction and progeny development.

Dourmad (1991) pointed out that energy intake during gestation affected voluntary energy consumption during lactation, and lactation energy intake influenced energy required in the subsequent gestation to maximize reproductive performance. Therefore, assessment of energy and protein requirement for sows during gestation and lactation may be difficult due to the confounding effects of one reproductive cycle on subsequent one (Coffey et al., 1994).

Energy intake during gestation

Sow performance

Studies on the effects of different energy intake during gestation on sow performance are summarized in Table 1-1. Numerous researchers have reported that consistent increase in

dietary energy intakes during gestation led to a linear increase of BW (Frobish et al., 1973; Buitrago et al., 1974; Libal and Wahlstrom, 1977; Okai et al., 1977; Young et al., 1990; Dourmad et al., 1996) and backfat (**BF**) (Young et al., 1990; Dourmad et al., 1996) gains during gestation. Additionally, the linear increase of BW and BF gains during gestation was associated with a linear increase of BW (Buitrago et al., 1974; Libal and Wahlstrom, 1977; Okai et al., 1977; Young et al., 1990) and BF (Young et al., 1990) loss/change during lactation. These effects were evident not only in primiparous sows (Frobish et al., 1973; Buitrago et al., 1974; Young et al., 1990), but also in multiparous sows (Libal and Wahlstrom, 1977; Okai et al., 1977; Dourmad et al., 1996). Even though the magnitude of effects was different in different parities, the effects of different energy intakes on gestation and lactation BW and BF changes were found to be similar among different parities. Frobish et al. (1973) examined the effects of 4 different energy levels (3.0, 4.5, 6.0 and 7.5 Mcal metabolizable energy (**ME**)/d) during gestation on sow performance for 3 reproductive cycles and reported that the rise of gestation energy intake increased sow BW gain in gestation with the magnitude of BW gain declining when parity increased, which may be explained by the fact that younger sows spent approximately 25% of their estimated energy requirement toward maternal and conceptus gain, while in higher parity sows, less proportion of daily energy allowance was needed for maternal gain (Cooper et al., 2001). Similarly, the effects of energy intake during gestation on gestation BW gain were also evident in the 4 consecutive parities in the studies reported by Young et al. (1990) with the reduction effect of parity on the gestation BW gain. It was also noted in the same study that lactation BW and BF losses/changes

declined with the increase of parity, probably due to reduction of gestation BW gains in higher parity sows.

As mentioned earlier, increasing gestation energy intake contributed to greater BW and BF gains during gestation, which was associated with less body gain or more BW and BF losses during lactation. One may wonder why the lactation BW and BF losses of sows increased when higher energy intake was provided in gestation. The direct reason for this phenomenon could be the reduction of lactation feed intake in sows fed higher energy intake during gestation. Indeed, Hoppe et al. (1990) reported that sows fed 6.0 Mcal ME/d during gestation consumed an average of 22 kg more feed during lactation than those sows receiving 9 Mcal ME/d. It was further reinforced by the evidence that lactation average daily feed intake (**ADFI**) was linearly reduced with the increase of gestation energy intake (Buitrago et al., 1974; Young et al., 1990). Reduction in the lactation feed intake associated with generous feed intake in gestation may be due to low plasma concentration of insulin (Weldon et al., 1994c).

Xue et al. (1997) demonstrated that sows fed higher energy intake during gestation showed 1.6 d longer weaning to estrus interval compared with the sows fed lower energy intake. The prolonged wean to estrus interval was associated with lower luteinizing hormone (**LH**) concentration on 1 d post-weaning in sows fed higher energy intake compared with sows fed lower energy intake during gestation. It was also suggested that low plasma insulin concentration during lactation was associated with lower secretion of LH (Tokach et al., 1992; Koketsu et al., 1996b). The low plasma insulin concentration may be responsible for the reduction of lactation feed intake (Weldon et al., 1994c). From

the study conducted by Xue et al. (1997), a definite mechanism concerning the delayed wean to estrus interval in the sows fed excessive energy intake during gestation could not be proposed. Whether it was a direct effect of body fatness at farrowing or an indirect effect through reduced feed intake during lactation was not clear, thus warranting further investigation. In contrast, Young et al. (1990) reported that wean to estrus interval tended to respond quadratically with the medium level of energy intake during gestation resulting in superior performance. This finding was consistent with the result of lactation ADFI which showed a slight greater feed intake during lactation in the sows fed the medium level of energy intake during gestation compared with the other two energy intake groups. However, sows on the medium level of energy intake during gestation lost 5.5 kg of BW and 2 mm BF during lactation, while sows on the low energy level during gestation gained 7.3 kg of BW and had no change in BF during lactation. Additionally, Coffey et al. (1994) did not observe superior effect of low energy intake during gestation on wean to estrus interval, even though higher BW loss was found in the sows fed the higher energy intake during gestation. Similarly, no effect of gestation energy intake on wean to estrus interval was reported (Heo et al., 2008). In their study, both gestation and lactation BW and BF changes were not different among different energy intake groups. These results suggested that wean to estrus interval, as a measure of reproductive efficiency, may be influenced by numerous factors, including body reserves at farrowing and weaning, lactation feed intake, lactation BW and BF changes and endocrine factors such as insulin and LH. These factors may not exert their effects in the single manner, but work in a synergetic and interactive manner.

One study conducted by van den Brand et al. (2001) examined different energy sources (Starch vs. Fat) fed from weaning to ovulation or from ovulation to d 35 of gestation on reproductive traits in primiparous sows. It was reported that higher proportion of sows exhibited estrus within 9 d after weaning in starch-rich diet (67%) in comparison with fat-rich diet (52%), whereas the wean to estrus intervals were 123 and 134 h in the Starch and Fat diet groups, respectively. Sows fed the starch-rich diet had higher plasma insulin concentration than sows fed fat-rich diet on d 4 post-weaning and d 32 of pregnancy. It was suggested that insulin was positively associated with LH pulse frequency (Tokach et al., 1992). Zak et al. (1998) indicated that LH pulsatility after weaning may play an important role in determining wean to estrus interval. Therefore, a positive effect of Starch-rich diet on wean to estrus interval could be expected.

Litter performance

Studies on the effects of different energy intake during gestation on litter performance are summarized in Table 1-2. Most publications reported that gestation energy intake did not affect the number of piglets in terms of total born, live born and weaning (Elsley et al., 1968; Okai et al., 1977; Hoppe et al., 1990; Young et al., 1990; Coffey et al., 1994; Dourmad et al., 1996; Xue et al., 1997). However, negative effects of increasing dietary energy intake on the number of piglets have been reported in several studies (Frobish et al., 1973; Buitrago et al., 1974; Libal and Wahlstrom, 1977). Specifically, number of total born piglets was reduced in a linear manner in the study conducted by Frobish et al. (1973), whereas numbers of live born piglets and piglets at weaning were not different among different energy intake groups. Similarly, Libal and Wahlstrom (1977) reported

that only number of live born piglets was reduced as gestation energy intake increased from 4.0 to 7.0 Mcal ME/d. However, numbers of piglets born total, alive and at weaning were all reduced as gestation energy intake increased from 2.1 to 7.5 Mcal ME/d (Buitrago et al., 1974).

In the studies conducted by several authors (Elsley et al., 1968; Frobish et al., 1973; Buitrago et al., 1974), increased average piglet and litter weights were evident at birth as gestation energy intake increased, however, piglet and litter weights at weaning were not different among different gestation energy intake groups. Interestingly, average piglet weight at birth was not different when energy intake during gestation increased from 5.7 to 13.1 Mcal ME/d, while the higher gestation energy intake led to increased piglet weight at weaning compared with lower gestation energy intake groups (Okai et al., 1977). In contrast, average piglet and litter weights at birth and weaning all increased quadratically as gestation energy intake increased from 4.0 to 7.0 Mcal ME/d, with the heaviest piglets and litters produced by sows receiving 6.0 or 7.0 Mcal ME/d (Libal and Wahlstrom, 1977). Similarly, Young et al. (1990) reported that average piglet weight at birth and weaning increased linearly and quadratically with the rise of gestation energy intake, respectively, litter weights at birth and weaning, however, were not affected by gestation energy intakes. Furthermore, Buitrago et al. (1974) reported that post-weaning growth performance was not different among the pigs from the dams fed different energy intake during gestation. These results indicated that numbers of piglets were generally not affected by gestation energy intakes with the exception that severe energy restriction or oversupply during gestation may reduce the number of live born piglets. However,

average piglet and litter weight at birth could be increased due to the increase of gestation energy intake. The positive effects of gestation energy intake on postnatal and postweaning piglet and litter performance may diminish due to the compensatory growth during lactation and post-weaning.

Energy intake during lactation

Elsley et al. (1968) examined the influence of energy intake during gestation and lactation on sow performance over 3 reproductive cycles and reported that feeding high level of energy intake (20 Mcal/d) during lactation resulted in a reduced sow weight loss during lactation of 20, 12 and 10 kg in the first, second and third reproductive cycle, respectively, as compared with sows fed low level of energy intake (13.8 Mcal/d). It was also reported, in the same study, that lactation energy intake did not impact weaning weight of piglets and wean to estrus interval, which was consistent with one recent study (Heo et al., 2008). In the study conducted by Coffey et al. (1994), 9% fat was included in the lactation diet to increase the energy density, however, this fat inclusion did not affect the lactation feed intake as compared with sows fed diet without fat addition. Increasing energy intake during lactation through fat supplementation resulted in greater pig weight gain to 21 d of age, however, pig survival rate was also not significantly improved through fat supplementation. Pettigrew (1981) summarized the results from 49 studies and reported that in 21 studies, fat supplementation during late gestation and lactation improved pig survival rate during lactation. However, this beneficial effect may be restricted to the special circumstances when pre-weaning survival rate in the herd was relatively low (< 80%) (Pettigrew, 1981).

Protein intake during gestation

Sow performance

In the past several decades, a great body of literature has been published concerning the effects of different protein or amino acid intake on sow performance (Table 1-3). Among them, most researchers demonstrated that increasing gestation protein levels could cause the sows to gain greater BW during gestation (Rippel et al., 1965; Holden et al., 1968; Baker et al., 1970; Mahan and Mangan, 1975; Shields et al., 1985), and lose more BW during lactation (Rippel et al., 1965; Holden et al., 1968; Baker et al., 1970). Mahan and Mangan (1975), however, did not detect difference of lactation BW losses among different gestation protein levels, even though, BW gain during gestation was greater in sows fed higher protein level diet. Interestingly, Mahan (1998) compared 2 different dietary protein levels (13 vs. 16%) during gestation and found that gestation and lactation BW changes did not differ among different protein levels, whereas sows fed low protein diet gained more BF during gestation and lost more BF during lactation, suggesting more energy was diverted from protein deposition to lipid deposition due to protein restriction.

Some researchers reported that ADFI during lactation was reduced when gestation protein level was increased (Holden et al., 1968; Mahan, 1998). The reduced lactation feed intake was responsible for the increased weight loss during lactation in these studies. In contrast, other researchers did not find differences among different gestation protein levels in terms of ADFI during lactation, even though BW losses during lactation were greater in the sows fed higher protein diet than sows fed lower protein diet during

gestation (Rippel et al., 1965; Baker et al., 1970). This observation suggested that sows fed lower protein diet during gestation had higher feed utilization efficiency than their counterparts fed higher protein diet. Therefore, the inconsistent findings were likely related to dietary protein inclusion levels, protein sources, nutrient compositions of the diets among studies and different replications among different studies.

Sows fed 5% protein diet in pregnancy resulted in more maternal fat but less protein accretion than those fed 14% protein diet (Shields et al., 1985). The effect of an increasing fat deposition as protein restriction occurred in gestation has been reported previously in growing pigs (Zimmerman and Khajarern, 1973; Hogberg and Zimmerman, 1978; Hogberg and Zimmerman, 1979). It was also noted that sows fed 5% protein diet mobilized body protein reserves during the last trimester, while sows fed the 5% protein lactation diet catabolized more maternal fat during lactation than those fed 14 and 23% protein lactation diets. This study suggested that the amount of tissue mobilization was dependent on the nutritional status imposed during gestation and the nutritional needs for milk synthesis and secretion. Sows with more tissue reserves stored in gestation mobilize larger quantities postpartum, but the protein levels of lactation diets may modify the rate of catabolism.

Cooper et al. (2001) reported that daily total lysine intake during gestation greater than 10.6 g did not affect sow performance in terms of BW changes during gestation and lactation, as well as feed intake during lactation. However, sows fed 24.0 g total lysine per day from d 80 to 110 of gestation had greater BW and BF gain during this period, but led to higher BW and BF losses during lactation compared with sows fed 18.0 g lysine

(Heo et al., 2008). Similarly, Kusina et al. (1999) reported that daily intake of 16.0 g lysine increased sow BW gain during gestation compared with sows fed 4.0 or 8.0 g lysine daily in gilts. In contrast to the results of Heo et al. (2008), higher lysine intake caused a decline of BF depth (Kusina et al., 1999). Some studies reported that dietary lysine intake during gestation had no effect on wean to estrus interval (Yang et al., 2000; Mejia-Guadarrama et al., 2002), however, Heo et al. (2008) reported that high lysine intake shortened the wean to estrus interval in gilts. The inconsistent results may be explained by the body reserve at farrowing and weaning, as well as the extent of tissue mobilization during lactation (Mullan and Williams, 1989; Yang et al., 1989).

Milk composition

Holden et al. (1968) reported that protein content in the milk increased linearly as the protein levels of gestation diets increased. However, fat contents in both colostrum and 21 d milk were not affected by two protein levels (13 and 16%) of gestation diets (Mahan, 1998; Heo et al., 2008). Additionally, increasing lysine intake of gestation and lactation sows could also increase the total solids and protein concentrations of colostrum and milk (Heo et al., 2008).

Litter performance

Based on the results of effects of different protein or amino acid intake on litter performance (Table 1-4), the amount of protein intake during gestation, expressed either in lowest amount consumed per day or percentage of the diets, was not an important factor in affecting litter size, individual piglet weight or litter weight. Rippel et al. (1965)

reported that diets supplying as little as 90 g protein per day from the corn-soybean meal-corn starch mixture generated normal litter performance over 3 reproductive cycles. However, decreased litter size at weaning (Baker et al., 1970), piglet and litter weight at weaning (Baker et al., 1970; Hesby et al., 1970) had been reported when sows fed the gestation diet with corn served as the only protein source compared with those fed the corn-soybean meal mixed diet. Shields et al. (1985) showed that not only number of piglets at weaning , but also weights of individual piglet and litter at birth and weaning were reduced when only 91 g of protein was supplied in the gestation diet. These results, therefore, indicated that protein restriction during gestation appeared to exert a negative impact on the milk production during lactation, as measured by the survival rate and litter growth rate.

In a series of experiments in which diets devoid of protein were fed to pregnant gilts during various intervals of gestation (Pond et al., 1968b; Pond et al., 1969), it was demonstrated that pregnant gilts were able to buffer against protein deficiency by drawing their own body reserve to meet the protein requirement for fetal development, yielding similar litter size at birth. The stage and duration of protein deprivation, however, had an important bearing on the prenatal and postnatal progeny development. Indeed, Pond et al. (1968b) observed similar birth weights of piglet from the gilts fed protein-free diet only from d 24 to 28 of gestation to parturition compared with those from gilts fed control diet throughout gestation. This effect was also confirmed in the follow-up experiment (Pond et al., 1969), which also indicated that the birth weight and progeny growth rate from gilts given transitory protein during implantation period (d 16 to 20 of

gestation) were superior than those from gilts deprived of protein throughout gestation. However, protein deprivation throughout gestation reduced the birth weights of piglets by 21 to 33% (Pond et al., 1968b; Pond et al., 1969). It was manifested that progeny growth rates from birth to weaning were reduced in the piglets reared by gilts fed protein-free diet throughout gestation regardless of the origin of piglets compared with piglets reared by gilts fed control diet during gestation, indicating that milk synthesis capacity was reduced when the gilts were deprived of protein throughout gestation (Pond et al., 1968b). Interestingly, postweaning growth performance and carcass characteristics were not different between pigs from the dams fed protein-free and control diets (Pond et al., 1968a). Conversely, Pond et al. (1969) observed reduced growth performance from weaning to slaughter at approximately 90 kg BW in pigs from dams fed protein-free diet throughout gestation. The inconsistent results may be explained by the relative small sample sizes in each experiment. Therefore, further studies were needed to draw a definite statement.

The stunting effect of protein restriction during gestation and lactation on progeny development has been well documented in rats (Hsueh et al., 1967; Zambrano et al., 2006). However, the nature of this effect is superficially examined in swine. The study conducted by Pond et al. (1969) shed limited light on this matter. It was reported that DNA contents of cerubrum, cerebellum and skeletal muscle were not different between offspring from dams fed the control and protein-free diets, but the RNA content of cerebrum (per gram of protein or total RNA) and RNA/DNA ratio in skeletal muscle were reduced in pigs from the gilts fed protein-free diet throughout gestation at 90 kg,

which indicated that the protein synthesis rate may be reduced in the pigs from the dams fed protein-free diet and thus the reduced the postweaning performance could be expected.

Protein intake during lactation

Mahan and Mangan (1975) observed that feed intake was greater for sows fed 18% vs. 12% protein diet during lactation, which corresponded to the positive weight gain of sows fed higher protein content diet and weight loss of sows fed lower protein content diet. In another study, the voluntary feed intake during the first 2 wk of lactation was not affected by protein content of the diet, but depended on body fatness at farrowing. Increasing dietary protein intake, however, increased voluntary feed intake during wk 3 to 4 of lactation (Revell et al., 1998). These studies suggested that milk production increased in mid-lactation in response to the more balanced amino acid concentrations and ratios in the diet with higher protein content. Due to the increased feed intake during lactation for sows fed higher protein diet, BW loss of lactation sows could be minimized by providing the higher protein diet during lactation (Mahan and Mangan, 1975; Revell et al., 1998).

Interaction between gestation and lactation protein intake

Mahan and Mangan (1975) clearly demonstrated interaction effects exhibited between protein levels of the diets provided in pregnancy and protein levels of the lactation diets in terms of voluntary feed intake during lactation in gilts. Specifically, when a high protein diet (18%) was provided in lactation, lactation feed intake was independent of protein levels in gestation diets. On the other hand, when a low protein diet (12%) was

given in lactation, lactation feed intake increased in a linear manner as protein levels in gestation diets increased from 9 to 17%. As a consequence, litter gains were also linearly related to the protein levels of gestation diets. The interaction effects indicated that a nutritional carryover effect existed from gestation to lactation. It was believed that even though tissue reserves may be in different states of curtailment as indicated by Shields et al. (1985) when diets with different protein levels were provided in gestation, if a proper lactation diet with sufficient amount of protein (amino acids) was supplied, the previous tissue reserves would not affect feed intake during lactation and litter performance (Mahan and Mangan, 1975). However, sows fed the low protein gestation diet could utilize the same diet in lactation more effectively as indicated by the similar lactation feed intake, but greater lactation BW gain.

Feeding level during gestation

Sow performance

Researchers in the past several decades have evaluated effects of different feeding levels during gestation on sow performance and these results were summarized in Table 1-5. Increasing feeding levels throughout gestation caused a linear increase of BW (Lodge et al., 1966a; Baker et al., 1969; Elsley et al., 1969; Whittemore et al., 1988; Dourmad, 1991) and BF (Whittemore et al., 1988; Dourmad, 1991) gains during gestation, but led to a linear increase of BW (Lodge et al., 1966a; Baker et al., 1969; Elsley et al., 1969; Whittemore et al., 1988; Dourmad, 1991) and BF (Whittemore et al., 1988; Dourmad, 1991) changes during lactation. These effects were not only exhibited in one reproductive

cycle (Baker et al., 1969; Dourmad, 1991), but also maintained throughout several reproductive cycles (Lodge et al., 1966a; Elsley et al., 1969; Whittemore et al., 1988). Hoving et al. (2011) reported that 30% higher feed intake during early gestation (d 3 to 32) increased sow BW gain by 8.7 kg during this period. Additionally, higher feed intake during mid-gestation to parturition (Weldon et al., 1994c) and late gestation (Cromwell et al., 1989) both increased sow BW gain during these periods and caused more BW loss during lactation. Interestingly, additional weight gain due to the higher feed intake during gestation was lost by the end of lactation in gilts, however, treated sows maintained a 6 to 7 kg weight advantage over control sows, suggesting that gilts were more vulnerable to the low capacity of feed intake during lactation (Mullan and Williams, 1990).

Several researchers reported that ADFI during lactation was reduced in a linear manner when gestation feeding levels were increased (Baker et al., 1969; Dourmad, 1991), even though feed intake of sows was only increased from d 60 of gestation to parturition (Weldon et al., 1994c). However, Elsley et al. (1969) obtained similar ADFI during lactation, although BW loss during lactation increased dramatically in the sows fed higher feeding levels during gestation.

There were only two studies which reported wean to estrus intervals. One did not observe difference among sows fed different feeding levels (Whittemore et al., 1988), whereas, the other one reported that wean to estrus intervals were prolonged in the sows fed higher feeding levels during gestation (Dourmad, 1991). The inconsistent results could be explained by the extent of BW and BF gains during gestation, body reserve at farrowing and weaning, as well as the extent of body reserve mobilization.

Litter performance

From results of different feeding levels during gestation on litter performance (Table 1-6), most researchers reported no differences in terms of numbers of total born, liveborn piglets at birth and weaning (Lodge et al., 1966b; Baker et al., 1969; Elsley et al., 1969; Whittemore et al., 1988; Dourmad, 1991; Weldon et al., 1994c). In contrast, increasing feeding levels during mid-gestation to parturition (Cromwell et al., 1989) and late gestation (Hoving et al., 2011) increased the numbers of liveborn piglets at birth and weaning. However, Musser et al. (2006) reported that higher feed intake from complete diet during early gestation (from d 30 to 50 of gestation) decreased number of piglets born alive. Additionally, most of the reported literature showed that increasing feeding levels during gestation increased piglet birth weight in a linear or quadratic manner (Lodge et al., 1966b; Baker et al., 1969; Elsley et al., 1969; Cromwell et al., 1989), and among them the advantage of increased birth weight was maintained until weaning with the exception that Lodge et al. (1966b) obtained similar weaning weights among different treatments. One could speculate that feed intake restriction during gestation reduced the extent of body reserve at farrowing, which may have a negative impact on the colostrum and milk production as reported by Salmon-Leganeur et al. (1960), thus reducing the growth rate of piglets during lactation. However, prolonged lactation length could restore body reserve of sows and cause a "catch-up" effect of piglets, thus yielding similar weaning weights.

Litter weight was a function of number of piglets and average piglet weight, indicating that it could be differentiated by either factor or both factors. Litter weight at birth (Elsley

et al., 1969), litter weight at weaning (Whittemore et al., 1988) and both (Cromwell et al., 1989) were increased when gestation feeding levels were increased.

Musser et al. (2006) reported that increased feed intake from complete diet resulted in heavier offspring at slaughter compared with sows fed control and control plus additional corn intake. In the same study, female offspring from sows that provided extra feed or corn had higher percentage of lean and fat-free lean index. However, the other experiment conducted by Musser et al. (2006) did not exhibit the beneficial effects of higher feed intake on carcass characteristics. Therefore, future research is needed to identify and evaluate the factors influencing these variations.

Feeding level during lactation

Generally, low feed intake during lactation would cause more BW and BF loss (Kirkwood et al., 1987a; Kirkwood et al., 1987b; Kirkwood et al., 1990; Baidoo et al., 1992a; Eissen et al., 2003; Sulabo et al., 2010). It was proposed that excessive BW and BF loss may adversely affect subsequent reproductive performance (Aherne and Kirkwood, 1985). Indeed, low level feeding in lactation resulted in an extension of wean to estrus interval, increased incidence of anestrus and reduction of pregnancy rate, but did not affect ovulation rate (Kirkwood et al., 1987a; Kirkwood et al., 1987b; Kirkwood et al., 1990; Baidoo et al., 1992). It was, however, reported that feed restriction during lactation reduced ovulation rate (Zak et al., 1997). Lactation energy or protein intake did not affect subsequent embryo survival (King and Williams, 1984). Numerous studies, however, have reported that feed restriction would result in an increased embryo mortality

(Kirkwood et al., 1987a; Kirkwood et al., 1987b; Kirkwood et al., 1990; Baidoo et al., 1992b). The etiology of this effect is still not clear, but may be related to the reduction of serum progesterone concentrations (Aherne and Kirkwood, 1985; Jindal et al., 1997). It has been demonstrated extensively that low feed intake during lactation would result in low plasma LH concentration (Kirkwood et al., 1987b; Kirkwood et al., 1990; Baidoo et al., 1992b). Circulating LH has been shown to influence progesterone secretion (Parvizi et al., 1976). Therefore, it could be speculated that low plasma LH concentration may lead to less stimulation in ovary and thus low plasma progesterone concentration could be expected, which may reduce the survival rate of embryo. This hypothesis could be further reinforced by the evidence that exogenous administration of gonadotropin-releasing hormone (**GnRH**) alleviated the negative effect of low feed intake during lactation on embryo survival (Kirkwood et al., 1987b).

Numerous studies have investigated the pattern of feed intake during lactation on subsequent reproductive performance (Koketsu et al., 1996a; Koketsu et al., 1996b; Koketsu et al., 1996c; Koketsu et al., 1997), follicular development and oocyte maturation (Zak et al., 1997). Koketsu et al. (1996c) used a database from 20,000 sows in commercial farms to characterize 5 different patterns of feed intake during lactation and reported that lactation feed intake was affected by parity, weaning litter weight, room temperature, lactation length and energy density of the diet. Regression analysis revealed that lactation feed intake was associated with wean to estrus interval, litter weight at weaning and subsequent litter size in a linear or nonlinear manner (Koketsu et al., 1996a), which corresponded to the proposition that lactation ME intake beyond 12 Mcal/d

produced little improvement of wean to estrus interval (Aherne and Kirkwood, 1985). It also appeared that sows consuming low feed intake (< 3.5 kg) during the first 2 wks had higher chance to be culled for anestrus (Koketsu et al., 1996a; Anil et al., 2006), suggesting feed intake in the early lactation had positive implications in sow longevity. Indeed, low feed intake during one of the first 3 wk of lactation has been found to have less LH frequencies and longer wean to estrus interval compared with sows fed ad libitum during the first 3 wk of lactation (Koketsu et al., 1996b). It was further suggested by Koketsu et al. (1997) that wean to estrus interval could be reduced by increased feed intake during early and mid-lactation than late lactation, and litter weight at weaning could be increased by higher feed intake during mid- to late lactation than early lactation. Therefore, ensuring adequate feed intake from the start of lactation may minimize sow removal from breeding herd (Anil et al., 2006).

Eissen et al. (2003) reported that a higher feed intake during lactation reduced tissue loss of sows, increased litter weight gain and reduced the probability of prolonged wean to estrus interval, which also yielded a larger litter size and reduced probability of prolonged wean to estrus interval in the subsequent reproductive cycle. In the same study, when primiparous sows nursed larger litters, increase in feed intake beyond a limit during lactation could not further reduce BW and BF loss, and increase litter weight gain, suggesting that higher feed intake was less efficient to be utilized to reduce BW and BF loss at higher litter size. It may imply that strategies other than stimulating lactation feed intake could be used to reduce BW loss in lactation.

Factors affecting voluntary feed intake during lactation

Lactation in swine, compared with gestation, is of a relatively short interval, requiring a large nutritional demand on the dam. Voluntary feed intake during lactation, however, is generally not enough to meet the high energy and nutrients demand for maintenance and milk production (Noblet et al., 1990), particularly in primiparous sows (NRC, 1987), which also require energy and nutrients for body maturation. Therefore, lactation sows are generally in a catabolic state.

Many factors may affect voluntary feed intake during lactation. Koketsu et al. (1996c) characterized different patterns of feed intake during lactation using more than 20,000 farrowing records in commercial farms and identified several risk factors which affected feed intake during lactation: parity, lactation length, litter weight at weaning, energy density of lactation diets and lactation room temperature. Detailed reviews concerning factors affecting voluntary feed intake during lactation could be found elsewhere (O'Grady et al., 1985; Eissen et al., 2000). The factors influencing voluntary feed intake during lactation include sow body reserve at farrowing, parity, litter size, genotype, diet composition and environmental temperature.

Body reserve at farrowing

As demonstrated above, sows fed a higher energy intake, or protein intake or feeding level during gestation would consistently generate greater BW and BF gains during gestation, rendering more body reserve at farrowing. As a consequence, voluntary feed intake during lactation is reduced, causing more BW and BF losses during lactation. The

relationships between BW and BF gains during gestation and ADFI during lactation are illustrated in Figures 1-1 and 1-2, which clearly show that the more BW and BF gains during gestation, the less feed intake sows consumed during lactation.

In the study conducted by Yang et al. (1989), a regression analysis showed that the inverse relationship between ADFI during lactation and BF depth at farrowing was less evident in primiparous sows (-18 $g \cdot d^{-1} \cdot mm^{-1}$), but was remarkable for multiparous sows (-129 $g \cdot d^{-1} \cdot mm^{-1}$). A recent publication from our lab based on over 10,000 farrowing records revealed that an increase of 1 mm BF depth at d 109 of gestation was associated with a reduction of 60–120 g of daily feed intake during lactation, which was parity dependent (Kim et al., 2015). It was reported that reduction of lactation feed intake associated with excessive BW and BF gains during gestation might be due to low plasma concentration of insulin during lactation (Weldon et al., 1994c). Indeed, exogenous insulin administration in lactation increased feed intake during the administration period, and this effect was more pronounced for sows fed generously during gestation than sows fed restrictedly (Weldon et al., 1994a). Another explanation for the lower lactation feed intake could be the higher non-esterified fatty acid (**NEFA**) in the fat sows compared with thin sows (Weldon et al., 1994a; Weldon et al., 1994c). It was reported that plasma NEFA concentration at d 1 postpartum was negatively correlated lactation feed intake at d 1 postpartum (Trottier and Easter, 1995). Increased insulin concentration in sows fed restrictedly in gestation may attenuate the release of NEFA from adipose tissue. It is known that insulin decreases lipolysis and increases lipogenesis (Hadley et al., 1988), as well as reducing the activity of carnitine palmitoyltransferase I (Gamble and Cook, 1985),

suggesting that oxidation of NEFA may be reduced. Therefore, insulin could increase lactation feed intake in two ways: the first could be that higher circulating insulin may increase the peripheral glucose usage and thus more feed intake was required for maintaining blood glucose concentration; the other one could be the inhibition of mobilization of adipose tissue and oxidation of NEFA.

Parity

With the increase of parity, sow BW also increases. Therefore, higher parity sows would consume more feed during lactation due to high maintenance requirement. It should also be borne in mind that primiparous sows are still immature, thus a great portion of energy and nutrients are needed for maternal growth in addition to milk production (Pluske et al., 1998).

O'Grady et al. (1985) conducted a systematic analysis and estimated that ADFI increased by 0.73 kg from parity 1 to 7. Similarly, Koketsu et al. (1996c) found that old sows consumed more feed during lactation than young sows. ADFI increased from 4.51 (parity 1) to 5.30 kg (parity 10). Specifically, three categories of feed intake by parity were noted: lower parity sows (≤ 2) which consumed less than 5.0 kg/d, mid-parity sows (3-6) which consumed 5.0-5.25 kg/d, and higher parity sows (≥ 7) which consumed more than 5.25 kg/d. Additionally, Mahan (1998) also reported that lactation feed intake increased in a quadratic manner in response to parity (from 1 to 5). Therefore, these studies suggested that the gradual increase of lactation feed intake in response to advancing parities could be commensurate with the rise of maintenance energy requirement due to the increase of

BW. Another possible reason could be the increase of milk with the occurrence of increased parity, which requires increased feed intake to meet the requirement. Indeed, milk yield increased from the first to second parity and maintained the similar yield until the fourth lactation, with the yield decreasing afterwards (Etienne et al., 1998).

Litter size

Numerous researchers have shown that milk yield during lactation increased in a linear manner in response to litter size (Toner et al., 1996; Auldist et al., 1998; Hansen et al., 2012). The higher milk production with the increase of litter size requires a larger voluntary feed intake to meet the energy and nutrient requirements (Figure 1-3).

According to O'Grady et al. (1985), ADFI during lactation increased by 0.96 kg when litter size increased from 3 to 13 piglets. Similarly, Koketsu et al. (1996c) used a database containing 19,393 litter records from commercial farms and revealed that ADFI increased gradually from 4.4 to 5.0 kg when litter size increased from 3 to 15 piglets. In contrast, a linear relationship between feed intake and litter size did not exist when litter size increased from 6 to 14 piglets (Auldist et al., 1998). The inconsistent results could be due to different feeding regime during lactation. In the study conducted by Auldist et al. (1998), maximum daily feed intake was restricted by 5.0 kg. It also should be noted that ADFI from sows having 14 and 15 piglets was not different from the sows having 7 to 13 piglets (Koketsu et al., 1996c). Therefore, one may conclude that lactation feed intake increased with the increase of litter size. The magnitude of increase in feed intake in

response to advancing parity seemed to be diminished, suggesting that other factors may become limiting for sows nursing large litters.

Genotype

Genetic changes during the last several decades have resulted in greater litter size, accompanying higher maintenance requirement and milk production of lactation sows, whereas the amount of body fat reserves (Whittemore, 1996) and the appetite have reduced (Kerr and Cameron, 1996). Therefore, genetic makeup has a great impact on feed intake of lactation sows.

It was shown that sows sired by Large White boars had greater feed intake during lactation than sows sired by Landrace (O'Grady et al., 1985). One study conducted by Grandhi (1997) revealed that Hamshire sows ate more during lactation than Yorkshire sows. Additionally, Sinclair et al. (1998) reported that Meishan sows consumed more feed during lactation compared with Large White and Landrace sows.

Sow selected for high lean growth rate generally had lower feed intake during the growth phase, and this effect is maintained during lactation (Kerr and Cameron, 1996). It was also shown that BF thickness prior to farrowing was higher for the high feed intake line, whereas the BWs were similar between two selection lines. It seemed contradictory to the previous statement that fat sows had less feed intake during lactation compared with lean sows. The possible explanation could be that feed intake during lactation depends on the difference between the actual body fatness at farrowing, depending on the feeding regime during gestation and the potential body fatness at farrowing, depending on the genotype.

One can speculate that the more actual body fatness approaches the genetic potential body fatness, the higher feed intake would be in lactation.

Diet composition

Increase in dietary energy during lactation by adding tallow did not affect ADFI during lactation, even though the litter weight gain increased due to the increased fat content of milk from sows fed tallow-supplemented diet (Tilton et al., 1999). Additionally, Mahan and Mangan (1975) observed that feed intake was greater for sows fed high protein diet (18%) compared with sows fed low protein diet (12%). It should also be noted that protein content of gestation diets also influenced lactation feed intake in an interactive manner with protein content of lactation diets. Specifically, when a higher protein lactation diet was provided, gestation diets with different protein levels did not affect ADFI of lactation; whereas when a lactation diet with low protein was given, ADFI of lactation increased in a linear manner in response to the rise of protein levels of gestation diets. Similarly, Revell et al. (1998) reported that increasing dietary protein content of lactation diet increased voluntary feed intake during wk 3 to 4 of lactation. Furthermore, Mahan (1998) identified a carryover effect of protein content of gestation diets on lactation feed intake. When offered a diet with higher protein content during gestation, primiparous sows during the whole lactation and multiparous sows during the first week of lactation consumed more feed. Therefore, these studies indicated that dietary energy and protein contents of either gestation or lactation diets could exert their effects on lactation feed intake in a single or interactive manner, and the realization of these effects could be achieved through the change of milk composition and production.

Environmental temperature

In general, temperature had a great impact on lactation feed intake. It was reported that the upper limit of thermal comfort zone for sows was around 22 ^{o}C (Black et al., 1993). Thus, when the environmental temperature rose above the upper limit temperature, sows would increase heat loss through evaporation or reduce heat generation by consuming less feed. Indeed, Messias De Bragança et al. (1998) reported that voluntary feed intake during lactation reduced by 43% when ambient temperature increased from 20 to 30 ^{o}C. The reduced feed intake was also reflective of the reduced milk production, since blood flow was redirected to the skin to increase evaporation with the occurrence of higher ambient temperature, at the expense of blood flow to the mammary gland (Black et al., 1993). Since the negative influence of high temperature on lactation performance could not be mimicked by the limitation of feed intake during lactation alone without increasing ambient temperature, other endocrine mechanism may be occurring. One possible mechanism could be the decrease of thyroid hormones and cortisol induced by high ambient temperature (Messias De Bragança et al., 1998), which contributed to limit body reserve mobilization and decrease milk production.

Gestation housing systems

Generally speaking, there are two main housing systems for gestation sows in United States (**U.S.**): individual stall and group pen housing systems. Currently, individual stall system is still the primary housing system for gestation sows. Group pen housing system is relatively more complex. Group sizes may range from 3 sows per pen up to more than

100 sows per pen, depending on the group pen size and space allowance for each sow. In addition, feeding methods can also be different, including free access stall feeding, trickle feeding and electronic sow feeding.

In the past several decades, intensive pig production has influenced the swine industry to keep sow individually during gestation and lactation, which enables easy management, accurate feeding and therefore more economic returns. In the recent years, the subject of conventional housing system for gestation sows in stalls has become the point of debate driven by societal concern about animal welfare, even though the scientific evidence remains equivocal with regard to which housing system is best for gestation sows. Following the banning of stall housing for gestation sows in the European Union in January 2013, nine U.S. states have instituted legislation to phase out the use of gestation stalls. Currently, more than a quarter of pork producers have committed to phase out individual crates for gestation sows in U.S. (CAST, 2009). In particular, Smithfield Foods reached 83% of sows housed in group pens during gestation in their company owned farms by December, 2015, and it is estimated that all individual stalls for gestation sows will be phased out by 2017. Additionally, 60 or more large national companies in retail and food service industry have pledged to eliminate gestation stalls from their supply chain over a 5 to 10 years time period. Furthermore, restriction of usage of gestation stalls for sows during pregnancy in Canada was placed with the release of a new practice in July 2014.

It is thought that housing systems for gestation sows have to meet the requirement of both sows and pork producers. According to Webster (1987), the requirement of sows can be

expressed in terms of five freedoms: "freedom from 1) malnutrition, 2) thermal and physical discomfort, 3) injury or disease, 4) suppression of normal behavior, and 5) fear and stress". For the requirement of pork producers, Edwards (1990) suggested: "1) high biological performance, 2) low labor input, 3) ease of management, 4) acceptable capital cost, and 5) acceptable financial return". Therefore, when new housing systems are undergoing development, all these aforementioned requirement must be considered and evaluated thoroughly before any scientific conclusion is drawn.

Some of disadvantages of individual stall housing include: 1) restriction of movement and exercise, 2) restricted ability to perform foraging behavior, and 3) limited social interactions (CAST, 2009). Group pens, however, can allow sows to move and exercise freely and more opportunities for social interactions among sows (Spoolder et al., 2009). Despite the notion held by animal welfare advocates that keeping sows in group pens during pregnancy is welfare-friendly, group pen housing system also has disadvantages. These disadvantages include aggression at mixing and feeding, increased injuries and lesions, increased variability in BW and body condition score (Gjein and Larssen, 1995). Therefore, housing pregnant sows in group pens does not guarantee excellent animal welfare.

Among several feeding options within group housing system, group pens with electronic sow feeders (**ESF**) seems to be the best in terms of precise control of feed intake of each sow and easy management (Edwards et al., 1998). Group pens with ESF can also generate an extreme competitive environment, especially centered around ESF, because only one sow can enter the feeding station. This practice may lead to higher aggression

and thus higher injury scores in these sows (Anil et al., 2005), however, ESF provides the opportunity to capture many advantages previously unrealized in management of gestation sows, including true individual animal nutrition, estrus control and autogenous immunization (Parsons, 2016).

In summary, public concern about animal welfare has given rise to both legislation and consumer pressure to influence the swine industry to move from individual stalls to group pen housing systems for gestation sows. Group pens with ESF seems to be the best replacement alternative for individual stalls, because it allows true individual animal nutrition and improved animal welfare.

Effects of gestation housing systems on sow performance

BW and BF thickness

It was reported that prefarrowing and weaning BF thickness were lower in sows housed in group pens compared with those in individual stalls, while BWs were similar between the two housing systems (von Borell et al., 1992). However, Estienne et al. (2006) reported that when gilts were housed in group pens until d 30 of gestation, they gained more, but similar BF thickness compared with gilts housed in stalls. In contrast, Jang et al. (2015) observed that BF thickness was higher at d 110 of gestation in group housed gilts compared with stall housed gilts, while BWs were similar between gilts in both housing. These inconsistent results may derive from different experimental conditions, such as pen size, group size and feeding strategies.

Johnston and Li (2013) evaluated the performance of sows in pens that were retrofitted from stalls and reported that sows in large pens with 26 sows gained less weight than sows in small pens with 6 sows and stalls. It should be noted that the space allowances for the three housing treatments were the same (1.5 m^2 per sow). However, high competition during feeding time may be expected in the large pens compared with small pens and thus growth performance may be compromised in large pens, because floor feeding is a competitive feeding system (Gonyou et al., 2003). Another possible reason for the lower weight gains of sows in large pens may be that sows in large group pens are more active due to more social interactions among sows (Anil et al., 2006). It was reported that physical activities, such as standing and walking, could increase energy expenditure by 15% over resting (Noblet et al., 1997). Therefore, sows in large group pens may spend more energy for activities and thus less energy remained for body growth.

Conception rate and farrowing rates

Schmidt et al. (1985) reported that sows kept in groups of 4 or 5 had a 12% greater farrowing rate than those kept in stalls when the housing treatments were imposed from weaning to breeding and from breeding to 30 to 35 d of gestation. Similarly, Bates et al. (2003) also observed a higher farrowing rate in sows housed in group pens compared with those housed in stalls. In contrast, numerous researchers reported that sows kept in individual stalls had greater farrowing rate than those kept in group pens (Love et al., 1995; Barbari, 2000; Johnston and Li, 2013; Li et al., 2014; Jang et al., 2015). However, Meat and Livestock Commission (**MLC**) reported that farrowing rates were similar between individual stall and group pen housing systems (MLC, 1994).

It is the common belief that mixing sows during time of implantation should be avoided. However, few studies have compared the conception and farrowing rate among different days of mixing in group pens and stalls. Hopgood et al. (2011) reported that mixing sows at d 3 and 14 of gestation can be associated with a 5-7% reduction in conception rate compared with sows housed in stalls and those mixed at d 35 of gestation. Sows mixed on d 35 of gestation had similar conception rate with sows in stalls. Interestingly, only sows mixed on d 3 of gestation had lower farrowing rate than sows mixed on d 35 of gestation. Another study that included 96 commercial farms in Europe showed that sows mixed within 1 wk after breeding had lower conception rate compared with sows mixed 1 mo after breeding (Spoolder et al., 2009). Therefore, mixing sows after d 35 of gestation would not reduce conception and farrowing rates compared with sows housed in individual stalls.

Wean to estrus interval

There were only a few studies that investigated the effects of housing systems on wean to estrus interval. Schmidt et al. (1985) reported that wean to estrus interval was shorter for sows housed in group pens with 4 or 5 sows per pen for the first 35 d of gestation than those housed in individual stalls. Similarly, Jang et al. (2015) also observed a shorter wean to estrus interval for gilts housed in group pen with ESF compared with those housed in individual stalls. In contrast, numerous studies reported that wean to estrus interval was shorter for sows housed in stalls than those in group pens (Backus et al., 1997; Langendijk et al., 2000; Bates et al., 2003).

It was reported that sows housed in individual stalls had higher serum cortisol concentration than those housed in group pens (Barnett et al., 1989; Estienne et al., 2006). It is likely that higher maternal cortisol concentration would negatively affect the reproductive performance, such as conception and farrowing rate, and wean to estrus interval.

Effects of gestation housing systems on litter performance

Numerous studies have evaluated the effects of gestation housing systems on litter performance. Bates et al. (2003) reported that group housed sows had higher birth and weaned weight, with similar litter size, compared with those housed in individual stalls. It was suggested that sows in groups had less fear than sows in stalls (Pedersen and Jensen, 1989). Additionally, Hemsworth et al. (1989) found that a lower level of fear exerted a positive effect on reproductive performance. Therefore, the improvement of litter birth and weaning weight in sows housed in group pens may be attributed to the enhanced welfare. However, den Hartog et al. (1993) reported that number of pigs born alive was 0.65 less for sows housed in group pens with ESF compared with those gestated in stalls. A recent study conducted by Li et al. (2014) also found that sows housed in group pens with ESF had 0.5 fewer live born piglets than those kept in stalls. In the same study, litter weight gain was also less for litters from group housed sows than those from stall housed sows (48.3 vs. 49.4 kg, respectively). Additionally, Barbari (2000) reported that average piglet weight was 0.5 kg lower for sows housed in group pens with ESF compared with those housed in stalls. Furthermore, Anil et al. (2005) found that stall housed sows had fewer mummies than those in group pens. Pre-weaning mortality was lower for litters

from sows housed in group pens than those from stalls. In contrast to the aforementioned literature, similar litter performance in terms of litter size and litter weight between individual stall and group pen housing systems was reported elsewhere (von Borell et al., 1992; Johnston and Li, 2013; Jang et al., 2015).

Anil et al. (2006) investigated different types of group formation and reported that either dynamic or static group formation did not affect litter performance. Hopgood et al. (2011) conducted a systematic study to examine different day of mixing gestation sows in group pens on reproductive performance. It was found that days of mixing on d 3, 14 and 35 would not affect litter performance in terms of total born, liveborn, stillborn and mummy piglets compared with those from stalls. In contrast, Li et al. (2014) observed a 0.5 fewer liveborn piglet from sows housed in group pens with ESF mixed on 1 wk after breeding compared with those kept in stalls during gestation.

In summary, sows housed in individual stalls generally have greater or similar litter performance compared with sows housed in group pens. Different types of group formation seem to have no effect on litter performance. Mixing sows before or during embryo implantation may impair the reproductive performance. However, more research is needed to verify this hypothesis.

Effects of gestation housing systems on progeny development

Environmental stress during pregnancy can exert its effect on progeny performance (Wu et al., 2006) and behavior (Harvey and Chevins, 1985). Estienne and Harper (2010) evaluated growth performance and reproductive characteristics of gilt offspring from

sows exposed in three different accommodation types during gestation: 1) individual crates throughout gestation, 2) group pens throughout gestation, and 3) crates for 30 d postmating and then group pens for the remainder of gestation. Results showed that growth performance during 5 wk period was similar among three groups, however, gilt offspring farrowed by sows housed in crates throughout gestation had higher BW gain during the last 4 wk, resulting in an enhanced feed efficiency for gilts farrowed by sows housed in crates. In the same study, even though the mean age at puberty did not differ among gilts from the three groups, fewer gilts farrowed by sows gestated in crates throughout gestation reached puberty by 165 d of age compared with the other 2 groups (13 vs 44%, respectively). It was further supported by the evidence that puberty in gilts farrowed by sows stressed during gestation was delayed (O'Gorman et al., 2007). Foxcroft and Town (2004) concluded that environmental influences on embryonic and fetal development were important components of the biological origins of variation on growth performance after birth and it was probable that these preprogrammed effects on growth performance most often expressed themselves in the late grower or finisher stage of production.

Zhou et al. (2014) examined the physiological parameters of offspring from sows housed in stalls and group pens and reported that serum total cholesterol and low density lipoprotein (**LDL**) cholesterol were higher in the offspring of sows housed in group pens. Additionally, in the same study, serum triiodothyronine (**T3**) concentrations tended to be higher in offspring piglets from group-housed sows compared with those from stall-

housed sows. It was likely that these changes of physiological parameters may affect the growth performance of offspring.

In summary, individual stall and group pen housing systems can potentiate their effects on growth and reproduction characteristics of their offspring through stress factors accumulated from different stage of gestation. The mechanism responsible for these effects on growth and reproduction of offspring may be attributed to the changes of physiological indices, however, more research is needed to shed light on these matters.

Effects of gestation housing systems on sow welfare

The welfare of an animal is the state regarding how the animal attempts to cope with the environment. Welfare assessment includes behavioral, physiological and health parameters (Broom, 1988).

Behavioral parameters

Anil et al. (2006) compared different types of group formation and found that non-agonistic interactions were lower in dynamic group compared with static and twice-mixed groups, indicating more agonistic interactions of sows in dynamic group. More fighting occurs in large groups in order to establish the hierarchy (Arey and Edwards, 1998). In dynamic group, batches of sows were added to the group pen repeatedly, disturbing the equilibrium before mixing and generating more agonistic interactions to achieve equilibrium again after mixing. Additionally, non-agonistic interactions were higher in the sows housed in group pens compared with sows kept in stalls, while the

frequency of agonistic and sham chewing demonstrated the opposite direction (Zhou et al., 2014).

It was shown that during pregnancy, stall housed sows spent more time standing, rooting, drinking and dog-sitting, while group pen with ESF housed sows spent less time rooting and drinking and more time lying (Weng et al., 2009). However, Zhou et al. (2014) reported that the duration of standing was longer in the sows housed in groups compared with those kept in stalls.

Physiological parameters

Despite the limitation, assessment of blood cortisol concentration has often been used as an stress indicator in farm animals (McGlone et al., 2004). High salivary cortisol concentrations in stall housed sows have been reported in comparison with those housed in group pens (Barnett et al., 1989; Anil et al., 2005; Zhou et al., 2014). In contrast, Estienne et al. (2006) and Jang et al. (2015) reported that blood cortisol concentrations were higher in the sows housed in group pens than those kept in stalls. However, Broom et al. (1995) observed similar cortisol concentrations between sows housed in stalls and group pens. The inconsistent results may be ascribed to the differences of collection methods, collection time and animal variations.

Within the same group pen, different hierarchy also affected the physiological indicators. Zhao et al. (2013) found that plasma concentration of protein carbonyl in high rank sows housed in group pen with 3 sows in each pen during gestation was higher than that in middle rank sows on d 3 of lactation. Plasma 8-hydroxy-deoxyguanosine (**8-OHdG**)

concentrations in low rank sows was greater than those in high rank sows on d 90 of gestation, d 3 and 18 of lactation. These results indicated that sows in both high rank and low rank from the group pens had increased oxidative damage during late gestation and lactation, which could contribute to the reduced litter size and weight at birth in high rank sows and lower farrowing rate in low rank sows.

Health parameters

Numerous studies have investigated the effects of housing systems on sow injuries and lameness. It was reported that total injury score (**TIS**) was higher at initial introduction and mixing in group pens (Anil et al., 2003; Anil et al., 2005). The total injury score was greater in the sows housed in group pens than those kept in stalls. As the parity increased, however, TIS decreased in group housed sows and increased in stall-housed sows (Anil et al., 2005). Dynamic group formation also generated higher TIS compared with static group formation (Anil et al., 2006).

Cronin (1985) reported that vulva biting occurs in the group housed sows, especially during the last 2 wk before farrowing. It was also evident that 20% sows had damaged vulvas in group housed sows with a feeder station on a slatted floor system as a result of aggression (Backus et al.,1991). In concert with Backus et al. (1991), group housed sows had a 15.2% occurrence of vulva lesion compared with no vulva lesions in sows housed in stalls (Gjein and Larssen, 1995).

It was reported that culling rate of sows housed in group pens was higher than those housed in stalls, which was mainly caused by higher lameness occurrence in sows housed

in group pens (Anil et al., 2005). Indeed, loose housed sows had higher risk of lameness (Calderón Díaz et al., 2014). It was also suggested by Anil et al. (2009) that lame sows had higher risk (1.71 times) of removal from the breeding herd.

In summary, sows housed in group pens have higher injury scores, higher risk of lameness and thus higher culling rate compared with sows housed in individual stalls. However, management of group formation, group size and feeding strategies may minimize the negative effects of group pen housing system on culling rate. The inconsistent results of behavioral and physiological parameters indicate that welfare assessment should not be established based on a single factor, but based on a combination of factors, such as behavior, physiology, health, culling rate and reproductive performance.

Factors affecting apparent digestibility of energy and nutrients

The apparent total tract digestibility (**ATTD**) is measured by subtraction of energy and nutrient contents in the feces from the energy and nutrient contents in the diet, divided by the energy and nutrient contents in the diet. It is well documented that ATTD of energy and nutrients are influenced by numerous factors, including animal factors such as age, BW, physiological stage, genotype, diet characteristics such as chemical composition and feeding strategies such as feeding levels and frequency.

Age, BW and physiological stage

It is well documented that age of animals has a dramatic effect on the development of gastrointestinal tract and digestive physiology (Efird et al., 1982). Due to the enhanced

digestive system, ATTD of energy and protein are increased in piglets weaned at 4 wk compared with piglets weaned at 3 wk (Ball and Ahernet, 1987).

The digestibility of energy and nutrients are generally improved with increased BW (Noblet and Shi, 1994; Morel et al., 2006; Noblet et al., 2013). The positive effect of BW on the apparent digestibility of energy and nutrients is maximized when mature sows fed at maintenance are compared with growing pigs fed *ad libitum* (Noblet and Shi, 1993). The enhanced ATTD of energy and nutrients in response to the increase of BW is probably due to the fact that adult pigs, especially mature sows, have a more developed and larger gastrointestinal tract, a lower feed intake per kg BW, a relatively slower digesta transit time and a cellulolytic activity than young pigs (Noblet and Le Goff, 2001). It was also demonstrated by Noblet and Shi. (1993) that the difference due to BW was more pronounced with fibrous feed ingredients in terms of ATTD of energy and nutrients. Therefore, it is suggested that at least two energy values should be provided for each ingredient: one for growing-finishing pigs and one for sows (Shi and Noblet, 1993).

Noblet and Shi (1994) investigated the digestive utilization of energy and nutrients of ingredients and diets in pigs categorized into 3 body stages (45, 100 and 150 kg BW). It was shown that ATTD of energy and nutrients were enhanced when BW is increased. However, the extent of improvement was decreased with the increase of BW. Specifically, on average of 6 diets, ATTD of energy was 82.6, 85.0 and 85.8% at 45, 100 and 150 kg BW, respectively. Therefore, it could be concluded that when expressed per 10 kg BW increase, BW effect is smaller in heavier pigs (more than 100 kg) than in young pigs.

Numerous studies have investigated the effect of gestation periods on digestibility of energy and nutrients. Noblet and Etienne (1987) reported that digestibility of energy and nitrogen was not affected by gestation periods when sows were fed a standard gestation diet (3.4% crude fiber). In contrast, digestibility of nutrients were increased between early and middle gestation when sows were fed a fibrous feed (Nuzback et al., 1984). This was not confirmed in the study conducted by Olesen et al. (2001), which reported that no effect of dietary fiber on the digestibility of nutrients on the stage of pregnancy. Calvert et al. (1985) found that the digestibility of nutrients was decreased in the late period of pregnancy, which could be supported by the evidence that increased passage rate was associated with advancing pregnancy (Forbes, 1970; Singh and Singh, 1990). These findings indicated that digestibility of energy and nutrients in pregnant sows were related to both feed characteristics and physiological stage of pregnancy.

Genotype

In the past several decades, numerous studies have been conducted to compare the ATTD of energy and nutrients in different kinds of feed ingredients and diets in pigs with different genotypes. These results were not consistent, mainly due to different experimental conditions, such as different genotypes and diet composition.

Varel et al. (1988) evaluated the apparent digestibility of energy and nutrients in 2 diets with different fiber levels for 3 genetically different lines (lean, obese and contemporary pigs) and found that ATTD of energy and nutrients in both diets were lower for obese pigs compared with lean and contemporary genotypes. The authors also reported that

passage rate of digesta was faster for obese pigs, which may explain the lower digestibility of fiber by the obese pigs than by the other 2 genotypes.

Several authors have compared the difference between Chinese Meishan pigs and Western genotypes in terms of apparent digestibility of energy and nutrients. Fevrier et al. (1988) reported that ATTD of energy was 1.5% higher in Meishan pigs of 40 kg compared with Large white pigs when they were fed a diet with 2.6% crude fiber on dry matter basis. The difference, however, was increased to 6.0% in favor of Meishan pigs when a diet with 6.0% crude fiber was provided. The improved energy digestibility could be explained by a relatively larger hindgut, more active microflora and a higher lipase capacity (Fevrier et al., 1988; Fevrier et al., 1992). In the study conducted by Kemp et al. (1991), Meishan pigs had similar ATTD of energy with Dutch Landrace pigs, although the ATTD of crude fiber and ether extract were higher in Meishan pigs. Additionally, Fevrier et al. (1992) revealed that effect of genotype on ATTD of energy and nutrients was also influenced by the diet composition. When soybean meal was included in the diet containing wheat and wheat byproduct, there were no differences between Meishan pigs and Large White pigs in terms of ATTD of energy and nutrients, whereas, when soybean meal was removed from the diet, Meishan pigs had higher ATTD of energy and nutrients than their counterparts. It seemed that the presence of soybean meal in association with wheat alone improved ATTD of energy and nutrients. Furthermore, Urriola and Stein (2012) reported that ATTD of energy and nutrients were greater in Meishan pigs than Large White pigs when they were fed corn-soybean meal basal diet and diet containing 30% DDGS, however, no differences were observed when the 2 genotypes were fed diets

containing soybean hulls, sugar beet pulp or pectin. The findings suggested that fiber source may interact with genotype to affect energy and nutrient utilization. The higher ATTD of energy and nutrients in Meishan pigs when corn-soybean meal diet and diet containing 30% DDGS were fed could be explained by the fact that fiber in these 2 diets were mainly insoluble dietary fiber, which may limit the ability of fermentation by Large White pigs.

Genotype effect on energy and nutrient utilization was also evaluated in other local breeds. Morel et al. (2006) reported that ATTD of energy and organic matter were higher in Kune-Kune pigs than Large White X Landrace pigs when they were fed high fiber diet. However, no differences were observed between the 2 genotypes when they were fed the low fiber diet. This finding indicated that fiber levels also interact with genotype to impact the energy and nutrient utilization. In another study conducted by von Heimendahl et al (2010), two local breeds were compared with 1 modern crossbred genotype and found that no differences existed among 3 different genotypes, indicating that modern crossbred pig genotype was able to utilize energy and nutrients as efficiently as the 2 old local breeds in that experimental condition.

Dietary factor

Fiber source and level

In growing pigs, the average values of ATTD of dietary fiber are about 40-50%. However, fiber sources dramatically affect the digestibility and fermentability of fiber. Specifically, ATTD of dietary fiber is about zero in ingredients containing high lignin and water-

insoluble dietary fiber such as wheat straw, whereas, the digestibility values are 80-90% in ingredients with high pectin or water-soluble dietary fiber such as sugar beet pulp and soybean hulls (Noblet and Le Goff, 2001). The higher fiber digestibility of sugar beet pulp could be explained by two factors. One possible reason is that sugar beet pulp has a high level of pectin polysaccharides that enhance attachment of microbes promoting microbial activity. Another reason could be that the high water holding capacity may cause the increased surface area to the microflora. These two factors may facilitate microflora colonization and fermentation of the fiber substrate.

Increasing dietary fiber levels constantly results in decreased digestibility of energy and nutrients (Ramonet et al., 1999; Ramonet et al., 2000; Olesen et al., 2001; Holt et al., 2006; Degan et al., 2009; von Heimendahl et al., 2010). In the study conducted by Morel et al. (2006), it was reported that for an increase of 1 g neutral detergent fiber per kg DM, the apparent digestibility of energy in Large White X Landrace pigs decreased by 0.06-0.09%, which was comparable with the value (0.09%) reported by Noblet and Le Goff (2001). Additionally, dietary fiber also interact with genotype to affect energy digestibility. Fevrier et al. (1992) demonstrated that for 1% increase of acid detergent fiber in the diet, ATTD of energy was reduced by 2.85 and 2.36% in Large White and Meishan pigs, respectively.

Feeding level and frequency

In the past several decades, numerous studies have been conducted to investigate the effect of feeding levels on the apparent digestibility of energy and nutrients in pigs at

different stages. It was reported that with the increase of feeding levels, ATTD of energy and nutrients were reduced in weaning piglets (Ball and Aherne, 1987; Goerke et al., 2014), growing pigs (Haydon et al., 1984; Smits et al., 1994), finishing pigs (Smits et al., 1994) and sows (Everts and Smits, 1987). The study conducted using African catfish also confirmed this finding (Henken et al., 1985). In contrast, other researchers observed no differences of ATTD of energy and nutrients in response to feeding levels (Mroz et al., 1994; Morel et al., 2006; García-Valverde et al., 2008), while Dourmad et al. (1996) even found that ATTD of dry matter, organic matter and gross energy increased linearly with the increase of energy intake. The inconsistent findings concerning the effect of feeding levels on digestibility of energy and nutrients could be attributed to several factors, such as feeding levels, source and level of dietary fiber and age of pigs (Van Es, 1982). It was found that an enhanced feeding level led to a faster passage rate in the gastrointestinal tract (Henken et al., 1985), which caused a decreased retention time in the large intestine, allowing less fermentation in the hindgut, thus reducing the digestibility of energy and nutrients (Van Es, 1982). However, it should not be overlooked that the apparent digestibility of energy and nutrients are subject to the influence of endogenous excretions whose contribution to the fecal output may be expected to vary according to both feeding level, the chemical composition and nature of the feed, as well as the animal body size. Sugimoto (1985) further suggested that apparent digestibility of energy and nutrients may depend on the quality of the feed fed to animals, i.e. diets containing less digestible nutrients could be influenced to a large extent by feeding levels than diets containing more digestible nutrients. It was possible that the interaction among these factors could generate different results in different experimental settings.

Effect of feeding frequency on apparent digestibility of energy and nutrients were also evaluated in several studies. Holt et al. (2006) reported that feeding gestation sows once or twice daily did not impact the apparent digestibility of energy and dry matter in gestation sows. The possible reason could be that gestation sows were fed restrictedly, therefore, strategies of increasing feeding frequency could not exert benefit effects. In the study conducted by Chastanet et al. (2007), it was shown that growing pigs given free access to the diet had lower apparent digestibility of energy and dry matter compared with pigs fed once or twice daily. In contrast, feeding dairy cows four time daily increased the postruminal digestibility compared with those fed twice daily (Shabi et al., 1999).

In summary, numerous factors, including animal age, BW, physiological stage, genotype, diet characteristics, feeding level and frequency, can influence the apparent digestibility of energy and nutrients. Therefore, within the framework of similar age, BW and physiological stage, strategies of genetic selection, modification of diet composition, feeding level and frequency could maximize the apparent digestibility of energy and nutrients, thus enhancing the animal performance.

Food intake regulation

Food ingestion is a necessary behavior that provides the energy and nutrients for maintenance requirement and/or other specific requirements, such as growth, pregnancy and lactation. Food intake regulation consists of complex systems, in which peripheral gastrointestinal mechanisms, peripheral adipose signals and central nervous system

integrate together and play a critical role. Studies of the subject have demonstrated the effects of gastrointestinal hormones, adiposity-related hormones and nervous systems on food intake regulation. In the following review, gastrointestinal hormones, adiposity signals (insulin and leptin) and their interaction on food intake regulation are discussed.

Gastrointestinal hormones

Ghrelin

Ghrelin, predominately produced in stomach fundus, was discovered by Kojima et al. (1999). Ghrelin discovery was motivated by the identification of the endogenous ligand for growth hormone secretogogue receptor 1a (GHSR1a). After the discovery, ghrelin quickly acquired widely research interest and intensive studies have been conducted and many functions of ghrelin have been revealed.

Tschöp et al. (2000) found that ghrelin could regulate food intake and body adiposity. In this early ghrelin study, the observation that ghrelin levels rise before feeding and decline after feeding suggests that ghrelin acts as a "hunger" hormone, which sends gastrointestinal fuel status signals to the central nervous system (**CNS**) in order to regulate food intake and energy expenditure (Cowley et al., 2003; Cummings et al., 2004; Cummings, 2006). However, the traditional defined function of ghrelin as "hunger" hormone has been changed due to the outcomes of extensive research of ghrelin. These functions of ghrelin include modulation of sleep-wake patterns, regulation of insulin synthesis and glucose metabolism, regulation of stress and anxiety, modulation of

cardiovascular function (see detalied review in Müller et al., 2015) and aging effect (Sun et al., 2007; Schneider et al., 2008; Nass et al., 2014).

Ghrelin acylation

Ghrelin requires the attachment of a medium fatty acid side-chain to its serine 3 residue, which is named as post-translational acylation which is completed by the ghrelin O-acyl-transferase (**GOAT**) (Gutierrez et al., 2008; Yang et al., 2008). It was thought that acylated ghrelin is the active form which can bind the GHSR1a and leads to specific functions. Des-acylated ghrelin, however, has been demonstrated to exert effects on glucose metabolism in GHSR1a-independent manner (Thompson et al., 2004; Zhang et al., 2008), possibly antagonizing the effect of acylated ghrelin. When des-acylated ghrelin was administrated together with ghrelin, plasma glucose and insulin levels change was tempered (Broglio et al., 2004). It have been speculated that lipid metabolism might be modulated by des-acyl-ghrelin, as evidenced by the fact that lower BW gain and adipose mass have been observed in the genetic-modified mice with increased expression of des-acyl ghrelin, as well as improved insulin sensitivity, in comparison with the wild type mice (Asakawa, 2005; Zhang et al., 2008). Additionally, administration of des-acyl ghrelin down-regulates the gene expression involved in lipogenesis in both white adipose tissue and muscle (Delhanty et al., 2010).

Factors affecting ghrelin levels

Plasma ghrelin levels are determined by several factors, including body energy reserve and caloric intake, as well as nutrient composition of the diet. It is believed that

circulating ghrelin concentration is inversely proportional to adiposity (Tschöp et al., 2001). It has been reported that obese subjects have reduced plasma ghrelin level compared with lean counterparts (Tschöp et al., 2001), however, the plasma ghrelin level in the obese subjects elevates to normal after the weight loss (Hansen et al., 2002). In addition, postprandial ghrelin regulation has been changed in obese individuals, whose plasma ghrelin concentration does not decrease rapidly after food ingestion, which may worsen the progression of obesity (Le Roux et al., 2005). In contrast, subjects with anorexia have higher plasma ghrelin concentration, which normalizes after the condition is improved (Otto et al., 2001).

It have been demonstrated extensively that ghrelin levels rise preprandially and decrease to baseline levels within the first hour after the meal (Liu et al., 2008b). The magnitude of the reduction of ghrelin level is proportional to the caloric load and macronutrient content. It was shown consistently that high carbohydrate diets resulted in the rapid drop of ghrelin levels, but also induced a subsequent rebound to preprandial levels (Foster-Schubert et al., 2008). Different protein sources may cause different ghrelin profile change. Milk protein ingestion led to postprandial decrease of ghrelin concentration (Foster-Schubert et al., 2008), however, meat protein even led to postprandial rise of ghrelin concentration (Erdmann et al., 2003; Erdmann et al., 2004). Lipid effect on plasma ghrelin concentration was somewhat intermediate between carbohydrate and protein (Foster-Schubert et al., 2008). More research is needed to study the mechanism regarding how the body adjust the plasma ghrelin synthesis and release in response to different macronutrients and the different sources of the same macronutrients.

The regulation of ghrelin levels

The regulation of circulating ghrelin levels is the subject of active research. Ghrelin secretion is regulated by the enteric nervous system, which have innervations from both sympathetic and vagus nerves. It has been shown that ghrelin-producing cells express the alpha-1 and beta-1 adrenergic receptors (Zhao et al., 2010; Iwakura et al., 2011; Engelstoft et al., 2013), and adrenaline and noradrenaline directly stimulate ghrelin secretion via the beta-1 receptors (Iwakura et al., 2011; Gagnon and Anini, 2012; Gagnon and Anini, 2013). Additionally, high doses of dopamine have been found to stimulate ghrelin secretion from a ghrelin-producing line mediated by D1a receptor (Iwakura et al., 2011). However, recent studies indicate that ghrelin-producing cells express low levels of acetylcholine receptor and no direct effect of acetylcholine on ghrelin secretion was observed in *in vitro* studies (de la Cour et al., 2007; Zhao et al., 2010; Iwakura et al., 2011), suggesting that vagus nerve may play an indirect role in the regulation of ghrelin secretion.

Cholecystokinin (CCK)

CCK is widely produced in the gastrointestinal tract (Larsson and Rehfeld, 1978), mainly in the enteroendocrine I cells of duodenum and jejunum. CCK has also been identified in the CNS, acting as a neurotransmitter regulating plenty of activities, such as satiety, rewarding behavior, anxiety and satiety (Crawley and Corwin, 1994). CCK is a family of hormones consisted of different numbers of amino acids in association with post-translational modification, and the common bioactive forms are CCK-8, CCK-33 and

CCK-58 (Baura et al., 1993). CCK is released into the circulation after nutrient ingestion, mainly lipids and protein. There are two kinds of G-protein coupled receptors identified for CCK: CCK receptor 1 (CCK1R) expressed dominantly in gastrointestinal tract system and CCK receptor 2 (CCK2R) expressed mainly in the brain.

CCK regulating food intake

The function of CCK in nutrient digestion, including stimulation of pancreatic enzymes and gall bladder release, inhibition of gastric empting and increase of intestinal motility (Liddle et al., 1985), has been known for several decades. In addition, CCK has been demonstrated to exert effects on short term regulation of food intake. Satiating effects of CCK have been confirmed in numerous animal species (Gibbs et al., 1973; Metzger and Hansen, 1983; Stein et al., 1986) and human beings (Pi-Sunyer et al., 1982; Geary et al., 1992). The mechanism for achieving the satiation is believed to be mediated by the activation of CCK1R (Miesner et al., 1992; Moran et al., 1992), which is expressed on vagal afferents. Study has shown that peripheral exogenous CCK administration increases vagal afferent discharge, as well as the *c-fos* protein expression in the nucleus of solitary tract (Zittel et al., 1999). Since the half life of CCK is only 1-2 min, its direct effect on the hypothalamus is relatively limited. Furthermore, abdominal, subdiaphragmatic vagotomy and vagal deafferentation compromise the anorectic effects of peripheral CCK administration (Joyner et al., 1993; Moran et al., 1997), which indicates that vagal pathway plays a critical role in CCK-induced satiation. Apart from the peripheral effect, CCK administration into dorsomedial hypothalamus (DMH) can

also reduce food intake (Blevins et al., 2000), which may be caused by the fact the NPY expression is reduced.

Although it has shown that CCK is important in food intake regulation, repeated CCK infusion does not alter BW of rats. It can be explained by the fact that overall food intake is not changed, even though meal size is reduced and meal frequency is increased (West et al., 1984; West et al., 1987). Similarly, CCK1R deficient mice have similar growth rate and food intake as the control wild type mice (Bi et al., 2004), which indicates that CCK plays little role in satiety, and other gastrointestinal hormones may also interact with CCK in regulation of food intake and satiety. As predicted, there is no inhibition of gastric empting and activation of neurons in solitary tract of nucleus, the region where vagal afferent neurons terminate in the brainstem, in response to exogenous CCK administration in CCK1R null mice (Whited et al., 2006).

Interaction with other factors controlling food intake

Leptin is mainly synthesized and released from white adipose tissue, and the circulating leptin plays a critical role in the central regulation of food intake and energy homeostasis (Cummings and Overduin, 2007). Leptin concentration is proportional to the body fat mass, which can act directly in the hypothalamus to indicate the body energy homeostasis and enhance the sensitivity to the short-term satiety signals, such as CCK. It is supported by the observation that leptin receptors are co-expressed with CCK1R on vagal afferents, and leptin administration enhances the activity of vagal neurons to the exogenous CCK (Peters et al., 2006). Additionally, leptin administration also enhances the inhibition

effects of exogenous CCK on gastric empting and food intake regulation (Wang et al., 2000).

Apart from leptin and CCK receptors, vagal afferents also have expression of receptors for many hormones that are released from gastrointestinal tract, pancreas and adipose tissue, which interact together to regulate both long-term and short-term food intake. These receptors expressed in vagal nerves include the receptors for orexigenic peptides such as ghrelin (Date et al., 2002), orexin (Burdyga et al., 2003) and cannabinoids (CB1) (Burdyga et al., 2004) and the receptors for anorectic peptides, such as PYY (Koda et al., 2005), GLP-1 (Nakagawa et al., 2004) and GLP-2 (Nelson et al., 2007). Fed status can affect the expression of these receptors, which are also influenced by circulating CCK level and existence of function CCK receptor. One study shows that CB1 receptor expression is increased by fasting, but reduced by refeeding or exogenous CCK administration (Burdyga et al., 2004). But the reduction effect of CB1 receptor expression is hampered by the exogenous administration of CCK1R antagonist (Burdyga et al., 2004). It can be speculated that CCK level rises up after eating, which plays a role to reduce the expression of receptors of orexigenic peptides. It is also shown that ghrelin administration does not affect the expression of CB1 receptor, but inhibits the reduction effect of CCK1R-dependent pathway on CB1 receptor expression in the vagal neurons in response to feeding (Burdyga et al., 2006). Ghrelin, therefore, may antagonize with CCK to inhibit the down-regulation of orexigenic hormones in response to feeding, thus increasing food intake (Date et al., 2005).

Glucagon-like peptide 1 (GLP-1)

GLP-1, a preproglucagon-derived peptide, is produced in L cells and pancreatic A cells, as well as in CNS (Tang-Christensen et al., 2001). Preproglucagon can be cleaved into several fragments depending on the post-translational modification (Mojsov et al., 1986; Orskov et al., 1986). The main preproglucagon-derived products are GLP-1, GLP-2, oxyntomodulin and glicentin in the gastrointestinal tract (Orskov et al., 1986; Orskov et al., 1987; Holst et al., 1994), and glucagon and glicentin-related polypeptide in the pancreas (Mojsov et al., 1986).

GLP-1 is synthesized predominantly by the L cells located in the distal ileum and colon, where it is co-expressed with oxyntomodulin and PYY (Habib et al., 2013). In the fasting condition, plasma GLP-1 concentration is very low. It is also shown that the fasting concentration can be reduced further by somatostatin administration (Toft-Nielsen et al., 1996), which indicates that GLP-1 is secreted in a certain rate during fasting. Meal ingestion, especially high in fat and carbohydrates, stimulates GLP-1 secretion probably by two mechanisms: one may be the indirect neuro-hormonal mechanism in duodenum and the other may be the direct contact with the L-cells in the distal intestine. It has been demonstrated that GLP-1 can be quickly degraded into the inactive form by dipeptidylpeptidase IV (DPP-IV) (Kieffer, 1995). DPP-IV is abundant in the brush border and endothelial cells of the capillaries (Bai, 1993; Holst and Deacon, 2005), which indicates that active GLP-1 remained in the systemic circulation only account for a very low percentage of the total GLP-1 production.

Insulinotropic function of GLP-1

GLP-1 plays a critical role in regulating glucose homeostasis. The performance of this function is through the incretin effect, which designates the amplification of insulin secretion elevated by hormones secreted from the gastrointestinal tract with the presence of elevated blood glucose concentration. The incretin effect is regulated by both GLP-1 and glucose-dependent insulinotropic peptide (**GIP**). GIP is released from K cells in the proximal intestine in response to nutrients and activates insulin secretion in a glucose-dependent manner (Parker et al., 2009). These two peptides work synergistically to potentiate the glucose-dependent insulin secretion, which accounts for around 60% total insulin secretion (Nauck et al., 1986). It has been demonstrated that oral glucose administration causes a two to three fold larger insulin response in comparison with the intravenous glucose infusion in healthy individuals (Nauck et al., 1993; Hansotia and Drucker, 2005), which indicates that the glucose absorption in the gastrointestinal tract contributes greatly to the incretin effect. Additionally, GLP-1R knockout mice exhibit modest blood glucose perturbations following oral and intraperitoneal glucose challenge (Scrocchi et al., 1996).

The GLP-1R is expressed in the beta pancreatic islet cells (Hörsch et al., 1997; Bullock and Scott, 1996). GLP-1 regulates glucose homeostasis by stimulating insulin release, increasing beta cell proliferation and decreasing beta cell apoptosis (Baggio and Drucker, 2007). The mechanism for the GLP-1 induced insulin secretion is that GLP-1 binds to its receptor in the beta islet cells and thus stimulate adenylate cyclase, which increase the cAMP production and thus the activation of the cAMP-regulated protein kinase, which

leads to the elevation of calcium concentration, leading to the exocytosis of insulin-containing granules (Holz, 2004).

The notion that the incretin effect of GLP-1 is mediated by its direct effect on pancreatic beta cells has been under debate, due to the fact that GLP-1 is degraded rapidly before and once released into the circulation. Thus GLP-1 concentration is considerably lower than GIP concentration and the intact GLP-1 reaching to the pancreas may be very limited. Interestingly, GLP-1Rs are found to be localized in the nerve terminals of portal vein, and blockage of these GLP-1Rs substantially impairs glucose tolerance in rats (Vahl et al., 2007). In addition, administration of active GLP-1 into the hepatic vein stimulate vagal neurons innervating the pancreas and the effect is attenuated by the ganglion blockage (Balkan and Li, 2000). Furthermore, vagal fiber deafferation attenuates the insulin secretion in response to exogenous GLP-1 administration (Ahren et al., 2003). Taken together, the peripheral insulinotropic effect of GLP-1 may be partly regulated via vagal afferent pathway.

GLP-1 in regulating food intake

Studies demonstrated that exogenous GLP-1 administration reduces short-term food intake in rats (Donahey et al., 1998) and humans (Verdich et al, 2001). Additionally, peripheral administration elicits satiety in both normal weight (Gutzwiller et al., 1999) and obese individuals (Näslund et al., 1999). Importantly, it is reported that BW is reduced dramatically in diabetes subjects treated repeatedly with GLP-1 and GLP-1R agonist exenatide (Zander et al., 2002; Henry et al., 2006). Studies indicate that

peripheral native GLP-1 infusion induces satiation but requires high doses than synthetic GLP-1R agonists in rodents (Rodriquez de Fonseca et al., 2000; Pérez-Tilve et al., 2007). Indeed, the effect of extendin-4 on inhibiting food intake is much more pronounced than the GLP-1 (Baggio et al., 2004). The reason for the long-lasting effect of the synthetic GLP-1R agonists may be that the body does not have the enzyme or have limited enzyme activity to degrade this compound, rendering them inhibiting food intake more efficiently. It should be noted that prolonged fasting attenuates the satiation effect of GLP-1, suggesting that satiation effects of GLP-1 is dependent on nutritional status (Sandoval et al., 2012; Ronveaux et al., 2014).

The mechanisms underlying the GLP-1-induced satiety are not fully understood. Peripheral administration of GLP-1 activates *c-fos* expression in the hindbrain and hypothalamus in rodents (Asarian, 2009; Baumgartner et al., 2010; Parker et al., 2013), which indicates that peripheral GLP-1 exerts its effects through activating central circuits. It is shown that the anorectic effects are absent in GLP-1R deficient mice and are restored with GLP-1R agonist (Baggio et al., 2004), indicating that the satiety effects of GLP-1 are mediated specifically by GLP-1R. Additionally, GLP-1 induced satiation is attenuated by blockage of either peripheral or central GLP-1R (Meeran et al., 1999; Williams et al., 2009). Furthermore, lesions in the brainstem-hypothalamic pathway attenuate GLP-1 induced satiation in rats (Abbott et al., 2005), suggesting CNS plays an important role in regulation of the satiation effect of GLP-1.

Studies demonstrate that 42% GLP-1R is expressed in vagal afferent neurons (Bucinskaite et al., 2009; Ronveaux et al., 2014). Vagatomy attenuates the satiation effect

induced by peripheral GLP-1 administration, indicating that the complete vagal afferent pathway is critical for the satiation effect induced by GLP-1. As we have mentioned, vagal afferent neurons express both orexigenic and anorexigenic receptors. Studies have shown that vagal afferent neurons exists in two different states that either promote the expression of orexigenic or anorexigenic receptors depending on the feeding status (Burdyga et al., 2008; Dockray and Burdyga, 2011). In the fasting state, orexigenic receptor expressions increase, while anorexigenic receptor expressions decrease . In contrast, these changes are reversed in the fed state. However, it is demonstrated that GLP-1Rs, in contrast to other receptors, alter the cellular localization depending on the feeding status, rather changing its rate of expression. Specifically, under fasting state, the majority of GLP-1Rs are located in the cytoplasm, while GLP-1Rs move to the cellular membrane postprandially with a increase rate of 42% (Ronveaux et al., 2014). Taken together, vagal-brainstem-hypothalamus pathway plays a critical role in the realization of GLP-1 induced satiation and the vagal afferent neurons can adjust the localization of GLP-1Rs according to different feeding status. However, the exact mechanism how the GLP-1Rs are translocated in the vagal afferent neurons is still not clear and warrants further investigation.

Glucose-dependent insulinotropic peptide (GIP)

GIP, a 42 amino acid peptide, is produced predominantly in duodenum K cells in the proximal small intestine (Buffa et al., 1975; Buchan et al., 1978). GIP has also been identified in the CNS, which may be associated with the regulation of cell survival (Nyberg et al., 2005). GIP secretion is stimulated by nutrient intake, especially glucose

and fat. More specifically, GIP release is stimulated by the rate of nutrient absorption rather than the nutrients presence *per se* in the gut. Thus, GIP secretion is reduced in the individuals with intestinal malabsorption or after the medicine administration that reduce the nutrient absorption (Besterman et al., 1979; Fushiki et al., 1992).

Circulating levels of GIP is low in fasted state and rises within minutes of food ingestion which is glucose-dependent. Like GLP-1, GIP is rapidly cleaved into the inactive form GIP(3-42) by DPP-IV before and after the release into the circulation (Kieffer et al., 1995). Therefore, circulating GIP represents a combination of active GIP (1-42) and the inactive form GIP (3-42), which suggests that experimental analysis of plasma GIP levels requires discrimination between the two forms. Interestingly, it is found that 40% GIP remains intact versus 20% for GLP-1 after the exogenous intravenous infusion of the respective hormones (Kieffer et al., 1995; Deacon et al., 2000), indicating that GIP may be less susceptible to DPP-IV degradation, and thus has longer half-life.

The insulinotropic function of GIP

As aforementioned, GIP is one of the other incretin hormones, which plays a critical role in glucose homeostasis. The stimulation of insulin secretion by GIP administration is found in isolated rat pancreas (Pederson and Brown, 1978) and human beings (Dupre et al., 1973; Elahi et al., 1979). However, as the same case with GLP-1, a significant insulinotropic effect of GIP is observed only after the presence of elevated blood glucose concentration has occurred after the ingestion of a mixed meal (Dupre et al., 1973), suggesting that the insulintropic effect of GIP is glucose-dependent. The glucose-

dependent insulinotropic effect is further confirmed by stepwise hypo-, eu- and hyperglycemic clamp studies with the administration of exogenous GIP (Elahi et al., 1979; Kreymann et al., 1987; Nauck et al., 1993). It is stated that GIP is responsible for approximately 60% of the incretin effect in the normal subjects (Nauck et al., 1986). Administration of GIP antagonists remarkably reduce the postprandial insulin secretion (Tseng, 1996; Tseng et al., 1999). It is further supported by the study in GIP receptor knockout mice, which display normal fasting glucose level, but have elevated plasma glucose concentration after oral glucose ingestion (Miyawaki et al., 1999), highlighting the importance of the insulinotropic effect of GIP via the activation of its receptor.

In addition to the insulin secretogogue, it has been shown that GIP exerts anti-apoptotic and proliferative effects on islet beta cells. Studies show that GIP improves survival of rat INS-1 cells after glucose deprivation or following exposure to streptozotocin (Ehses et al., 2003). Additionally, a 2 week infusion of GIP also down-regulate Bax and increase Bcl-2 expression in pancreatic beta cells of ZDF rats (Kim et al., 2005). These studies indicate that GIP plays a critical role in the maintenance of islet beta cell mass, further supporting its performance of insulin-stimulating function.

It should be noted that in contrast to GLP-1, the insulinotropic effect of GIP is dramatically reduced in type 2 diabetic patients (Meier et al., 2001), indicating a diminished insulintropic effect of GIP in this condition. However, diabetic patients treated with glyburide 1 hour prior to GIP administration show an increased insulin response (Meneilly et al., 1993), which suggest that the diminished response to GIP in the diabetic patient can be restored after hyperglycemia treatment.

GIP in lipid metabolism

Fat ingestion can increase GIP secretion (Elliott et al., 1993). The increased GIP secretion caused by fat ingestion alone cannot stimulate insulin secretion at the basal glucose level (Ross and Dupré, 1978). The exact mechanism under this phenomenon is still not clear; it may be a body protection mechanism in order to avoid potential hypoglycemia due to an increased insulin secretion. From another perspective, GIP may display an insulin-independent action in fat metabolism. Indeed, an anabolic function is expected from three observations that plasma GIP concentrations are elevated in both obese and type 2 diabetic patients compared with normal individuals (Creutzfeldt et al., 1978; Salera et al., 1982; Elahi et al., 1984). It is further supported by the study that postprandial plasma triglyceride levels are reduced in subjects who have higher plasma GIP levels, indicating a role of GIP in the uptake of fatty acids (Raben et al., 1994). It is suggested that GIP might achieve this partly by increasing the enzyme activity of lipoprotein lipase, which is located in the capillaries that can liberate the fatty acids from triglycerides in chylomicrons. Thus the uptake of fatty acid in the adipose tissue can be used for synthesis of triglycerides, which may contribute to the role of GIP in etiology of obesity.

Even though GIP is a potent insulinotropic peptide, its effects on the development of obesity renders the controversy of the clinical application. Miyawaki et al. (2002) supports the hypothesis that GIP is involved in development of obesity. In this study, the authors report that GIP receptor knockout mice do not gain excessive weight and insulin sensitivity remains normal when placed on high-fat diet, while in the control mice, BW is increased by 35% with the development of insulin resistance. But it should be mentioned

that GIP receptor knockout mice display glucose intolerance (Miyawaki et al., 1999), which is expected due to the importance of insulinotropic effect. These studies indicate that antagonizing GIP receptor could have negative effect on the glucose homeostasis. However, it is believed that long term administration of GIP receptor antagonist could outweigh the negative effect on glucose homeostasis through its effects on reducing body fatness and thus increasing insulin sensitivity.

Peptide YY (PYY)

PYY is one of the three pancreatic polypeptide family; the other two are neuropeptide Y (**NPY**) and pancreatic peptide (**PP**). All these peptides contain 36 amino acids which requires carboxy terminal amidation for biological activity. They exert their action via the G protein-coupled receptors (Y1R, Y2R, Y4R, Y5R and Y6R).

PYY is expressed predominantly in distal intestinal L cells. It is released following the meal ingestion in response to nutrient intake, especially by fat (Lin and Chey, 2003). Like GLP-1, meal-induced PYY secretion occurs before the nutrients have reached the distal intestine where the PYY-secreting L cells are predominantly located, which suggests a neural mechanism is involved (Fu-Cheng et al., 1997). Once released, intact PYY(1-36) is rapidly cleaved to PYY (3-36) by DPP-IV (Mentlein et al., 1993). However, unlike GLP-1, both forms of PYY are bioactive. However, it should be noted that the enzymatic transformation also cause the shift of Y receptor subtypes activated by the peptide: intact PYY (1-36) activates Y1, Y2 and Y5 receptors, while PYY (3-36) activates preferentially Y2 and to a less extent Y5 receptors (McGowan and Bloom, 2004; Cox, 2007).

PYY in regulating gastrointestinal motility and gastric acid secretion

As indicated previously, both PYY(1-36) and PYY(3-36) are bioactive, which have dramatic effects on gastrointestinal motility and gastric acid secretion. It is shown that administration of exogenous PYY mimicking the postprandial level inhibits gastric acid secretion, gastric emptying and gallbladder contraction (Allen et al., 1984; Adrain et al., 1985; Hoentjen et al., 2001). In addition, Cox (2007) reports that short chain fatty acid (SCFA) stimulates PYY secretion, which inhibits gastrointestinal motility, water and electrolyte secretion. The mechanism of gastric acid inhibition is thought to be mediated both by vagal afferent pathway and directly action on the stomach with the activation of Y1 and Y2 receptors (Yang, 2002).

The physiological function of inhibiting gastric emptying and intestinal motility by PYY is characterized as the "ileal and colonic brake" effect (Cox, 2007). It is shown that in the mice model, PYY (1-36) and PYY(3-36) exert their colonic brake effect through the enteric nervous system mediated by Y2 receptor (Wang et al., 2010; Tough et al., 2011). Evidence shows that gastrointestinal motility and secretory activity is inhibited by PYY. It is supported by the fact that Y1 and Y2 receptor antagonism, as well as PYY knockout, inhibit colonic ion transport and motility (Tough et al., 2011).

PYY in regulating food intake and energy metabolism

Peripheral infusion of PYY has numerous effects. In addition to inhibition of gastric acids secretion and gastrointestinal motility, it also decreases food intake, thus reducing growth rate, in several species, including mice, rat and primates (Batterham et al., 2002; Challis

et al., 2003; Moran et al., 2005), which may be contributed from its inhibition of gastrointestinal motility, thus increasing the feeling of satiety. PYY (3-36), which is the main circulating form of PYY, is effective in inhibiting food intake in both lean and obese individuals, and fasting PYY levels are negatively correlated with the body mass index (Batterham et al., 2002; Batterham et al., 2003). The exact mechanism for the inhibition effects of PYY on food intake is still not clear. But currently, two mechanisms have been proposed. One is the direct action of circulating PYY on the hypothalamus. The other is indirect effect via the vagal afferent pathway which relay information to hypothalamus. Indeed, there is evidence that PYY has the ability to cross from the blood to brain direction via non-saturable mechanism (Nonaka et al., 2003). It is reinforced by the fact that peripheral PYY (3-36) reduces the activity of arcuate neurons and decreases the NPY mRNA expression (Challis et al., 2003), as well as increasing the arcuate proopiomelancortin (POMC) mRNA expression (Challis et al., 2003), which may be achieved via the participation of pre-synaptic Y2 receptors (Broberger et al., 1997). It should be noted that Y2 receptors also exists in vagal afferent nerves via transportation from the nodose ganglion (Koda et al., 2005), which suggests that vagal afferent pathway may play a role in the food intake regulation. Supporting this hypothesis, indeed, anorectic effect and arcuate neuron activation induced by peripheral PYY(3-36) administration are eliminated by either truncation of vagal-brainstem-hypothalamic pathway or abdominal vagotomy (Abbott et al., 2005; Koda et al., 2005).

In contrast to peripheral PYY administration, central injection of either PYY(1-36) or PYY(3-36) increase food intake. For instance, food intake is stimulated in rodents in a

dose-response manner in several studies where exogenous PYY is injected to third or the fourth ventricles of the brain (Clark et al., 1987; Corp et al., 2001) and the paraventricular nucleus of hypothalamus (Stanley et al., 1985). However, food induction effect of central administration of PYY is attenuated in both Y1 and Y5 receptors deficient mice (Kanatani et al., 2000). These studies suggest that Y1 and Y5 receptors are involved in the realization of the central effects of both PYY forms, while the peripheral effects are mediated via Y2 receptor.

It is interesting that PYY also possesses incretin-like activity via GLP-1 (Cox et al., 2010), which is also produced mainly in enteroendocrine L cells. These cells release GLP-1 responding to the luminal nutrients via the G protein-coupled receptor GPR119 mediated by PYY, thus increasing the plasma insulin concentration and glucose tolerance. This finding adds to the complexity of gut hormones on the glucose homeostasis and proposes the potential role of PYY on the intervention of diabetes.

Oxyntomodulin (OXM)

OXM, consisting of 37 amino acids, is co-expressed with GLP-1 in distal intestinal endocrine L cells following nutrient ingestion. OXM, composed of the whole glucagon amino acid sequence and a carboxy-terminal (Larsen et al., 1997), is one of the preproglucagon-derived peptides, which also include glucagon, glicentin, glicentin-related pancreatic peptide (GRPP), GLP-1 and GLP-2. Different terminal products are tissue-specific and depend on different enzymatic processing. In the distal intestinal endocrine L cells, prohormone convertase 1/3 produces predominantly glicentin, OXM,

GLP-1 and GLP-2 (Ghatei et al., 1983; Habib et al., 2012), whereas prohormone convertase 2 produces glucagon in pancreatic alpha cells (Rouillé et al., 1994; Furuta et al., 2001).

It has been reported that OXM increases the cAMP levels in the proglucagon-derived peptide receptors expressing cell-lines through either GLP-1 or glucagon receptor, although the affinity is reduced in comparison with GLP-1, GLP-1 agonist extendin-4 and glucagon (Baldissera et al., 1988; Gros et al., 1993; Schepp et al., 1996; Baggio et al., 2004; Jorgensen et al., 2007; Pocai et al., 2009). It is also found that OXM acts as a full agonist to recruit beta-arrestin 2 to glucagon receptor, but with less potency in recruiting beta-arrestins and G-protein-coupled receptor kinase to GLP-1 receptor (Jorgensen et al., 2007). Baggio et al. (2004) reports that both GLP-1 agonist extendin-4 and OXM can activate *c-fos* expression in the nucleus of paraventricular hypothalamus, postrema and NTS following peripheral administration. This finding suggests that peripheral circulating OXM is able to cross blood-brain-barrier and convey the physiological signals to the brain.

OXM in regulating food intake and BW

Studies have shown that, in rats, both central and peripheral exogenous OXM administration inhibits food intake (Dakin et al., 2001; Dakin et al., 2004), and chronic infusion reduces the rate of BW gain (Dakin et al., 2004). Consistent with mice study, in humans, intravenous infusion acutely decreases food intake and increase satiety (Cohen

et al., 2003) and repeated infusion decreases BW by 0.5 kg/week in comparison with control group in a 4 week trial (Wynne et al., 2005).

Although there may be a possibility that the inhibition effect of OXM on food intake may be initiated by a separate and unidentified receptor, the study using GLP-1 receptor knockout mice illustrates that a functional GLP-1 receptor is required for the anorectic effect of OXM (Baggio et al., 2004). It is further supported by the fact that the inhibition effects of both OXM and GLP-1 are attenuated by the central co-administration of GLP-1 receptor antagonist extendin 9-39 (Dakin et al., 2001). It is known that GLP-1 receptors are expressed in hypothalamus and NTS (Uttenthal et al., 1992; Shughrue et al., 1996) and also widely expressed in peripheral tissues (Wei and Mojsov, 1995; Bullock et al., 1996). OXM and GLP-1 elicit anorexia at equimolar basis (Fehmann et al., 1994), although OXM has a lower affinity to GLP-1 receptor compared with GLP-1 (Dakin et al., 2004), which indicates that different mechanism or pathways are involved. Indeed, studies show that OXM activates the *c-fos* expression in arcuate neurons, while GLP-1 activates the hindbrain (Dakin et al., 2004). Moreover, extendin 9-39 prior infusion in hypothalamus attenuates the inhibition effect of OXM on food intake, but the effect of GLP-1 is not affected (Dakin et al., 2004). Taken together, the action of OXM on food intake inhibition is mediated through the activation of GLP-1 receptor in the hypothalamus, not in the hindbrain, which suggests that OXM may exhibit the action on hypothalamus via directly crossing the blood brain barrier, not vagal afferent pathway.

OXM in regulating glucose metabolism

It is suggested that OXM may also be involved in glucose homeostasis. During a glucose challenge study, acute OXM administration improves glucose tolerance in mice (Maida et al., 2008). Additionally, Parlevliet et al. (2008) reported that OXM administration improves glucose intolerance by increasing glucose disposal in diet-induced insulin-resistant mice during a hyperinsulinemic clamp study. It is proposed that OXM acts only on GLP-1 receptor to modulate glucose homeostasis following acute injection, while OXM increases hepatic glucose production during the hyperinsulinenmic study via activation of hepatic glucagon receptor. Supporting the hypothesis, Du et al. (2012) found that in GLP-1 receptor knockout mice, OXM administration decreases glucose tolerance compared with control, which indicates that GLP-1 receptor knockout mice are glucose intolerant and effect of OXM administration on glucose homeostasis may be confounded by compensatory mechanisms. It is further reinforced by the study that demonstrates the activation of GLP-1 receptor by OXM administration counteracting the hyperglycemic effect of glucagon *in vivo* (Du et al., 2012), which suggests that the antiglycemic effect of OXM is predominantly mediated by GLP-1 receptor activation, and activation of glucagon receptor seems to attenuate the efficiency of acute antihyperglycemic effect by OXM.

Adiposity signals

Insulin and leptin are recognized as "adiposity signals" which are proportional to body fat mass. It is believed that these two adiposity signals play a critical role in the long-term

regulation of food intake and BW. Accordingly, plasma insulin and leptin concentration indicates the status of energy homeostasis and adiposity, and the signals transmitted to the brain causes the brain to fine-tune food intake in order to maintain BW and adiposity to the original state (Baskin et al., 1999).

Insulin as an adiposity signal

Insulin, secreted by the beta cells in islets of Langerhans of pancreas, is the first identified hormone in the central regulation of BW (Schwartz et al., 1992). It has a well-documented role in the nutrient metabolism associated with insulin-dependent tissues including muscle and adipose tissue. Excess energy intake is stored in adipose tissue with the presence of insulin, which leads to adipose tissue increment. The outcome of increased adiposity because of the long term positive energy balance is the increased insulin concentration. A great body of literature have been demonstrated that circulating insulin can enter the brain to exert anorectic response. It is shown that intracerebroventricular insulin infusion inhibits food intake in baboon and rats (Woods et al., 1979; Brief and Davis, 1984). It is also evident that the insulin concentration in cerebrospinal fluid is proportional to plasma insulin concentration in normal conditions, which indicates that insulin can enter into the central nervous system, and in fact it is determined that insulin crosses the blood-brain-barrier by a insulin-receptor regulated transport mechanism (Baura et al., 1993). The anorectic action of insulin exhibited in the CNS is further supported by the fact that insulin receptors are widely present in the hypothalamus (Corp et al., 1986; Marks et al., 1990) and insulin inhibits the mRNA expression of NPY (Schwartz et al., 1992), substantiating the anorectic effect.

Leptin as an adiposity signal

Leptin, a hormone secreted predominantly by the white adipose tissue, is the *ob* gene product (Zhang et al.,1994). It is well-documented that plasma leptin concentration is proportional to body mass index (Maffei et al., 1995). It has been shown that both acute peripheral and central exogenous leptin administration reduce food intake (Ahima et al., 1996), while chronic peripheral and central administration leads to the reduction of adipose tissue mass and BW (Hallas et al., 1997). Additionally, it is evident that leptin receptor is expressed in the hypothalamus (Tartaglia et al., 1995). Collectively, these studies indicate that leptin exerts its anorectic effect in CNS.

Leptin exerts its action via a single-transmembrane domain receptor belonging to the family of the cytokine receptor (Tartaglia et al., 1995). Leptin receptors (Ob-R) have several splice variants, generating three different isoforms: long form, short form (Tartaglia, 1997) and secreted form (Ge, 2002). The long form leptin receptor (Ob-R_L) is expressed widely in the hypothalamus, including arcuate, dorsomedial, ventromedial, and ventral premamillary nuclei (Fei et al., 1997; Elmquist et al., 1998), supporting the central role of leptin in food regulation. Specifically, within arcuate nucleus, Ob-R_L mRNA expression is identified in orexigenic neurons expressing neuropeptide Y (**NPY**) (Mercer et al., 1996), as well as anorexigenic neuorons containing proopiomelanocortin (**POMC**) (Cheung et al., 1997). Indeed, exogenous administration of leptin inhibits the activity of orexigenic NPY neurons, while increases the activity of POMC neurons, resulting in the reduced and increased expression of these two peptides, respectively (Stephens et al., 1995; Schwartz et al., 1996; Elias et al., 1999). Therefore, during the

time of food shortage, circulating leptin concentration is low, resulting in the up-regulation of NPY, while during the time of plenty food availability, the circulating leptin concentration is high, leading to the activation of anorectic POMC neurons. The other two forms of leptin receptors, although, are not directly involved in the food intake regulation, they have specific biological implications. It has been speculated that the short form of leptin receptor (Ob-R_S) plays a role in the transport of leptin crossing the blood brain barrier (Tartaglia et al., 1995). The secreted form of leptin receptor, which binds to the circulating leptin, may play a critical role in modulating the biological activity of leptin (Ge et al., 2002).

Interaction among long-term adiposity signals and short-term satiation signals

A particular satiating peptide or its receptor knockout animal, such as CCK (Lo et al., 2008), GLP-1 (Scrocchi et al., 2000) and ghrelin (Sun et al., 2003), exhibit normal food intake and BW, implicating that other signals can compensate for the absence of the particular peptide. It seems that the body consists of multiple satiation regulating signals with considerable interaction and redundancy, probably generating the most accurate information regarding energy and nutrients consumption to the CNS.

The adiposity signals, insulin and leptin, have been illustrated that they can act on the hypothalamus to enhance the central sensitivity of short-term peripheral satiation signals, such as CCK. It is evident that vagal afferent neurons express both the long form of leptin receptor and CCK-1R (Burdyga et al., 2002). Additionally, leptin enhances the CCK activation of the vagal afferent neurons, potentiating the anorectic effect of each other

(Wang et al., 1997). These long-term adiposity signals also have a direct impact on the short-term satiety signals. Indeed, leptin receptors are expressed in the distal intestinal enteroendocrine L cells, and activation of these receptors increase the GLP-1 secretion (Anini and Brubaker, 2003), further enhancing the anorectic effects.

Summary

Modification of energy, protein intakes and feeding levels during gestation has been widely used in sow management. Among these nutritional strategies, changing feeding levels during gestation could be an easy management practice which does not need extra labor input. Public concern of impairment of animal welfare for sows housed in individual stalls is driving the industry to move from individual stall to group pen housing system, even though the scientific evidence remains equivocal with regard to which housing system is best for gestation sows. If mixing sows after embryo implantation, both housing systems yield similar reproductive performance. Interactive effects between gestation housing systems and feeding levels during gestation may exist in terms of reproductive performance. Additionally, considering that feeding levels during gestation may or may not affect reproductive performance, it would be interesting to examine the effect of feeding levels on apparent digestibility of energy and nutrients. Furthermore, different feed intakes may generate different diurnal profiles of hormones and metabolites related to feed intake regulation and energy homeostasis.

Therefore, subsequent chapters of this dissertation were focused on developing a better understanding of the interactive effects of feeding levels during 4 short periods of

gestation and housing systems on sow and litter performance (Chapter 2). In order to confirm the finding from Chapter 2, effects of feeding levels during 3 short periods of gestation on sow and litter performance and its impact on subsequent reproductive performance was assessed (Chapter 3). Additionally, effects of different feeding levels during 3 short periods of gestation on apparent digestibility of energy and nutrients (Chapter 4), plasma hormones and metabolites related to feed intake regulation and energy homeostasis (Chapter 5) were also determined. Furthermore, best physiological indicators were proposed to predict the hunger status or energy homeostasis in pregnant gilts.

Table 1-1. Effect of different energy intake during gestation and/or lactation on sow performance

References	No. of sows/group	Starting animal	Energy intake		Duration	Gestation		Lactation			WEI
			Gestation	Lactation		BW gain	BF gain	BW change	BF loss	ADFI	
Elsley et al. (1968)	13	Gilt	+	+	3 cycles	+	NA	-	NA	NA	NA
Frobish et al. (1973)	19	Gilt	+	same	3 cycles	+	NA	NA	NA	NA	NA
Buitrago et al. (1974)	28	Gilt	+	same	1 cycle	+	NA	-	NA	-	NA
Libal and Wahlstrom (1977)	25	Sow	+	same	1 cycle	+	NA	-	NA	NA	NA
Okai et al. (1977)	26	Sow	+	same	1 cycle	+	NA	NS	NA	NA	NA
Hoppe et al. (1990)	32	Gilt	+	same	4 cycles	+	+	-	+	-	NS
Young et al. (1990)	62	Gilt	+	same	4 cycles	+	+	-	+	-	Qua.
Coffey et al. (1994)	83	Sow	+	+	3 cycles	NA	NA	-	NA	-	NS
Dourmad et al. (1996)	7	Sow	+	NA	d 1 to 109	+	+	NA	NA	NA	NA
Xue et al. (1997)	8	Gilt	+	same	d 30 to 105	+	+	-	NS	-	+
Heo et al. (2008)	18	Gilt	+	+	d 80 to 110	NS	NS	NS	NS	NS	NS

Note: "+" represents increasing energy intake or increased effect; "-" represents decreased effect; "Qua" represents quadratic effect; "NA" and "NS" represent data not available and non-significant, respectively.

Table 1-2. Effect of different energy intake during gestation and/or lactation on litter performance

References	No. of sows/group	Starting animal	Energy intake		Duration	Weaning age (d)	No. of piglets			Piglet wt.		Litter wt.	
			Gestation	Lactation			Total born	Liveborn	Wean	Birth	Wean	Birth	Wean
Elsley et al. (1968)	13	Gilt	+	+	3 cycles	56	NS	NS	NS	+	NS	+	NS
Frobish et al. (1973)	19	Gilt	+	same	3 cycles	14	-	NS	NS	+	NS	NA	NA
Buitrago et al. (1974)	28	Gilt	+	same	1 cycle	56	-	-	-	+	NS	+	NS
Libal and Wahlstrom (1977)	25	Sow	+	same	1 cycle	21	NS	-	NS	+	+	+	+
Okai et al. (1977)	26	Sow	+	same	1 cycle	21	NS	NS	NS	NS	+	NA	NA
Hoppe et al. (1990)	32	Gilt	+	same	4 cycles	21	NS	NA	NS	NS	NS	NS	NS
Young et al. (1990)	62	Gilt	+	same	4 cycles	21	NS	NS	NS	Lin.	Qua.	NS	NS
Coffey et al. (1994)	83	Sow	+	+	3 cycles	21	NS	NS	NS	+	+	NA	NA
Xue et al. (1997)	8	Gilt	+	same	d 30 to 110	22	NA	NS	NA	NA	NA	NS	NS
Heo et al. (2008)	18	Gilt	+	+	d 80 to 110	25	NS	NA	NS	NA	NA	NS	NS

Note: "+" represents increasing energy intake or increased effect; "-" represents decreased effect; "Lin" and "Qua" represent linear and quadratic effects, respectively; "NA" and "NS" represent data not available and non-significant, respectively.

Table 1-3. Effect of different protein/lysine intake during gestation on sow performance

References	No. of sows/group	Starting animal	Protein intake (g)	Protein/Lysine level		Duration	Gestation		Lactation		
				Gestation	Lactation		BW gain	BF gain	BW change	BF change	ADFI
Rippel et al. (1965)	27	Gilt/Sow	90	+	same	1 cycle	+	NA	-	NA	NS
Frobish et al. (1966)	70	Gilt	182	+	same	1 cycle	NS	NA	NS	NA	NS
Holden et al. (1968)	16	Sow	146	+	same	4 cycles	+	NA	-	NA	-
Baker et al. (1970a)	54	Gilt	167	+	same	1 cycle	+	NA	-	NA	NS
Baker et al. (1970b)	18	Gilt	157	+	same	1 cycle	+	NA	-	NA	NS
Mahan and Mangan (1975)	31	Gilt	164	+	+	1 cycle	+	NA	NS	NA	-
Shields et al. (1985)	22	Gilt	91	+	+	1 cycle	+	NA	NA	NA	NA
Mahan (1998)	25	Gilt	235	+	same	5 cycles	NS	NS	NS	NS	-
Copper et al. (2001)	210	Sow	10.6 g Lys	+	same	1 cycle	NS	NS	NS	NS	NA
Heo et al. (2008)	18	Gilt	18.0 g Lys	+	+	d 80 to 110	+	NS	-	NS	NS

Note: "+" represents increasing protein/lysine intake or increased effect; "-" represents decreased effect; "NA" and "NS" represent data not available and non-significant, respectively.

Table 1-4. Effect of different protein/lysine intake during gestation on litter performance

References	No. of sows/group	Starting animal	Protein intake (g)	Protein/Lysine level		Duration	Weaning age (d)	No. of piglets			Piglet wt.		Litter wt.	
				Gestation	Lactation			Total born	Liveborn	Wean	Birth	Wean	Birth	Wean
Rippel et al. (1965)	27	Gilt/Sow	90	+	same	1 cycle	14	NS	NS	NS	NS	NS	NA	NA
Frobish et al. (1966)	70	Gilt	182	+	same	1 cycle	14	NS	NS	+	NS	NS	NA	NA
Holden et al. (1968)	16	Sow	146	+	same	4 cycles	14	NA	NS	NS	NS	NS	NA	NA
Baker et al. (1970a)	54	Gilt	167	+	same	1 cycle	21	NS	NS	+	NS	NS	NS	+
Baker et al. (1970b)	14	Sow	157	+	same	1 cycle	21	NS	NS	NS	NS	+	NS	+
Mahan and Mangan (1975)	31	Gilt	164	+	+	1 cycle	28	NS	NS	NS	NS	NS	NS	NS
Shields et al. (1985)	22	Gilt	91	+	+	1 cycle	NA	NS	NS	+	+	+	+	+
Mahan (1998)	25	Gilt	235	+	same	5 cycles	21	NS	NS	NS	-	NS	NS	NS
Copper et al. (2001)	210	Sow	10.6 Lys	+	same	1 cycle	NA	NS	NS	NA	-	NA	-	NA
Heo et al. (2008)	18	Gilt	18.0 Lys	+	+	d 80 to 110	25	NS	NA	+	NA	NA	+	+

Note: "+" represents increasing protein/lysine intake or increased effect; "-" represents decreased effect; "NA" and "NS" represent data not available and non-significant, respectively.

Table 1-5. Effect of different feed intake during gestation on sow performance

References	No. of sows/group	Starting animal	Gestation feed intake	Duration	Gestation		Lactation			WEI
					BW gain	BF gain	BW change	BF change	ADFI	
Lodge et al. (1966b)	12	Gilt	+	3 cycles	+	NA	-	NA	NA	NA
Baker et al. (1969)	62	Gilt	+	1 cycle	+	NA	-	NA	-	NA
Elsley et al. (1969)	44	Gilt	+	3 cycles	+	NA	-	NA	NS	NA
Whittemore et al. (1988)	20	Gilt	+	5 cycles	+	+	-	+	NA	NS
Cromwell et al. (1989)	180	Gilt/Sow	+	d 90 to farrowing	+	NA	-	NA	NS	NA
Dourmad et al. (1991)	16	Gilt	+	1 cycle	+	+	-	+	-	+
Weldon et al. (1994a)	9	Gilt	+	d 60 to farrowing	+	NA	-	NA	-	NA
Hovings et al. (2011)	47	Gilt/Sow	+	d 3 to 32	+	NS	NA	NA	NA	NA

Note: "+" represents increasing feed intake or increased effect; "-" represents decreased effect; "NA" and "NS" represent data not available and non-significant, respectively.

Table 1-6. Effect of different feed intake during gestation on litter performance

References	No. of sows/group	Starting animal	Gestation feed intake	Duration	Weaning age (d)	No. of piglets			Piglet wt.		Litter wt.	
						Total born	Liveborn	Wean	Birth	Wean	Birth	Wean
Lodge et al. (1966b)	12	Gilt	+	3 cycles	56	NS	NA	NS	+	NS	NS	NS
Baker et al. (1969)	62	Gilt	+	1 cycle	21	NS	NS	NS	Qua.	Lin.	NA	NA
Elsley et al. (1969)	44	Gilt	+	3 cycles	56	NS	NA	NS	+	+	+	NS
Whittemore et al. (1988)	20	Gilt	+	5 cycles	32	NA	NS	NS	NA	NA	NS	+
Cromwell et al. (1989)	180	Gilt/Sow	+	d 90 to farrowing	21	NA	+	+	+	+	+	+
Dourmad et al. (1991)	16	Gilt	+	1 cycle	28	NS	NS	NS	NS	NS	NA	NA
Weldon et al. (1994a)	9	Gilt	+	d 60 to farrowing	27	NA	NS	NS	NA	NA	NS	NS
Hovings et al. (2011)	47	Gilt/Sow	+	d 3 to 32	NA	+	+	NA	NS	NA	NA	NA

Note: "+" represents increasing feed intake or increased effect; "-" represents decreased effect; "Lin" and "Qua" represent linear and quadratic effects, respectively; "NA" and "NS" represent data not available and non-significant, respectively.

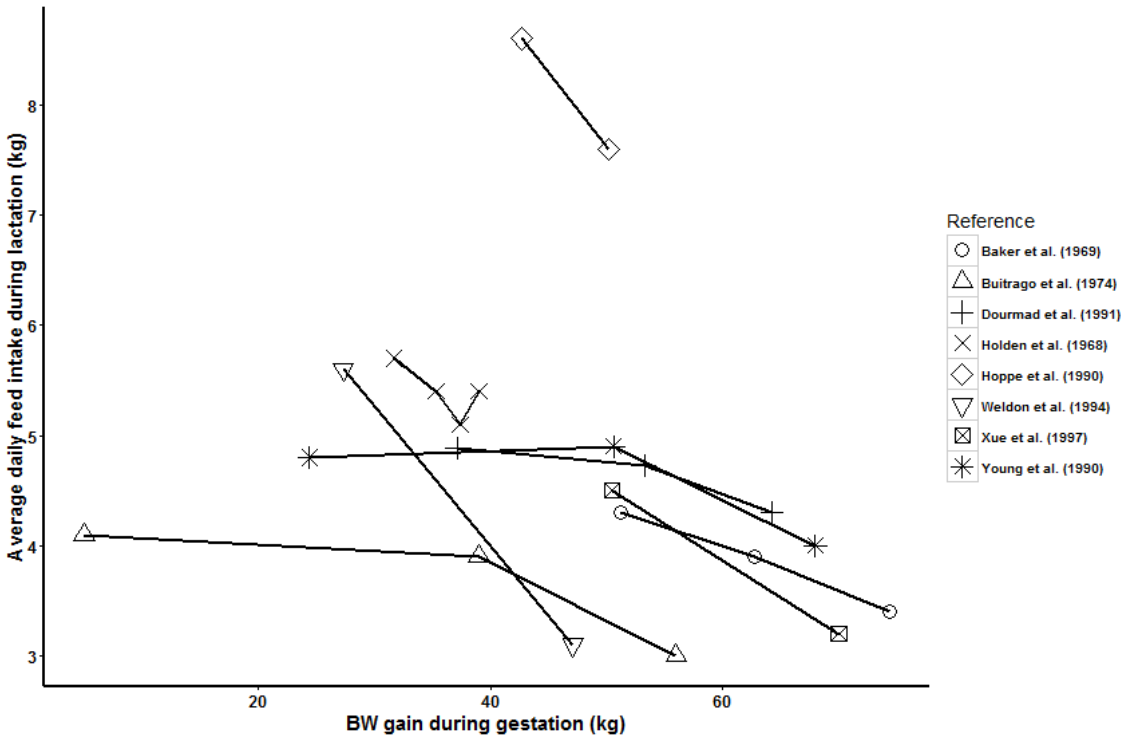

Figure 1-1. Relationship between sow BW gain during gestation (kg) and average daily feed intake during lactation (kg)

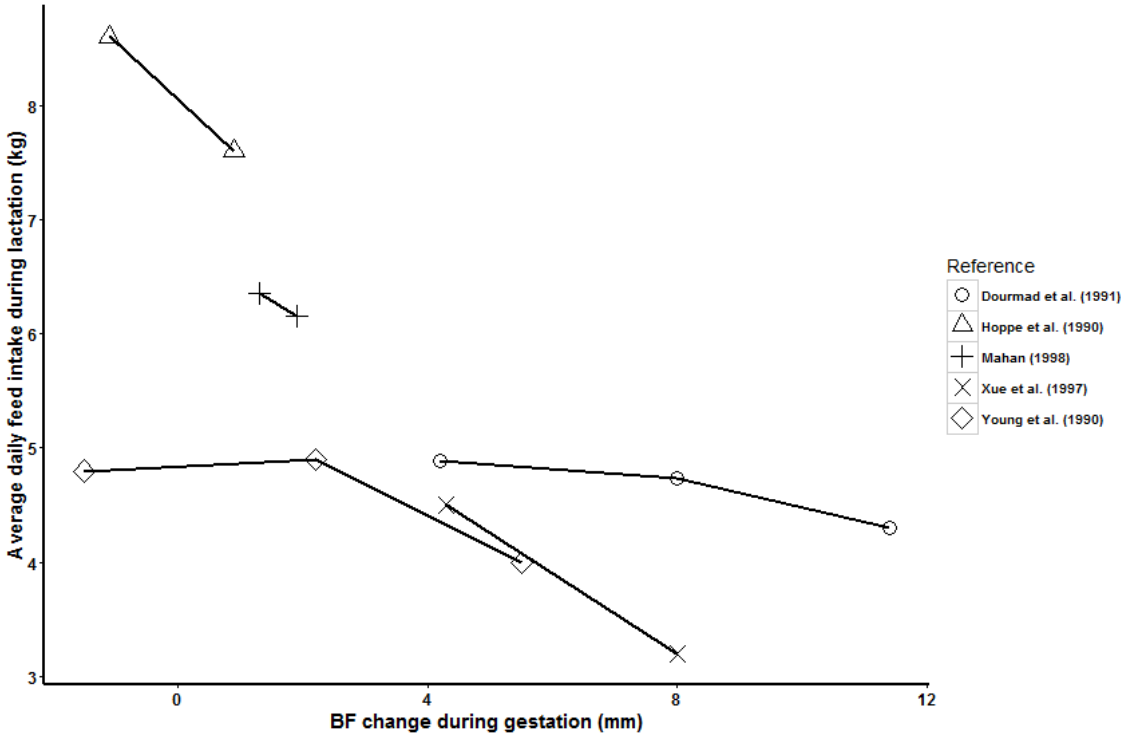

Figure 1-2. Relationship between sow backfat change during gestation (mm) and average daily feed intake during lactation (kg)

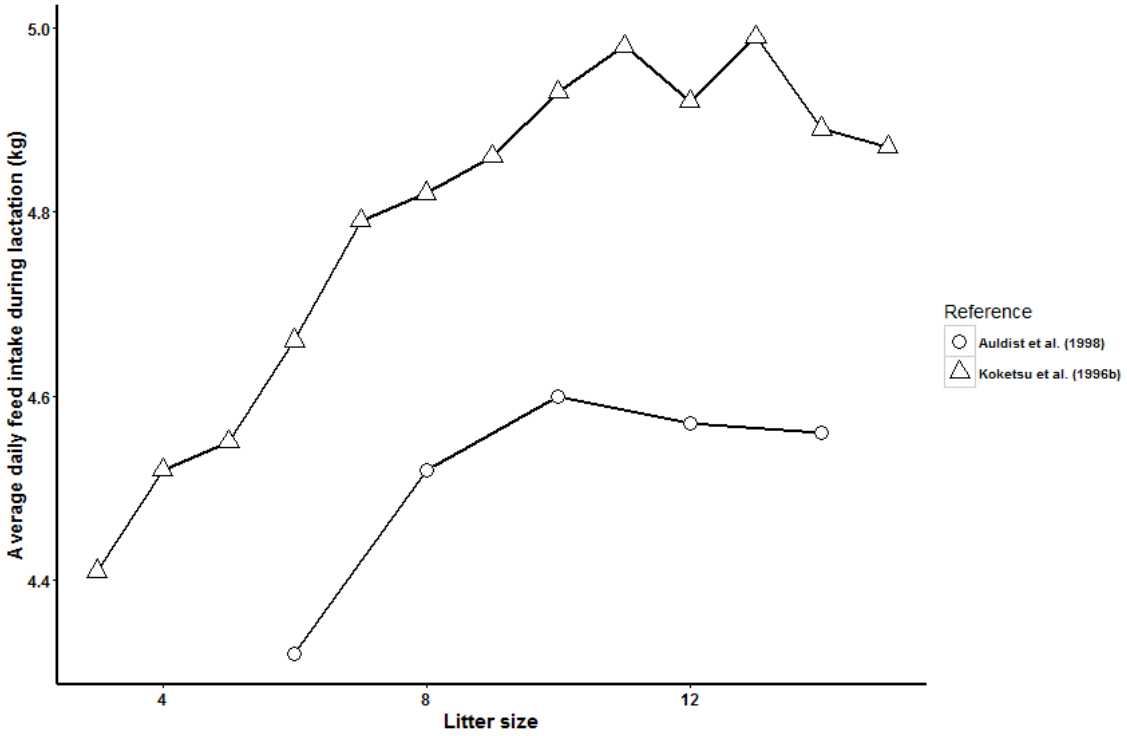

Figure 1-3. Relationship between litter size and average daily feed intake during lactation (kg)

Chapter 2. Effects of different feeding levels during four short periods of gestation and housing systems on sows and litter performance

SUMMARY

The current study investigated the effects of different feeding levels during four short periods of gestation and housing systems on sow and litter performance. A total of 255 multiparous sows were allotted to 1 of 4 dietary treatments using a randomized complete block design blocking by initial BW (**BW**), backfat (**BF**) and parity. Sows were housed either in individual stalls (n = 129) or group pens (n = 126) with electronic sow feeder during gestation. The experiment started from d 27 of gestation throughout gestation and lactation. All sows were fed one common corn-soybean meal-based diet with the amount of 1.0 × maintenance energy feeding level (106 × $BW^{0.75}$) throughout gestation except 4 periods of 7 d when dietary treatments imposed on d 28, 55, 83 and 97 of gestation. During the 4 periods, sows were fed 1 of 4 different feeding levels: 0.5, 1.0, 1.5 and 2.0 × maintenance energy level (0.5M, 1.0M, 1.5M and 2.0M, respectively). Both BW gain (26.1, 35.6, 49.7 and 52.5 kg, respectively) and BF change (-0.1, 0.1, 3.1 and 3.7 mm, respectively) from d 27 to 109 of gestation increased linearly ($P < 0.01$) with the increase of gestation feeding levels. In contrast, with the increase of feeding levels during periods of gestation, lactation weight gain (18.4, 11.4, 3.3 and 3.4 kg, respectively) decreased linearly ($P < 0.01$), while BF loss (-2.5, -2.1, -3.6 and -3.1 mm, respectively) during lactation increased linearly ($P < 0.01$). Additionally, average daily feed intake during lactation (6.6, 6.3, 6.0 and 5.9 kg, respectively) decreased linearly ($P = 0.01$) with the rise of gestation feeding levels. There were no differences ($P > 0.1$) among 4 feeding levels in terms of numbers of total born and weaning piglets, as well as average weaning weight of

piglets. Sows housed in group pens had greater ($P < 0.01$) net BW gain (24.7 vs. 19.2 kg) during gestation and lactation compared with sows housed in individual stalls. However, there were no differences ($P > 0.1$) between the 2 housing systems in terms of litter performance. In conclusion, increasing feeding levels during 4 short periods of gestation increased BW and BF gain during gestation and led to less BW gain and more BF loss during lactation. Both gestation feeding levels and housing systems did not affect reproductive performance. Group pen housing system may be beneficial in terms of increased overall BW gain during gestation and lactation.

KEYWORDS: Feeding levels, housing system, sows, litter, performance

INTRODUCTION

Enhancing reproductive performance through nutrition and management strategies in gestation and lactation sows has been the research interest for several decades. It has been proposed that maintaining an ideal body condition throughout a sow lifetime is essential for maximizing reproductive performance and sow longevity (Young et al., 2004). However, modern crossbred sows have been shown to gain adequate BW over the reproductive cycle while simultaneously losing considerable amount of fat mass (Whittemore et al., 1988; Dourmad, 1991), which may compromise subsequent reproductive performance (Yang et al., 1989).

Different feeding levels during early gestation (Musser et al., 2006; Hoving et al., 2011), mid-late gestation (Cromwell et al., 1989; Weldon et al., 1994c; Heo et al., 2008) and whole gestation (Dourmad, 1991; Mahan, 1998) have been conducted to evaluate their effects on sow and litter performance. These studies consistently showed that increasing

feeding levels during gestation increased sow BW gain during gestation, but caused sows to lose more BW and backfat during lactation, with inconsistent results for litter performance. However, we were not aware of any research on investigation of feeding levels during several short periods of gestation on sow and litter performance.

Housing systems for gestation sows have become the research interest in recent years. Similar reproductive performance of sows housed either in group pens or individual stalls has been reported (Anil et al., 2005). However, Li et al. (2014) reported that long-term housing of sows in group pens decreased litter size and sow longevity. It was not known whether feeding levels during periods of gestation may interact with gestation housing systems on sow and litter performance. Therefore, the objective of this study was to examine the effects of different feeding levels during four short periods of gestation and housing systems on sow and litter performance.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee of University of Minnesota approved the experimental protocol used in this study.

Animals and Management

The current experiment was conducted at the Southern Research and Outreach Center, University of Minnesota in Waseca, MN. The experiment started on March 8, 2012 and ended on December 3, 2012. A total of 255 multiparous Large White x Danish Landrace crossbred sows (Topigs 20, Topigs Inc.; Winnipeg, Manitoba, Canada) consisting of 5 different batches were used in this study. After breeding by artificial insemination with

mixed semen from Duroc boars (Compart's Boar Store, Nicollet, MN), all sows in each batch stayed in the individual stalls (2.1 m length x 0.6 m width x 0.6 m height) for about 35 d; then about half of the sows were moved to the group pens (13.1 m length x 6.9 m width x 0.7 m height) with electronic sow feeders (3.7 m length x 0.5 width x 0.7 m height) in the center and half of the sows remained in the individual stalls until moving to farrowing crates. During gestation, all sows were fed the same gestation diet with different amounts of feed in different periods of gestation. On d 109 of gestation, sows from either individual stall or group pen systems were moved into the farrowing rooms with environmental control systems and housed in individual farrowing crates (2.13 m length × 0.66 m width × 0.97 m height). All sows were fed 2.27 kg lactation diet beginning from d 109 of pregnancy to the date of farrowing. After parturition, the amount of feed was increased gradually to allow for *ad libitum* feed intake from d 5 until weaning at about d 19 of lactation. After weaning, sows were moved to the environmental controlled gestation room with individual stalls. Estrus were checked on the daily basis with a mature boar. From weaning to breeding, sows were fed 2.0 kg gestation diet. Sows were allowed free access to water throughout the experiment period. Sows were culled according to the Standard Operation Procedure of the Swine Research Facility.

Piglets were processed within 24 h after birth according to the standard piglet management procedure of the facility, such as iron shot, tail docking, and treating the umbilical cord with tincture of iodine. Cross-fostering was conducted within 48 h after birth within dietary treatment and housing systems to equalize litter size around 11 or 12 piglets per litter. Heat lamps were provided for newborn piglets for 48 h and piglets had access to heat pad from birth to weaning. Physical castration was conducted on all male

piglets between 5 and 9 d of age. No creep feed was provided during lactation and all piglets were weaned at about d 19 of lactation.

Dietary Treatments, Experimental Design and Housing Systems

After breeding, sows in each batch were allotted to 1 of 4 experimental treatments using a randomized complete block design by initial BW (**BW**) and backfat (**BF**) at d 27 of gestation and balanced by parity among treatments. Within each dietary treatment, sows were randomly allotted to 1 of 2 gestation housing systems: individual stall (n = 129) and group pen systems (n = 126). The experiment started from d 27 of gestation throughout gestation and lactation. All sows were fed a common corn-soybean meal basal diet (Table 2-1) with the amount of 1.0 × maintenance energy intake (106 × $BW^{0.75}$ kcal ME/d; NRC, 1998) throughout the gestation period except 4 periods of 7 d dietary treatments imposed on d 27, 55, 83 and 97 of gestation. During these 4 periods, sows were fed 1 of 4 different feeding levels based on maintenance energy intake: 1) 0.5 × maintenance energy level (0.5M); 2) 1.0 × maintenance level (1.0M); 3) 1.5 × maintenance energy level (1.5M); 4) 2.0 × maintenance energy level (2.0M). Gestation and lactation diets (Table 2-1) met or exceeded NRC (1998) nutrient recommendations.

After breeding, all sows stayed in the individual stalls for about 35 d; then sows allotted to group pen system were moved to group pens and the rest of the sows remained in the individual stalls. All sows remained in their respective gestation housing systems until d 109 of gestation. In each batch, around 23 to 26 sows were transferred to group pens and

each pen was equipped with 4 nipple drinkers and fully slatted concrete floor. In the center of the pen is an electronic sow feeder (Osborne Industries, Osborne, Kansas, USA). Each pen was divided into two sub-pens with a diagonal panel along the electronic sow feeder and the subgroup of each batch were placed in 1 of the 2 sub-pens. Excluding the space occupied by the electronic sow feeder, each sow in the group pens had the floor space allowance of 2.2 m^2. The feed intake in the group pen system was manipulated through different feeding curves which were set by a computer program. Each sub-pen had a 12 h feeding cycle on daily basis. Sows in the group pens were equipped with the transponders in their left ears. Each time only 1 sow was allowed to enter the electronic sow feeder. Once the sow entered the electronic sow feeder, the entrance was locked so that other sows could not enter the feeder. The system sensed the transponder in that sow's ear and determined the feed curve assigned to that sow. Once the sow finished her daily amount of feed, the door would open automatically and other sows would push her out. Individual stalls (Crystal Spring Hog Equipment, Ste. Agathe, Manitoba) were equipped with individual feeders and nipple drinkers. Each stall was located on the fully slatted concrete floor. The feed intake of sows in the individual stalls were managed via setting different feed drops with different volume. All the sows in the individual stalls were fed at 7:30 am each day.

Collection of Sow and Litter Performance Data

Sow BW was recorded and BF thickness was measured using ultrasonic detection machine (Preg-Alert Pro, Renco Corp., Minneapolis, USA) on both the left and right sides at the P2 position (6.5 cm from the dorsal mid-line at the level of the last rib) on d

27, 55, 83, 97, 109 of gestation and at weaning to measure the BW and BF change during the gestation and lactation periods. Assuming the farrowing weight was similar to the sow weight on d 109 of gestation, post-farrowing weight was estimated by subtracting total born × 1.85 kg from sow BW at farrowing (Aherne, 1999). Based on the 4 dietary treatments imposing periods, sow BW change, sow BF change, average daily gain, feed intake and gain to feed ratio for 4 periods (d 27-55, 55-83, 83-97 and 97-109, respectively) were calculated. Farrowing date, litter size (number of total piglets born, born alive, after cross-fostering and at weaning), and piglet deaths during lactation were recorded. Litter weight at birth, after cross-fostering and at weaning was also recorded. Feed intake was recorded on daily basis until weaning. Preweaning mortality of piglets within litter was calculated using the live born piglets that died before weaning divided by the number of live born piglets. Litter weight gain and piglet average daily gain (**ADG**) were also calculated. Average daily feed intake (**ADFI**) was calculated using the summation of daily feed intake divided by the lactation period.

Protein and fat mass on d 27 and 109 of gestation, post-farrowing and weaning was estimated using the prediction equation from Dourmad et al. (1997). The corresponding changes of protein and fat mass during gestation and lactation were calculated.

Chemical Analysis

Concentrations of dry matter (method 934.01; AOAC, 2006), crude protein (method 984.13; AOAC, 2006), ether extract (method 920.39; AOAC, 2006), neutral detergent fiber (**NDF**, method 973.18; AOAC, 2006), acid detergent fiber (**ADF**, method 973.18; AOAC, 2006) in gestation and lactation diets were analyzed at University of Minnesota's

Southern Research and Outreach Center. Concentrations of calcium (method 958.01; AOAC, 2006), phosphorus (method 958.01; AOAC, 2006) and amino acids (method 982.30 E (a, b, c); AOAC, 2006) were analyzed by the University of Missouri Experiment Station Chemical Laboratories (Columbia, MO).

Statistical Analysis

SAS 9.4 (SAS Inst. Inc., Gary, NC) was used in all data analysis. Individual sow served as the experimental unit. The LSMEANS statement was used to calculate the least squares means. Tukey-Kramer adjustment was used for multiple comparisons of least squares means. Covariates were used to adjust response means and presented as a footnote for each table. Pooled SE was calculated for each measurement. A probability $P < 0.05$ was considered as significant and $0.05 < P < 0.1$ was declared as a trend.

The GLIMMIX procedure was used to analyze all data. Dietary treatments and housing system were considered as fixed effects. Batch was considered as a random effect. Sow BW and backfat measured on d 27, 55, 83, 97, 109 and at weaning were considered as repeated measurements in time. Different covariance structure candidate models were examined and the best fit model was selected for the collected data on the basis of Akaike Information Criterion (**AIC**) and Bayesian Information Criterion (**BIC**) values. Model testing results indicated that heterogeneous compound symmetry (csh) was the best covariance models for both sow BW and backfat data. The SLICE option by time was used to test the effects of the dietary treatments, housing systems, and their interactions at each of the different time points.

Sow BW change, BF change, ADG, feed intake and gain to feed ratio calculated for the 4 periods were also considered as repeated measurements. The best covariance structure selected using the aforementioned technique was first-order ante-dependence (ante(1)), unstructured (un), ante(1), csh, and ante(1) for sow BW change, sow BF change, average daily gain, feed intake, and gain to feed ratio during the 4 periods, respectively. The SLICE option by period was used to test effect of the dietary treatments, housing systems, and their interactions at different periods.

For litter performance, litter weight and average piglet weight at birth and weaning, and average daily gain of piglets were normally distributed, so the data were analyzed in the default normal linear regression model. Count data, such as liveborn, total born, after cross-fostering, death and wean number of piglets were analyzed using the Poisson regression model, while the zero-inflated Poisson regression model was used to analyze stillborns and mummies. Furthermore, the binomial regression model was used to analyze piglet pre-weaning mortality.

The REG procedure was used to establish the simple linear regression equations and examine the effects of BW gain during gestation on BW change during lactation, BF gain during gestation on lactation BF loss, as well as the effect of BF gain during gestation and post-farrowing BF on average daily feed intake during lactation.

RESULTS

Generally, there were no interaction ($P > 0.1$) effects of feeding levels and housing systems on sow performance during gestation and lactation. Therefore, main effects of feeding levels and housing systems on sow performance are presented.

Effects of feeding levels on sow performance

There were no differences in sow BW and BF depth at the start of the experiment (d 27 of gestation; P = 0.21 and 0.87, respectively) and d 55 of gestation (P = 0.26 and 0.35, respectively) among the 4 dietary feeding levels (Tables 2-2 and 2-3). However, sows on 2.0M feeding level tended to have greater (P = 0.08) BW than sows on 0.5M and 1.0M feeding levels, and sows on both 1.5M and 2.0M feeding levels had greater (P < 0.01) BF depth compared with sows on 0.5M and 1.0M feeding levels at d 83 of gestation. On d 97 and 109 of gestation, and at post-farrowing and weaning, sow BW was significant higher (P < 0.01) in the 2.0M group compared with sows on 0.5M and 1.0M feeding levels, whereas sow BF depth was greater (P < 0.01) in sows on 1.5M and 2.0M feeding levels in comparison with sows on 0.5M and 1.0M feeding levels. Additionally, sow BW and BF depth on d 83, 97, and 109 of gestation, and at post-farrowing and weaning increased linearly (P < 0.01) with the increase of dietary feeding levels.

From d 27 to 109 of gestation, BW gain of sows on 1.0M feeding level was greater (P < 0.01) than sows in the 0.5M group, and sows in the 1.5M and 2.0M groups had greater BW gain and BF change (P < 0.01) compared with sows on 0.5M and 1.0M groups. Both gestation weight gain (26.1, 35.6, 49.7 and 52.5 kg, respectively) and BF change (-0.1, 0.1, 3.1 and 3.7 mm, respectively) increased linearly (P < 0.01) with the increase of dietary feeding levels. In contrast, sows on 1.5M and 2.0M feeding levels during periods of gestation gained less BW (P < 0.01) and lost more BF (P < 0.01) during lactation in comparison with sows on 0.5M and 1.0M feeding levels. Lactation weight change (+18.4, +11.4, +3.3 and +3.4, respectively) decreased linearly (P < 0.01) with the increase of feeding levels during periods of gestation, while BF loss (-2.5, -2.1, -3.6 and -3.1 mm,

respectively) during lactation increased linearly ($P < 0.01$) with the increase of feeding levels during periods of gestation. Additionally, average daily feed intake during lactation tended to be higher ($P = 0.06$) in sows on 0.5M feeding levels during the 4 periods of gestation compared with sows on 1.5M and 2.0M feeding levels. With the rise of feeding levels during gestation, average daily feed intake (6.6, 6.3, 6.0 and 5.9 kg, respectively) of lactating sows decreased linearly ($P = 0.01$). Furthermore, sow net BW changes from d 27 of gestation to weaning were significantly higher ($P < 0.01$) in sows fed the 1.5M and 2.0M diets compared with sows fed the 0.5M diet, while sow net BF changes from d 27 of gestation to weaning were greater ($P < 0.01$) in sows fed the 1.5M and 2.0M diets in comparison with sows fed the 0.5M and 1.0M diets. Changes of both net BW and BF of sows from d 27 of gestation to weaning increased linearly ($P < 0.01$) with the rise of feeding levels during the 4 periods of gestation. Furthermore, both feeing levels and housing systems did not affect the wean to estrus interval.

The results of feeding levels during periods of gestation on sow performance during the 4 periods of gestation are presented in Tables 2-4 and 2-5. For period 1 (d 27 to 55 of gestation), sows on 1.0M feeding level had higher BW ($P < 0.01$) and BF ($P = 0.03$) gains than their counterparts on 0.5M feeding level, and sows on 1.5M and 2.0M feeding levels had greater BW ($P < 0.01$) and BF ($P = 0.03$) gains in comparison with sows on 0.5M and 1.0M feeding levels, which was the same case for average daily gain of sows during period 1. As expected, feed intake of sows increased linearly ($P < 0.01$) with the increase of feeding levels. Additionally, sows on 0.5M feeding level had lower ($P < 0.01$) gain to feed ratio compared with sows on the other feeding levels, and sows on 1.5M

feeding level had higher ($P < 0.01$) feed efficiency than their counterparts on 1.0M feeding level.

For period 2 (d 55 to 83 of gestation), sows on 1.5M and 2.0M feeding levels had higher BW ($P < 0.01$) and BF ($P = 0.04$) gains compared with their counterparts on 0.5M and 1.0M feeding levels. The result of average daily gain of sows was consistent with sow BW and BF change. As expected, feed intake of sows increased linearly ($P < 0.01$) with the increase of feeding levels. However, there was no difference among different feeding levels in terms of feed efficiency.

For period 3 (d 83 to d 97 of gestation), sows gained more BW ($P < 0.01$) when they were on higher feeding levels (1.5M and 2.0M) compared with sows on lower feeding levels (0.5M and 1.0M). BF change during period 3 was greater ($P = 0.02$) in sows on 2.0M feeding level compared with sows on the other feeding levels. Additionally, average daily gain of sows and feed efficiency were greater ($P < 0.01$) in sows on the two higher feeding levels (1.5M and 2.0M) than sows on the two lower feeding levels (0.5M and 1.0M). Furthermore, as expected, feed intake of sows increased linearly ($P < 0.01$) with the increase of feeding levels.

For period 4 (d 97 to d 109 of gestation), sows on the higher feeding level (1.0M, 1.5M and 2.0M) gained more BW ($P < 0.01$) than sows on lower feeding level (0.5M). In addition, sows on the two higher feeding levels (1.5M and 2.0M) gained more BF ($P < 0.01$) than sows on the two lower feeding levels (0.5M and 1.0M), which was consistent with the result of average daily gain of sows. As expected, feed intake of sows increased linearly ($P < 0.01$) with the increase of feeding levels. Furthermore, feed efficiency was

lower ($P < 0.01$) in sows on 0.5M feeding level compared with sows on the other 3 feeding levels.

Effect of housing systems on sow performance

At the initiation of the experiment (d 27 of gestation), there were no differences ($P > 0.10$) in sow BW and BF between group pens and individual stalls systems (Tables 2-2 and 2-3). Similar BWs of sows housed in group pens and individual stalls were maintained on d 55, 83 and 97 of gestation. On d 109 of gestation, however, sow BW was significantly higher ($P < 0.01$) in group pens than in individual stalls. Sow BW also tended to be greater ($P = 0.09$) for sows housed in group pens compared with sows housed in individual stalls at weaning. Additionally, sow BF was greater ($P < 0.01$) for sows housed in group pens than in individual stalls on d 83, 97 and 109 of gestation. However, the difference in BF did not exist ($P = 0.19$) at weaning between two housing systems.

Sow weight and BF gains from d 27 to d 109 of gestation were greater ($P < 0.01$) in sows housed in group pens (45.2 kg for BW gain, 2.4 mm for BF gain) in comparison with sows housed in individual stalls (36.8 kg for BW gain, 1.0 mm for BF gain). However, there was no difference ($P > 0.1$) for sow BW change during lactation between the two housing systems. Interestingly, during lactation sows housed in group pens (-3.5 mm) lost more ($P < 0.01$) BF compared with sows housed in individual stalls (-2.1 mm). Additionally, there was no difference ($P > 0.1$) in average daily feed intake of sows housed in either group pens or individual stalls. As a whole, the net sow BW gain from d 27 of gestation to weaning was greater ($P < 0.01$) in sows housed in group pens

compared with sows housed in individual stalls, while the net BF change from d 27 of gestation to weaning was not different ($P = 0.89$) between the two housing systems.

The results of housing system on sow performance during the 4 periods of gestation are presented in Tables 2-4 and 2-5. In period 1 (d 27 to d 55 of gestation), housing systems had no effect ($P > 0.1$) on sow performance in terms of BW change, BF change, average daily gain and feed efficiency. However, in period 2 (d 55 to d 83 of gestation), sows housed in group pens had higher BW gain ($P < 0.01$; 17.22 and 13.02 kg, respectively), average daily gain ($P < 0.01$; 0.56 and 0.45 kg/d, respectively) and feed efficiency ($P < 0.01$; 0.31 and 0.24 $kg \cdot kg^{-1}$, respectively) compared with sows housed in individual stalls. In addition, sow BF tended ($P = 0.10$) to increase more in sows housed in group pens compared with sows housed in individual stalls. In period 3 (d 83 to d 97 of gestation), there were no differences ($P > 0.1$) for sow BW change, BF change, average daily gain and feed efficiency between the two housing systems. In period 4 (d 97 to d 109 of gestation), sows housed in group pens had greater BW gain ($P < 0.01$; 12.80 and 9.93 kg, respectively), average daily gain ($P < 0.01$; 0.94 and 0.70 $kg \cdot d^{-1}$, respectively) and feed efficiency ($P < 0.01$; 0.39 and 0.31 $kg \cdot kg^{-1}$, respectively) in comparison with sows housed in individual stalls.

Effects of feeding levels and housing systems on litter performance

There were no differences ($P > 0.1$) among feeding levels and between the housing systems in terms of numbers of stillborn, mummy, total born, after cross-fostering, death and weaning piglets (Tables 2-6 and 2-7). Litter weights at weaning were also not

different (P > 0.1) among the 4 feeding levels and between the 2 housing systems. However, there were interaction effects (P = 0.02) between feeding levels and housing systems on number of liveborn piglets and litter weight of liveborn at birth. Within 0.5M and 1.0M feeding levels, sows housed in group pens had fewer number of liveborn piglets and lower litter weight at birth than sows housed in individual stalls, while within 2.0M feeding level, sows housed in group pens had higher number of liveborn piglets and greater litter weight at birth compared with sows housed in individual stalls. Additionally, average weight of liveborn piglets at birth from sows on 1.0M and 1.5M feeding levels tended (P = 0.09) to be greater than that from sows on 0.5M feeding level. However, there was no significant difference (P > 0.1) among the 4 feeding levels in terms of piglet weaning weight. Interestingly, there was a quadratic (P = 0.02) effect with the increase of feeding levels for piglet weaning weight. Specifically, piglet weaning weight reached the maximum (6.64 kg) at 1.5M feeding level, then was reduced to 6.38 kg at 2.0M feeding level. Furthermore, no differences (P > 0.1) were found among the 4 feeding levels and between the 2 housing systems in terms of average daily gain of piglet and pre-weaning mortality of piglets.

Predicted protein, fat mass and their change during gestation and lactation

At the initiation of the experiment, there were no differences (P > 0.1) among the 4 different feeding levels in terms of predicted protein and fat mass (Tables 2-8 and 2-9). At the end of gestation (d 109) and post-farrowing, sows on the 1.5M and 2.0M feeding levels had greater (P < 0.01) protein and fat mass compared with sows on the 0.5M and 1.0M feeding levels. However, sow protein mass at weaning was similar (P = 0.30) among the 4 feeding levels, while fat mass continued to be higher (P < 0.01) in the two

higher feeding levels (1.5M and 2.0M) compared with the two lower feeding levels (0.5M and 1.0M) at weaning. Additionally, gains of sow body protein (4.17, 6.23, 7.84 and 8.52 kg, respectively) and fat (3.47, 7.86, 14.95 and 16.35 kg, respectively) from d 27 to d 109 of gestation increased linearly ($P < 0.01$) with the rise of feeding levels. In contrast, protein mass change (4.01, 2.69, 1.78 and 1.59 kg, respectively) during lactation decreased linearly ($P < 0.01$) with the rise of gestation feeding levels, while fat mass change (0.81, -0.36, -4.12 and -3.26 kg, respectively) during lactation increased linearly ($P < 0.01$) with the rise of gestation feeding levels.

Sows housed in group pens had greater protein mass gain (7.08 vs. 6.30 kg; $P = 0.02$) and fat mass gain (12.81 vs. 8.51 kg; $P < 0.01$) during gestation compared with sows housed in individual stalls. Additionally, sows housed in group pens during gestation tended to have more protein mass gain during lactation in comparison with sows housed in individual stalls during gestation (2.83 vs. 2.20 kg; $P = 0.07$), whereas during lactation they tended to lose more (-2.63 vs. -0.84 kg, $P = 0.06$) fat mass compared with their counterparts.

Relationship between BW and BF change during gestation and lactation

For an increase of 1 kg of sow BW gain during gestation (d 27 to 109 of gestation), lactation BW gain decreased by 0.58 kg (Equation 1, Table 2-10), while for an increase of 1 mm of sow BF gain during gestation, lactation BF loss increased by 0.43 mm (Equation 2, Table 2-10). Additionally, lactation average daily feed intake was negatively correlated with gestation BF gain and post-farrowing BF. Specifically, for an increase of 1 mm BF gain during gestation, lactation average daily feed intake decreased by 150 g,

while for 1 mm increase in post-farrowing BF, average daily feed intake during lactation decreased by 100 g.

DISCUSSION

Effects of feeding levels on sow and litter performance

The present study showed that increasing feeding levels during 4 short periods of gestation resulted in remarkable gains of BW and BF during periods of gestation and from the initiation of the study to parturition, whereas the more gains of BW and BF during gestation led to less BW gain and more BF loss during lactation. These results were consistent with previous literature (Cromwell et al., 1989; Hoppe et al., 1990; Coffey et al., 1994). Most of the aforementioned literature showed that sows lost considerable amount of BW and BF during lactation. However, in our study, sows in all treatments gained weight during lactation and the amount of BW gain during lactation was negatively correlated with gestation weight gain. It was estimated from the present study that for one extra kg of BW gain during gestation, BW gain during lactation decreased by 0.58 kg. Similarly, Cooper et al. (2001) reported that every extra kg of BW gain in gestation resulted in a loss of 0.3 kg of BW during lactation. It should also be noted that with the increase of feeding levels during the 4 short periods of gestation, lactation BF loss increased linearly, which indicated that modern genotype of sows have the potential to accumulate BW whilst losing considerable amount of body BF during lactation (Mullan and Williams, 1989; Yang et al., 1989). The phenomenon was further supported by the fact that the predicted protein mass during lactation increased linearly with the rise of feeding levels during gestation, while the predicted fat mass loss during

lactation increased linearly with the increasing of feeding levels during gestation with the exception that sows on the lowest feeding level during gestation gained 0.81 kg fat mass during lactation. Indeed, it was reported that BF depth measured at the P2 site was not a good predictor for pig fat content (Suster, 2003). It was possible that sows favored to mobilize BF to meet the energy requirement for milk production during lactation, while sows could also deposit fat in other parts of the body, rendering the net body fat mass increased in the sows on the lowest feeding level during gestation.

The negative relationship between gestation feeding levels and lactation feed intake has been observed by Baker et al. (1969), Buitrago et al. (1974), Dourmad et al. (1991), Coffey et al. (1994) and Weldon et al., (1994). It was suggested that the reduction of lactation feed intake was associated with the increased BW and BF gains during gestation (Yang et al., 1989). It could be calculated from the present study that for one extra mm BF gain during gestation, average daily feed intake during lactation decreased by 150 g. It was also suggested that body composition, especially BF at farrowing, was negatively associated with lactation feed intake (Dourmad, 1991). It was calculated that 1 mm BF gain during gestation was associated with a decrease of 63 $g \cdot d^{-1}$ of lactation feed intake. In the study conducted by Yang et al. (1989), the inverse relationship between average daily feed intake during lactation and BF depth at farrowing was not evident for primiparous sows (-18 $g \cdot d^{-1} \cdot mm^{-1}$), but was remarkable for multiparous sows (-129 $g \cdot d^{-1} \cdot mm^{-1}$). In our present study, an increase of 1 mm of post-farrowing BF was associated with a decrease of 100 g of lactation daily feed intake. A recent publication from our lab based on over 10,000 farrowing records revealed that an increase of 1 mm BF depth at d 109 of gestation was associated with a reduction of 60–120 g of daily feed intake during

lactation, which was parity dependent (Kim et al., 2015). It was reported that reduction of lactation feed intake associated with excessive BW and BF gains during gestation might be due to low plasma concentration of insulin during lactation (Weldon et al., 1994c). In contrast with the aforementioned literature and the present study, Mahan (1998) and Van der Peet-Schwering et al. (2004) reported that gestation feeding levels had no effect on lactation feed intake, although the sows on the higher feeding levels gained more BW and BF during gestation compared with sows on the lower feeding levels. The inconsistent results among these studies may be attributed to the differences in feeding levels and the diet composition. For instance, in the study conducted by Mahan (1998), the higher feeding level was only 0.13 $kg \cdot d^{-1}$ more than the control feeding level, generating only 4 kg more BW gain during gestation in sows on the higher feeding level compared with the control. It was apparent that this less amount of BW gain during gestation was not able to differentiate the feed intake during lactation. Van der Peet-Schwering et al. (2004) compared sow performance in response to a diet with a high level of fermentable nonstarch polysaccharide fed *ad libitum* and a conventional diet fed restrictedly. Sows fed the high nonstarch polysaccharide diet *ad libitum* gained more BW and BF during gestation but lost more BW and BF during lactation. However, the lactation feed intake was similar for sows fed restrictedly or *ad libitum* during gestation. It was probable that sows fed high-fiber diet had an extended gastrointestinal tract, which might stimulate feed intake during lactation (Jørgensen et al., 1996).

In the present study, the numbers of total piglets born, live born piglets and piglets at weaning were not different among different feeding levels during the 4 periods of gestation, which was in agreement with the results of previous literature (Baker et al.,

1969; Dourmad, 1991; Weldon et al., 1994c; van der Peet-Schwering et al., 2004). However, Libal and Wahlstrom (1977) reported that number of live born piglets decreased as the daily energy intake increased from 4,000 to 7,000 kcal of metabolizable energy in gestation. Likewise, Musser et al. (2006) reported that sows fed increased complete diet from d 30 to 50 of gestation had reduced number of piglets born alive. It was speculated that the higher energy intake or feeding levels during gestation may increase the progesterone clearance rate, which in turn may result in lower circulating progesterone concentration (Prime and Symonds, 1993), thus reducing embryo survival and eventually fewer live born piglets. In contrast, Hoving et al. (2011) reported the higher feed intake during early gestation increased litter size at birth in primiparous sows. De et al. (2009) indicated that an increased feeding level during early pregnancy increased growth hormone and insulin-like growth factor 1 concentrations in plasma, as well as in uterine flushings, which could influence embryonic development and survival in a direct or indirect manner. In agreement with Baker et al., (1969), Libal and Wahlstrom (1977), Hoppe et al. (1990) and Coffey et al. (1994), in the present experiment, piglet birth weight tended to increase linearly with the rise of feeding levels during 4 periods of gestation, while piglet weaning weight maximized at 1.5M feeding level. Similarly, Baker et al. (1969) and Libal and Wahlstrom (1977) reported that piglet birth and weaning weights increased as feed intake (or energy intake) increased and reached a plateau at a daily energy intake of 6,000 kcal of metabolizable energy during gestation.

Wean to estrus interval was not different among the 4 feeding levels, although sows all lost different amount of BF during lactation in response to different feeding levels.

Whittemore (1996) suggested that excessive losses of fat and/or muscle during lactation as well as insufficient body reserves at farrowing and weaning were major factors responsible for delayed wean to estrus intervals. It was further reinforced by the fact that wean to estrus interval and subsequent reproductive performance would be negatively affected if primiparous sows mobilized more than 12% of their body protein mass during lactation (Clowes et al., 2003). There was a good evidence that, in the present study, predicted body protein mass of sows all increased during lactation, which may be responsible for the similar wean to estrus intervals among the 4 feeding treatments. Additionally, the amounts of BF mobilization during lactation were not severe enough to delay the initiation of estrus after weaning.

Effects of housing systems on sow and litter performance

One of the interesting findings of this study was that sows housed in group pens had greater BW and BF gain during gestation compared with sows housed in individual stalls, rendering them having greater BW and BF at the end of gestation (d 109) and post-farrowing. It should be borne in mind that the initial BWs and BF depth were not different between sows housed in group pens and individual stalls. Li et al. (2014) reported that group housed sows of parity 3 had greater BW and BF gain during gestation compared with parity 3 sows housed in individual stalls, but the effect was not evident in parity 1 and 2 sows. In the study conducted by Li et al. (2014), sows in group pens were managed in a dynamic manner, with sows adding to the group pens at different time. It was evident that younger sows were in the low rank of hierarchy when mixing with mature sows, leading to higher total injury occurrence in the younger sows (Anil et al., 2005), which may compromise their growth rate in the group pens. The definite

mechanism explaining the sows housed in group pens had increased growth rate compared with sows housed individual stalls was still not clear and warranted further investigation. It could be postulated that sows housed in group pens were able to exercise freely compared with sows restricted in individual stalls, which may increase the energy and nutrient digestibility of the diet and thus group housed sows could extract more energy and nutrients from the same diet to accumulate more body reserves in comparison with sows housed in individual stalls. On the other hand, Cronin (1985) reported that sows with high activity levels produced more heat and consequently less energy was retained compared with sows with low activity level in gestation. It could be speculated that the advantage of increased energy and nutrient digestibility may outweigh the increased heat increment due to increased physical activity in sows housed in group pens.

Sows housed in group pens during gestation lost more body BF during lactation compared with sows housed in individual stalls. Interestingly, the BW gain during lactation was not different between the two housing systems. This phenomenon could be further supported by the evidence that the predicted protein mass gain during lactation was not different between the two housing systems, while the group housed sows lost more predicted fat mass during lactation in comparison with sows housed in individual stalls. It could be speculated that higher BF loss in sows housed in group pens was due to the greater BW and BF gain during gestation compared with the sows housed in individual stalls.

In agreement with Anil et al. (2005) and Johnston and Li (2013), litter performance was not different between the two housing systems in terms of the number of total born piglet, live born piglets, piglet birth and weaning weight and litter weight at birth and weaning.

However, Li et al. (2014) reported that sows housed in group pens farrowed 0.5 fewer live born piglet per litter compared with sows housed in individual stalls. In their study, sows were moved to group pens around one week after breeding. In our study, however, sows were mixed in group pens around d 35 of gestation. It could be speculated that mixing sows in group pens exposed them to an aggressive environment, which may be deleterious for embryo implantation and thus reduce the embryonic survival in the sows mixed only one week after breeding.

Interestingly, there were interaction effects between gestation feeding levels and housing systems on number of liveborn piglets and litter weight of liveborn at birth. Within 0.5M and 1.0M feeding levels, sows housed in group pens had fewer number of liveborn piglets and lower litter weight of liveborn at birth than sows housed in individual stalls, while within 2.0M feeding level, sows housed in group pens had higher number of liveborn piglets and greater litter weight at birth compared with sows housed in individual stalls. It was possible that sows housed in group pens had reduced fetal development in the lower feeding levels compared with sows housed in individual stalls. When higher feeding levels were provided, however, sows housed in group pens had increased fetal development compared with sows housed in individual stalls.

To our best knowledge, this was the first study investigating different feeding levels based on maintenance energy intake during 4 short periods of gestation on sow and litter performance. In addition, we also evaluated the interaction effects between gestation feeding levels and housing systems on sow and litter performance. It should be noted that sows on 1.0M feeding level throughout gestation had considerable amount of BW gain with no change in BF depth during gestation, indicating that the maintenance energy

requirement (106 × $BW^{0.75}$ kcal ME/d) proposed by NRC (1998) may overestimate the actual maintenance requirement of gestation sows. However, we could not exclude the possibility that gestation sows had increased energy and nutrient digestibility when feeding levels were reduced. Furthermore, the fact that gestation sows had greater energy and nutrient digestibility than growing pigs (Le Goff and Noblet, 2001) may render the usage of tabulated values derived from the growing pigs underestimating the metabolizable energy value of the diet.

CONCLUSION

In conclusion, increasing feeding levels during 4 short periods of gestation increased BW and BF gain during gestation and led to less BW gain and more BF loss during lactation. Both gestation feeding levels and housing systems did not affect reproductive performance. Group pen housing system may be beneficial in terms of increased overall BW gain during gestation and lactation.

IMPLICATIONS

Sows on the 4 feeding levels during the 4 short periods of gestation all gained considerable amount of BW during the whole gestation and lactation cycle, but only sows on 2.0M feeding level had limited BF gain during the whole reproductive cycle. These results indicated that feeding gestation sows at two times maintenance energy intake level for only one month with the maintenance energy intake level during the rest of the gestation period was able to meet the energy and nutrient requirement of gestating sows for optimum reproductive performance. It should also be kept in mind that insufficient feed intake during gestation cannot be compensated by *ad libitum* feed intake during

lactation. Thus, a target of BF gain, rather BW gain during gestation, should be taken into consideration in order to achieve the optimum reproductive performance and increase the longevity of breeding herd.

Table 2-1. Ingredient and nutrient composition of experimental diets for gestation and lactation (as-fed basis)

Item	Gestation	Lactation
Ingredient, %		
Corn	65.22	61.15
Soybean meal	10.00	17.20
cDDGS[1]	20.00	15.00
Choice white grease	1.50	3.00
Limestone	1.00	0.88
Dicalcium phosphate	1.20	1.15
Lysine HCl (78%)	0.10	0.46
DL-Methionine	-	0.01
L-Threonine	-	0.13
L-Tryptophan	-	0.04
Salt	0.35	0.35
Premix[2]	0.50	0.50
Tylan[3]	0.13	0.13
Nutrient composition		
ME, [4] kcal/kg	3,300	3,380
CP, [5] %	15.70	18.01
Total Ca, [5] %	0.75	0.80
Available P, [4] %	0.35	0.40
SID[6] Lys, [4] %	0.57	1.00
SID Met + Cys, [4] %	0.52	0.54
SID Thr, [4] %	0.44	0.64
SID Trp, [4] %	0.12	0.19

[1]cDDGS = Corn distillers dried grains with solubles.

[2]Supplied the following nutrients per kilogram of diets: vitamin A, 12,114 IU; vitamin D, 2,753 IU; vitamin E, 66 IU; vitamin K, 4.4 mg; thiamine, 1 mg; riboflavin, 10 mg; niacin, 55 mg; pantothenic acid, 33 mg; pyridoxine, 2.2 mg; folic acid, 1.6 mg; vitamin B_{12}, 0.06 mg; I, 0.5 mg from ethylenediamine dihydriodide; Se, 0.3 mg from sodium selenite; choline, 548 mg from choline chloride; and metal polysaccharide complexes of zinc

sulfate (125 mg of Zn), iron sulfate (125 mg of Fe), manganese sulfate (40 mg of Mn), and copper sulfate (15 mg of Cu).

[3]TylanTM 40 (Tylosin phosphate 40), Elanco Animal Health, Indianapolis, IN.

[4]Caculated values according to NRC (1998).

[5]Analyzed values.

[6]SID = standardized ileal digestible.

Table 2-2. Least squares means for effects of feeding levels during periods of gestation and housing systems on sow performance at different time points and during gestation and lactation

							Feeding levels X Housing systems							
	Feeding levels[1]				Housing system[2]		0.5M		1.0M		1.5M		2.0M	
Item	0.5M	1.0M	1.5M	2.0M	GP	IS	GP	IS	GP	IS	GP	IS	GP	IS
Number of sows	60	66	65	64	129	126	32	28	32	34	33	32	32	32
Average parity	4.9	4.7	4.9	5	4.6	5.2	4.6	5.2	4.2	5.1	4.7	5.2	4.9	5.2
Sow BW, kg														
d 27	223.4	216.1	218.0	221.0	219.3	220.0	226.3	220.5	210.7	221.6	217.0	219.1	223.3	218.7
d 55	225.4	221.2	226.3	228.7	225.5	225.3	227.7	223.2	216.3	226.0	225.9	226.7	232.1	225.3
d 83	237.8	235.5	241.8	245.8	242.5	237.9	241.2	234.3	233.1	238.0	242.7	240.9	253.0	238.6
d 97	242.3	240.7	251.4	256.8	250.2	245.4	245.8	238.8	237.4	244.1	252.7	250.1	264.9	248.6
d 109	247.2	250.3	264.7	271.2	262.0	254.6	251.1	243.2	247.8	252.8	267.7	261.7	281.6	260.8
Post-farrowing[3]	220.2	224.3	239.8	244.2	234.7	229.5	227.7	212.7	220.7	227.8	243.0	236.6	247.3	241.1
Weaning	239.8	236.9	243.6	250.8	245.6	239.9	243.1	236.5	235.8	238.0	246.9	240.3	256.7	244.8
Sow BF, mm														
d 27	19.1	18.5	18.7	18.7	19.2	18.3	20.0	18.3	18.1	18.5	18.9	19.1	19.7	18.5
d 55	19.1	18.9	19.3	20.2	19.9	18.9	19.9	18.4	18.4	19.2	19.8	19.2	21.2	19.3
d 83	19.2	19.3	20.8	21.3	21.0	19.3	20.3	18.2	19.1	19.3	21.4	20.0	23.0	19.8
d 97	19.3	19.0	20.6	22.2	21.1	19.5	20.4	18.3	18.8	19.2	20.9	20.2	23.8	20.9
d 109	19.4	18.9	22.1	22.9	22.0	19.7	19.6	18.3	18.6	18.5	24.1	20.8	23.9	21.0
Post-farrowing	19.4	18.9	22.1	22.9	22.0	19.7	19.6	18.3	18.6	18.5	24.1	20.8	23.9	21.0
Weaning	16.2	16.4	18.7	19.0	17.9	17.2	16.2	16.2	16.2	16.6	19.5	17.9	19.9	18.2
Gestation weight change[4]	26.1	35.6	49.7	52.5	45.2	36.8	28.0	24.2	38.7	32.4	54.3	45.1	59.7	45.3
Gestation BF change[5]	-0.1	0.1	3.1	3.7	2.4	1.0	0.2	-0.5	0.8	-0.6	4.3	2.0	4.4	3.0
Lactation weight change	18.4	11.4	3.3	3.4	9.5	8.7	17.7	19.1	14.4	8.3	4.6	2.0	1.3	5.5
Lactation BF change	-2.5	-2.1	-3.6	-3.1	-3.5	-2.1	-3.4	-1.5	-2.3	-1.9	-4.4	-2.7	-3.8	-2.4
Lactation ADFI[6]	6.6	6.3	6.0	5.9	6.1	6.2	6.5	6.6	6.5	6.2	5.9	6.0	5.7	6.2

Net weight change[7]	15.5	19.0	24.8	28.4	24.7	19.2	15.4	15.6	22.9	15.1	28.9	20.6	31.3	25.5
Net BF change[8]	-2.6	-1.6	-0.4	0.4	-1.1	-1.1	-3.1	-2.1	-1.4	-1.9	-0.1	-0.7	0.5	0.2
Wean to estrus interval	5.5	5.1	5.5	5.2	5.3	5.3	5.1	6.0	5.3	4.9	5.8	5.2	5.4	5.0

[1]0.5M, 1.0M, 1.5M and 2.0M represented 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (106 × $BW^{0.75}$ kcal $ME \cdot d^{-1}$), respectively.

[2]GP and IS represented group pen and individual stall housing systems, respectively.

[3]Assuming the farrowing weight was similar to sow weight at d 109 of gestation, post-farrowing BW was estimated by subtracting total born × 1.85 kg from weight at farrowing (Aherne, 1999).

[4]Weight change from d 27 to 109 of gestation.

[5]BF change from d 27 to 109 of gestation.

[6]Lactation length was used as a covariate in the statistical model.

[7]Weight change from d 27 of gestation to weaning.

[8]BF change from d 27 of gestation to weaning.

Table 2-3. Standard errors of means and probability values for effects of feeding levels during periods of gestation and housing systems on sow performance at different time points and during gestation and lactation

	Feeding levels[1]		Housing system[2]		Interaction[3]		Polynomial contrasts[4]		
Item	SEM	*P* value	SEM	*P* value	SEM	*P* value	Linear	Quadratic	Cubic
Sow BW, kg									
d 27	6.23	0.21	5.94	0.81	6.88	0.20	0.98	0.02	0.24
d 55	6.29	0.26	5.97	0.94	7.00	0.34	0.12	0.11	0.13
d 83	6.42	0.08	6.04	0.14	7.25	0.31	< 0.01	0.15	0.14
d 97	6.52	< 0.01	6.09	0.14	7.43	0.24	< 0.01	0.16	0.06
d 109	6.65	< 0.01	6.15	0.03	7.65	0.23	< 0.01	0.50	0.02
Post-farrowing[5]	6.50	< 0.01	6.13	0.14	7.45	0.16	< 0.01	0.96	0.13
Weaning	6.59	0.02	6.12	0.09	7.58	0.66	< 0.01	0.05	0.18
Sow BF, mm									
d 27	0.66	0.87	0.55	0.09	1.08	0.48	0.82	0.43	0.40
d 55	0.67	0.35	0.55	0.07	0.85	0.31	0.11	0.30	0.68
d 83	0.70	0.02	0.57	< 0.01	1.05	0.26	< 0.01	0.55	0.40
d 97	0.73	< 0.01	0.59	0.01	1.12	0.25	< 0.01	0.10	0.52
d 109	0.73	< 0.01	0.58	< 0.01	0.97	0.21	< 0.01	0.74	< 0.01
Post-farrowing	0.65	< 0.01	0.49	0.19	0.92	0.40	< 0.01	0.95	0.09
Weaning	0.65	< 0.01	0.49	0.19	0.92	0.40	< 0.01	0.95	0.09
Gestation weight change[6]	2.43	< 0.01	2.18	< 0.01	2.99	0.10	< 0.01	0.03	0.02
Gestation BF change[7]	0.48	< 0.01	0.38	< 0.01	0.68	0.55	< 0.01	0.67	< 0.01
Lactation weight change	2.93	< 0.01	2.52	0.74	3.75	0.41	< 0.01	0.12	0.34
Lactation BF change	0.49	0.03	0.39	< 0.01	0.66	0.47	0.05	0.91	0.02
Lactation ADFI[8]	0.33	0.06	0.30	0.65	0.39	0.53	0.01	0.58	0.64
Net weight change[9]	3.27	< 0.01	3.10	< 0.01	3.70	0.19	< 0.01	0.96	0.52
Net BF change[10]	0.50	< 0.01	0.38	0.89	0.79	0.56	< 0.01	0.85	0.74
Wean to estrus interval	0.31	0.70	0.21	0.96	0.48	0.35	0.76	0.81	0.25

[1]Feeding levels included 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (106 × $BW^{0.75}$ kcal ME·d^{-1}).

[2]Housing systems included group pens and individual stalls.

[3]Interaction between feeding levels and housing systems.

[4]Linear, quadratic and cubic effects of increasing feeding levels

[5]Assuming the farrowing weight was similar to sow weight at d 109 of gestation, post-farrowing BW was estimated by subtracting total born × 1.85 kg from weight at farrowing (Aherne, 1999).

[6]Weight change from d 27 to 109 of gestation.

[7]BF change from d 27 to 109 of gestation.

[8]Lactation length was used as a covariate in the statistical model.

[9]Weight change from d 27 of gestation to weaning.

[10]BF change from d 27 of gestation to weaning.

Table 2-4. Least squares means for effects of feeding levels during periods of gestation and housing systems on sow performance during 4 periods of gestation

							Feeding levels X Housing systems							
	Feeding levels[1]				Housing system[2]		0.5M		1.0M		1.5M		2.0M	
Item	0.5M	1.0M	1.5M	2.0M	GP	IS	GP	IS	GP	IS	GP	IS	GP	IS
Number of sows	60	66	65	64	129	126	32	28	32	34	33	32	32	32
Average parity	4.9	4.7	4.9	5.0	4.6	5.2	4.6	5.2	4.2	5.1	4.7	5.2	4.9	5.2
Period 1 (d 27-55)														
BW change	2.20	5.28	8.70	8.21	6.37	5.83	1.38	3.02	5.89	4.68	9.22	8.18	8.98	7.45
BF change	0.00	0.38	0.94	1.32	0.70	0.62	0.07	-0.07	0.46	0.29	0.86	1.02	1.41	1.23
ADG	0.08	0.20	0.35	0.33	0.25	0.23	0.05	0.12	0.22	0.18	0.37	0.32	0.35	0.30
Feed intake	39.72	45.30	52.17	59.14	48.84	49.33	39.90	39.53	44.65	45.96	51.64	52.70	59.17	59.11
Gain to Feed	0.05	0.11	0.17	0.14	0.12	0.11	0.03	0.07	0.13	0.10	0.18	0.16	0.16	0.13
Period 2 (d 57-83)														
BW change	12.59	14.52	15.89	17.48	17.22	13.02	13.71	11.46	16.84	12.20	17.21	14.56	21.12	13.84
BF change	-0.25	0.08	1.18	0.64	0.73	0.10	0.19	0.68	0.45	-0.28	1.25	1.12	1.02	0.26
ADG	0.42	0.48	0.54	0.59	0.56	0.45	0.44	0.40	0.54	0.42	0.56	0.51	0.70	0.48
Feed intake	46.29	51.37	58.55	65.59	56.15	54.75	47.22	45.36	51.58	51.16	58.84	58.27	66.96	64.21
Gain to Feed	0.27	0.28	0.27	0.27	0.31	0.24	0.29	0.26	0.32	0.24	0.30	0.25	0.32	0.22
Period 3 (d 83-97)														
BW change	4.71	5.30	10.16	11.45	7.88	7.94	4.52	4.91	4.45	6.16	10.32	10.00	12.23	10.68
BF change	-0.01	-0.49	-0.41	0.78	-0.06	-0.01	-0.15	0.13	-0.52	-0.47	-0.62	-0.21	1.06	0.51
ADG	0.24	0.29	0.55	0.64	0.43	0.42	0.23	0.25	0.24	0.33	0.57	0.54	0.70	0.57
Feed intake	29.06	33.84	43.50	50.72	38.16	40.40	27.59	30.54	31.86	35.83	42.86	44.15	50.35	51.10
Gain to Feed	0.15	0.15	0.24	0.23	0.19	0.19	0.14	0.15	0.13	0.17	0.24	0.23	0.25	0.21
Period 4 (d 97-109)														
BW change	5.90	10.42	13.90	15.23	12.80	9.93	6.80	5.01	11.46	9.37	15.85	11.95	17.07	13.38
BF change	0.21	0.28	1.87	0.82	1.02	0.56	0.07	0.35	0.35	0.20	2.85	0.89	0.83	0.81

ADG	0.43	0.74	1.00	1.10	0.94	0.70	0.49	0.37	0.84	0.65	1.17	0.84	1.26	0.95
Feed intake	19.51	26.25	34.59	42.13	30.66	30.58	19.64	19.38	25.92	26.59	34.63	34.56	42.44	41.82
Gain to Feed	0.27	0.39	0.39	0.36	0.39	0.31	0.29	0.25	0.43	0.34	0.45	0.33	0.41	0.31

[1]Feeding levels included 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (106 × $BW^{0.75}$ kcal ME·d^{-1}).

[2]Housing systems included group pens and individual stalls.

Table 2-5. Standard errors of means and probability values for effects of feeding levels during periods of gestation and housing systems on sow performance during 4 periods of gestation

	Feeding levels[1]		Housing system[2]		Interaction[3]		Polynomial contrasts[4]		
Item	SEM	*P* value	SEM	*P* value	SEM	*P* value	Linear	Quadratic	Cubic
Period 1 (d 27-55)									
BW change	0.83	< 0.01	0.68	0.43	1.10	0.33	< 0.01	0.01	0.07
BF change	0.36	0.03	0.27	0.80	0.56	0.94	< 0.01	0.62	0.58
ADG	0.03	< 0.01	0.03	0.46	0.04	0.41	< 0.01	0.02	0.05
Feed intake	1.06	< 0.01	0.84	0.59	1.44	0.30	< 0.01	0.08	0.26
Gain to Feed	0.02	< 0.01	0.01	0.53	0.02	0.26	< 0.01	< 0.01	0.13
Period 2 (d 57-83)									
BW change	0.96	< 0.01	0.75	< 0.01	1.29	0.07	< 0.01	0.84	0.90
BF change	0.40	0.04	0.28	0.10	0.61	0.50	< 0.01	0.25	0.07
ADG	0.03	< 0.01	0.02	< 0.01	0.04	0.03	< 0.01	0.82	0.97
Feed intake	1.17	< 0.01	0.90	0.17	1.60	0.54	< 0.01	0.19	0.15
Gain to Feed	0.02	0.95	0.01	< 0.01	0.02	0.16	0.95	0.69	0.89
Period 3 (d 83-97)									
BW change	0.81	< 0.01	0.66	0.93	1.27	0.25	< 0.01	0.67	0.01
BF change	0.36	0.02	0.26	0.89	0.55	0.94	0.06	0.02	0.75
ADG	0.04	< 0.01	0.03	0.71	0.05	0.13	< 0.01	0.53	< 0.01
Feed intake	1.37	< 0.01	1.03	0.07	1.90	0.39	< 0.01	0.15	0.11
Gain to Feed	0.02	< 0.01	0.01	0.97	0.03	0.31	< 0.01	0.87	0.01
Period 4 (d 97-109)									
BW change	0.95	< 0.01	0.74	< 0.01	1.33	0.37	< 0.01	0.01	0.64
BF change	0.36	< 0.01	0.26	0.17	0.55	0.03	0.03	0.13	< 0.01
ADG	0.06	< 0.01	0.05	< 0.01	0.10	0.38	< 0.01	0.01	0.62
Feed intake	0.64	< 0.01	0.60	0.84	0.74	0.67	< 0.01	0.22	0.11
Gain to Feed	0.03	< 0.01	0.02	< 0.01	0.04	0.58	0.01	0.00	0.59

[1]Feeding levels included 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (106 × $BW^{0.75}$ kcal ME·d^{-1}).

[2]Housing systems included group pens and individual stalls.

[3]Interaction between feeding levels and housing systems.

[4]Linear, quadratic and cubic effects of increasing feeding levels.

Table 2-6. Least squares means for effects of feeding levels during periods of gestation and housing systems on litter performance

							Feeding levels X Housing systems							
	Feeding levels[1]				Housing system[2]		0.5M		1.0M		1.5M		2.0M	
Item	0.5M	1.0M	1.5M	2.0M	GP	IS	GP	IS	GP	IS	GP	IS	GP	IS
Number of litters	60	66	65	64	129	126	32	28	32	34	33	32	32	32
Litter size														
Liveborn	13.05	13.25	13.26	13.27	13.35	13.07	12.84	13.26	12.95	13.56	13.34	13.19	14.32	12.29
Stillborn	1.01	1.25	1.13	1.22	1.12	1.18	0.97	1.06	1.45	1.07	0.97	1.32	1.15	1.28
Mummy	0.28	0.22	0.19	0.22	0.28	0.18	0.35	0.22	0.20	0.24	0.25	0.14	0.34	0.14
Total born	14.41	14.82	14.68	14.84	14.85	14.85	14.23	14.59	14.71	14.92	14.61	14.75	15.91	13.85
After cross-fostering	12.51	12.45	12.67	12.58	12.64	12.46	12.70	12.32	12.21	12.70	12.87	12.48	12.80	12.36
Death	1.50	1.65	1.57	1.60	1.66	1.50	1.64	1.36	1.50	1.82	1.68	1.46	1.85	1.39
Weaning	10.98	10.73	11.04	10.93	10.94	10.90	11.04	10.92	10.68	10.79	11.14	10.95	10.90	10.96
Litter wt, kg														
Liveborn	19.00	19.96	20.24	19.99	20.05	19.55	18.72	19.28	19.85	20.07	20.12	20.36	21.50	18.48
Weaning	70.08	70.51	73.49	70.24	71.26	70.90	70.64	69.53	71.06	69.96	73.77	73.20	69.58	70.91
Gain	51.03	50.55	53.26	50.21	51.16	51.37	51.83	50.24	51.16	49.93	53.64	52.88	48.00	52.43
Piglet wt, kg														
Liveborn	1.46	1.52	1.53	1.51	1.51	1.50	1.46	1.45	1.55	1.49	1.52	1.55	1.51	1.51
Weaning	6.37	6.55	6.64	6.38	6.49	6.48	6.39	6.35	6.62	6.48	6.62	6.67	6.34	6.41
Piglet ADG, g	250.73	249.01	256.57	245.78	250.70	250.34	247.09	254.37	253.96	244.06	256.75	256.39	245.00	246.55
Piglet preweaning mortality, %	11.94	13.29	12.45	12.71	13.15	12.05	12.88	11.06	12.28	14.38	13.10	11.83	14.42	11.18
Lactation length, d	19.64	20.22	19.94	19.80	19.91	19.88	20.02	19.27	20.00	20.45	19.92	19.96	19.72	19.88

[1]Feeding levels included 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (106 × $BW^{0.75}$ kcal ME·d^{-1}).

[2]Housing systems included group pens and individual stalls.

Table 2-7. Standard errors of means and probability values for feeding levels during periods of gestation and housing systems on litter performance

	Feeding levels[1]		Housing system[2]		Interaction[3]		Polynomial contrasts[4]		
Item	SEM	*P* value	SEM	*P* value	SEM	*P* value	Linear	Quadratic	Cubic
Litter size									
Liveborn	0.38	0.96	0.29	0.39	0.55	0.02	0.65	0.75	0.89
Stillborn	0.20	0.74	0.14	0.72	0.27	0.46	0.49	0.63	0.44
Mummy	0.10	0.81	0.08	0.15	0.15	0.68	0.51	0.51	0.88
Total born	0.41	0.84	0.30	0.38	0.61	0.08	0.49	0.74	0.61
After cross-fostering	0.30	0.86	0.26	0.36	0.38	0.24	0.63	0.93	0.48
Death	0.21	0.94	0.15	0.37	0.32	0.48	0.77	0.73	0.65
Weaning	0.28	0.63	0.25	0.85	0.35	0.92	0.85	0.72	0.21
Litter wt, kg									
Liveborn	0.58	0.20	0.47	0.27	0.76	0.02	0.11	0.17	0.93
Weaning	1.73	0.36	1.25	0.82	2.47	0.94	0.63	0.24	0.20
Gain	1.66	0.47	1.21	0.89	2.36	0.47	0.97	0.39	0.17
Piglet wt, kg									
Liveborn	0.03	0.09	0.03	0.71	0.04	0.54	0.10	0.06	0.99
Weaning	0.14	0.12	0.11	0.90	0.17	0.86	0.79	0.02	0.50
Piglet ADG, g	7.04	0.31	6.31	0.93	8.40	0.49	0.70	0.27	0.12
Piglet preweaning mortality, %	1.36	0.87	1.01	0.36	2.00	0.43	0.78	0.64	0.53
Lactation length, d	0.22	0.14	0.17	0.87	0.30	0.12	0.84	0.05	0.21

[1]Feeding levels included 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level ($106 \times BW^{0.75}$ kcal ME·d^{-1}).

[2]Housing systems included group pens and individual stalls.

[3]Interaction between feeding levels and housing systems.

[4]Linear, quadratic and cubic effects of increasing feeding levels

Table 2-8. Least square means of effects of feeding levels during periods of gestation and housing systems on predicted sow body compositions

							Feeding levels X Housing systems							
	Feeding levels[1]				Housing system[2]		0.5M		1.0M		1.5M		2.0M	
Item	0.5M	1.0M	1.5M	2.0M	GP	IS	GP	IS	GP	IS	GP	IS	GP	IS
Number of sows	60	66	65	64	129	126	32	28	32	34	33	32	32	32
Average parity	4.9	4.7	4.9	5	4.6	5.2	4.6	5.2	4.2	5.1	4.7	5.2	4.9	5.2
Estimated protein mass, kg[3]														
d 27	34.15	33.35	33.80	33.93	33.47	34.14	35.13	33.17	32.42	34.28	33.03	34.57	33.31	34.55
d 109	39.00	39.67	41.27	42.16	40.64	40.41	39.89	38.11	38.94	40.41	41.11	41.42	42.61	41.70
Post-farrowing	34.39	34.95	36.48	37.40	35.86	35.75	35.20	33.57	34.29	35.62	36.38	36.58	37.57	37.22
Weaning	38.41	37.65	38.25	38.96	38.71	37.93	39.47	37.35	37.57	37.73	38.73	37.76	39.05	38.88
Change from d 27 to 109	4.17	6.23	7.84	8.52	7.08	6.30	4.74	3.59	6.48	5.99	7.91	7.77	9.19	7.85
Change during lactation	4.01	2.69	1.78	1.59	2.83	2.20	4.24	3.79	3.26	2.13	2.35	1.20	1.48	1.70
Estimated fat mass, kg[4]														
d 27	46.03	46.03	46.47	45.25	45.39	45.79	48.82	43.23	42.43	46.79	45.99	46.95	44.31	46.19
d 109	50.62	52.23	60.43	60.76	58.27	53.75	54.36	54.36	51.61	52.85	63.77	57.09	63.35	58.18
Post-farrowing	44.88	46.36	54.52	54.89	52.34	47.99	48.52	41.25	45.81	46.91	57.92	51.12	57.11	52.68
Weaning	45.67	46.03	50.35	51.51	49.75	47.03	47.89	43.45	46.07	45.99	52.64	48.06	52.39	50.62
Change from d 27 to 109	3.47	7.86	14.95	16.35	12.81	8.51	5.74	1.20	9.25	6.48	17.33	12.58	18.92	13.77
Change during lactation	0.81	-0.36	-4.12	-3.26	-2.63	-0.84	-0.68	2.29	0.15	-0.88	-5.26	-2.98	-4.74	-1.79

[1]Feeding levels included 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (106 × $BW^{0.75}$ kcal ME·d^{-1}).

[2]Housing systems included group pens and individual stalls.

[3]Protein mass was estimated using the equation from Dourmad et al. (1997): 2.3 + 0.178 × empty BW (kg) − 0.33 × BF depth (mm); empty BW = 0.905 × $(BW)^{1.013}$.

[4]Fat mass was estimated using the equation from Dourmad et al. (1997): -26.40 + 0.221 × empty BW (kg) + 1.33 × BF depth (mm); empty BW = 0.905 × $(BW)^{1.013}$.

Table 2-9. Standard error of means and probability values of feeding levels during periods of gestation and housing systems on predicted sow body compositions

	Feeding levels[1]		Housing system[2]		Interaction[3]		Polynomial contrasts[4]		
Item	SEM	*P* value	SEM	*P* value	SEM	*P* value	Linear	Quadratic	Cubic
Estimated protein mass, kg[5]									
d 27	0.80	0.67	0.65	0.18	1.06	0.03	0.92	0.34	0.43
d 109	0.60	<.01	0.43	0.67	0.88	0.16	<.01	0.84	0.48
Post-farrowing	0.59	<.01	0.42	0.83	0.86	0.25	<.01	0.75	0.48
Weaning	0.58	0.30	0.44	0.12	0.83	0.37	0.32	0.13	0.55
Change from d 27 to 109	0.48	<.01	0.43	0.02	0.65	0.47	<.01	0.03	0.72
Change during lactation	0.41	<.01	0.33	0.07	0.58	0.42	<.01	0.09	0.82
Estimated fat mass, kg[6]									
d 27	2.48	0.69	2.32	0.76	3.09	0.05	0.94	0.94	0.23
d 109	1.66	<.01	1.24	<.01	2.40	0.10	<.01	0.66	0.02
Post-farrowing	1.63	<.01	1.20	<.01	2.38	0.12	<.01	0.70	0.02
Weaning	1.44	<.01	1.07	0.03	2.10	0.49	<.01	0.75	0.18
Change from d 27 to 109	1.29	<.01	1.12	<.01	1.81	0.75	<.01	0.09	0.03
Change during lactation	1.23	<.01	0.99	0.06	1.68	0.35	<.01	0.28	0.07

[1]Feeding levels included 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (106 × $BW^{0.75}$ kcal ME·d^{-1}).

[2]Housing systems included group pens and individual stalls.

[3]Interaction between feeding levels and housing systems.

[4]Linear, quadratic and cubic effects of increasing feeding levels

[5]Protein mass was estimated using the equation from Dourmad et al. (1997): 2.3 + 0.178 × empty BW (kg) − 0.33 × BF depth (mm); empty BW = 0.905 × $(BW)^{1.013}$.

[6]Fat mass was estimated using the equation from Dourmad et al. (1997): -26.40 + 0.221 × empty BW (kg) + 1.33 × BF depth (mm); empty BW = 0.905 × $(BW)^{1.013}$.

Table 2-10. Relationship between BW (BW, kg) and BF (BF, mm) change during gestation and lactation and effects of BF gain during gestation and BF after farrowing on lactation average daily feed intake (kg)

Equation number	Equations	R^2	Root MSE
1	Lactation BW change = 33.30 - 0.58 x gestation BW gain[1]	0.33	13.27
2	Lactation BF loss = -2.02 - 0.43 x gestation BF gain[2]	0.29	2.40
3	Lactation ADFI = 6.64 - 0.15 x gestation BF gain	0.16	1.22
3	Lactation ADFI = 8.46 - 0.10 x postfarrowing BF	0.13	1.26

[1]Weight gain from d 27 to 109 of gestation.

[2]BF gain from d 27 to 109 of gestation.

Chapter 3. Effect of different feeding levels during three short periods of gestation on sow and litter performance over two reproductive cycles

SUMMARY

The present study investigated the effects of different feeding levels during 3 short periods of gestation on sow and litter performance. A total of 160 multiparous sows were allotted to 1 of 4 dietary treatments using a randomized complete block design with initial BW (**BW**) and backfat (**BF**) as the blocking criteria. All sows were fed one common corn-soybean meal-based diet with the amount of 1.0 × maintenance energy intake (100 × $BW^{0.75}$ kcal ME/d) throughout gestation except 3 periods of 7 d when dietary treatments were imposed on d 27, d 55 and d 83 of gestation. During the 3 short periods, sows were fed 1 of 4 different feeding levels: 0.5, 1.0, 1.5 and 2.0 × maintenance energy level (0.5M, 1.0M, 1.5M and 2.0M, respectively). Results showed that both BW gain (16.12, 24.74, 30.62 and 36.71 kg, respectively) and BF change (-0.27, 0.99, 1.49 and 2.45 mm, respectively) from d 27 to 109 of gestation increased linearly ($P < 0.01$) with the increase of gestation feeding levels. In contrast, with the rise of gestation feeding levels, lactation BW gain (14.31, 9.84, 7.09 and 3.50 kg, respectively) decreased linearly ($P < 0.01$), while BF loss during lactation (-0.79, -0.92, -1.12 and -1.57 mm, respectively) increased linearly ($P = 0.05$). It was estimated that requirements of 1.20M, 0.66M and 0.65M feeding levels were needed to maintain a constant BW during these 3 short periods. Additionally, average daily feed intake during lactation (7.05, 7.00, 6.91 and 6.52 kg, respectively) tended to decrease linearly ($P = 0.09$) in response to the increase of gestation feeding levels. Furthermore, piglet birth weights increased linearly ($P < 0.01$) with the increase of gestation feeding levels, while piglet weaning weights were similar

(P > 0.10) among treatments. Subsequent reproductive performance was not affected (P > 0.10) by feeding levels during the previous reproductive cycle. In conclusion, increasing feeding levels during 3 short periods of gestation increased BW and BF gains during gestation and caused less BW gain and more BF loss during lactation due to the reduction of lactation feed intake in response to increasing gestation feeding levels. Increasing feeding levels during 3 short periods of gestation increased piglet birth weight, but did not affect piglet weaning weight. The feeding strategies in the current reproductive cycle did not impact subsequent reproductive performance. The data indicated that the current maintenance energy requirement of gestation sows may be underestimated or overestimated depending on gestation periods.

KEYWORDS*:* Feeding levels; sow performance; litter performance

INTRODUCTION

Nutritional strategies have been the research focus to improve reproductive performance of sows for several decades. It was previously thought that a feeding regime which could allow an adequate BW gain accounted for the maternal weight gain, developing fetus and placenta with no detrimental effects on reproductive performance would improve overall energetic efficiency of reproduction (Frobish et al., 1973). However, modern crossbred sows, which have increased potential of large litter size and high lean mass (Whittemore, 1996), have been shown to gain adequate BW over the reproductive cycle while simultaneously losing considerable fat mass (Yang et al., 1989; Dourmad et al., 1991), which may compromise subsequent reproductive performance (Yang et al., 1989).

In the past several decades, numerous studies have been conducted to investigate effects of energy concentrations (Buitrago et al., 1974; Hoppe et al., 1990; Dourmad et al., 1996; Heo et al., 2008) and protein levels (Mahan and Mangan, 1975; Mahan, 1998) during gestation on sow and litter performance. Additionally, feeding levels during different stages of gestation (Cromwell et al., 1989; Weldon et al., 1994b; Musser et al., 2006; Heo et al., 2008; Hoving et al., 2011) and whole gestation (Dourmad et al., 1991; Mahan, 1998) over one or several reproductive cycles have also been studied to evaluate their effects on sow and litter performance. These studies consistently showed that increasing feeding levels during gestation increased sow BW gain during gestation, but the sows consuming higher feeding levels during gestation lost more BW and backfat during lactation, with inconsistent results for litter performance. However, we are not aware of any research on investigation of feeding levels during several short periods during gestation on sow and litter performance. Therefore, the objective of this study was to determine effects of different feeding levels during 3 short periods of gestation on sow and litter performance and its impact on the subsequent reproductive performance.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee of University of Minnesota approved the experimental protocol of this study.

Animals and Management

The present experiment was conducted at the University of Minnesota - Southern Research and Outreach Center, Waseca, MN. The experiment started on February 4, 2014 and ended on November 13, 2014. A total of 160 multiparous Large White x Danish

Landrace crossbred sows (TOPIGS 20, TOPIGS Inc., Winnipeg, Manitoba, Canada) consisted of 4 different batches were used in this study. After breeding, all sows in each batch stayed in the individual stalls (2.1 m length x 0.6 m width x 0.6 m height) for about 35 d; then pregnancy check was conducted for all these bred sows; after pregnancy check, all the pregnant sows were moved to the same group pen (13.1 m length x 6.9 m width x 0.7 m height) with electronic sow feeders (3.7 m length x 0.5 m width x 0.7 m height) in the center. Another pregnancy check was conducted 2 wk later on these sows in the pen to confirm the pregnancy. During gestation, all sows were fed their respective gestation diets with different amounts of feed during different periods of gestation. On d 109 of gestation, sows were moved into the farrowing rooms with environment controlled systems and housed in individual farrowing crates (2.13 m length × 0.66 m width × 0.97 m height). All sows were fed 2.27 kg lactation diets beginning from d 109 to the date of farrowing. After parturition, the amount of feed was increased gradually to allow for *ad libitum* feed intake from d 5 until weaning at about d 19 of lactation. After weaning, sows were moved to the environmental controlled gestation room with individual stalls. Estrus was checked on the daily basis. Sows were bred via artificial insemination on 2 consecutive days. From weaning to breeding, sows were fed 2.0 kg gestation diet. Sows were allowed free access to water throughout the experimental period and remained in the study and the subsequent reproductive performance was recorded. Sows were culled according to the Standard Operation Procedure of the Swine Research Facility.

In each batch, 2 sows of parity 3 with similar BW and BF from each treatment were selected before farrowing. New born piglets from these sows were weighted immediately and notched individually after the last piglet within each litter was farrowed. These

piglets were also weighed individually at weaning. Piglets from other sows were processed within 24 h after birth according to the standard piglet management procedure of the facility, such as iron shot, tail docking and navel cut and disinfection. Cross-fostering was conducted within 48 h after birth within dietary treatment to equalize litter size around 11 or 12 piglets per litter. Heat lamps were provided for newborn piglets for 48 h and piglets had access to heat pad from birth to weaning. Physical castration was conducted on all male piglets between 5 and 9 d of age. No creep feed was provided during lactation and all piglets were weaned at about d 19 of lactation.

Dietary Treatments and Experimental Design

At d 27 of gestation, sows in each batch were allotted to 1 of 4 experimental treatments using a randomized complete block design by initial BW (**BW**) and backfat (**BF**) at breeding and balanced by parity among treatments. The experiment started from d 27 of gestation throughout the gestation and lactation period. All sows were fed one common corn-soybean meal-based basal diet (Table 3-1) with the amount of 1.0 × maintenance energy intake (100 × $BW^{0.75}$ kcal ME/d, NRC, 2012) throughout the gestation period except 3 periods of 7 d dietary treatments imposing at d 27, d 55 and d 83 gestation. During these 3 periods, sows were fed 1 of 4 different feeding levels based on maintenance energy intake: 1) 0.5 × maintenance level (0.5M); 2) 1.0 × maintenance level (1.0M); 3) 1.5 × maintenance level (1.5M); 4) 2.0 × maintenance level (2.0M). Gestation diet and lactation diet (Table 3-1) met or exceeded NRC (2012) nutrient recommendations.

After breeding, all sows in each batch stayed in the individual stalls for about 35 d until pregnancy check; then the pregnant sows were moved to the same group pen. All sows were remained in the group pen until d 109 of gestation. Each batch, around 45-50 sows were transferred to group pens with the dimension of 13.1 m length x 6.9 m width x 0.7 m height and each pen was equipped with 4 nipple drinkers and fully slatted concrete floor. An electronic sow feeder (Osborne Industries, Osborne, Kansas, USA) was installed in the center of the pen. Excluding the space occupied by the electronic sow feeder, each sow in the group pens had the floor space allowance of 1.8 m^2. The feed intake in the group pen system was manipulated through different feeding curves, which were set in the program in the computer. Each pen had 24 h feeding cycle on the daily basis. Sows in the group pens were equipped with the transponders in their left ears. Each time only 1 sow was allowed to enter the electronic sow feeder. Once the sow entered the electronic sow feeder, the entrance was locked so that other sows could not enter the feeder. The system sensed the transponder in that sow's ear and determined the feed curve assigned to that sow. Once the sow finished her daily amount of feed, the door would open automatically and other sows would push her out. Individual stalls (Crystal Spring Hog Equipment, Ste. Agathe, Manitoba) were equipped with individual feeders and nipple drinkers. Each stall was located on the fully slatted concrete floor. The feed intake of sows in the individual stalls was managed via setting different feed drops with different volumes, which was calibrated, monthly by weighing the feed to assure correct weight and volume of feed. All the sows in the individual stalls were fed at 7:30 am each day.

Data Collection and Chemical Analysis

Sow and Litter Performance

Sow BW was recorded and BF thickness was measured using ultrasonic detection machine (Preg-Alert Pro, Renco Corp., Minneapolis, USA) on both the left and right sides at the P2 position (6.5 cm from the dorsal mid-line at the level of the last rib) on d 27, 34, 55, 62, 83, 90, 109 of gestation, within 24 h after farrowing and at weaning to measure the BW and BF change during gestation and lactation periods. During lactation, farrowing date, litter size (number of total piglets born, born alive, after cross-fostering and at weaning), piglet deaths were recorded. Litter weight at birth, after cross-fostering and at weaning was also recorded. Feed intake was recorded on daily basis until weaning. Preweaning mortality of piglets within litter was calculated using the live born piglets died before weaning divided by the number of live born piglets. Litter weight gain and piglet average daily gain (**ADG**) were also calculated. Average daily feed intake (**ADFI**) was calculated using the summation of daily feed intake divided by the lactation period. Within-litter variation of liveborn piglet birth and weaning weights were calculated using the notched piglets. Subsequent reproductive performance was also recorded for each previous gestation feeding level treatment.

Protein and fat mass on d 27, d 109 of gestation, post-farrowing and weaning was estimated using the prediction equation of Dourmad et al. (1997). The corresponding changes of protein and fat mass during gestation and lactation were calculated.

Chemical Analysis

Concentrations of dry matter (method 934.01; AOAC, 2006), crude protein (method 984.13; AOAC, 2006), ether extract (method 920.39; AOAC, 2006), neutral detergent fiber (NDF, method 973.18; AOAC, 2006), acid detergent fiber (ADF, method 973.18; AOAC, 2006) in gestation and lactation diets were analyzed in University of Minnesota's Southern Research and Outreach Center's Swine Research Lab. Concentrations of calcium (method 958.01; AOAC, 2006), phosphorus (method 958.01; AOAC, 2006) and amino acid (method 982.30; AOAC, 2006) were analyzed in Experiment Station Chemical Laboratories (University of Missouri, Columbia, MO).

Statistical Analysis

SAS 9.4 (SAS Inst. Inc., Gary, NC) was used in all data analysis. Individual sow served as the experimental unit. The LSMEANS statement was used to calculate the least square means. Tukey-Kramer adjustment was used for multiple comparisons of the least square means. Covariates was used to adjust the least square means of response and presented as a footnote for each table. Pooled SEM was calculated for each measurement. A probability of $P < 0.05$ was considered as significant and $0.05 < P < 0.1$ was declared as a trend.

The GLIMMIX procedure was used to analyze all the data. Dietary treatment was considered as the fixed effect. Batch and block within each batch were considered as random effects. Sow BW and BF measured on d 27, 55, 83, 109, post-farrowing and at weaning were considered as repeated measurements in time. Different covariance structure candidate models were examined and the best fit model was selected for each measurement based on Akaike Information Criterion (**AIC**) and Bayesian Information

Criterion (**BIC**) values. Model examination results indicated that heterogeneous first-order autoregressive (arh(1)) and heterogeneous Toeplitz (toeph) were the best covariance models for sow BW and BF measurements, respectively. The SLICE option by time was used to test the effect of dietary treatments at each of the different time points.

Sow BW change, BF change, ADG, feed intake and gain to feed ratio calculated for the 3 short periods were also considered as repeated measurements. After model testing, the best covariance structure models selected using the aforementioned technique for sow BW change, BF change, ADG, feed intake and gain to feed ratio were all arh(1). The SLICE option by period was used to test the effect of dietary treatments at the 3 short periods.

For litter performance of both reproductive cycles, the data of litter weight and average piglet weight at birth and weaning, and average daily gain of piglets were analyzed in the default normal linear regression model. Count data, such as number of liveborn, total born, after cross-fostering, death and wean piglets were analyzed using Poisson regression model, while zero-inflated Poisson regression model was used to analyze the numbers of stillborn and mummies. Furthermore, the binomial regression model was used to analyze pre-weaning piglet mortality.

The CORR procedure was used to examine the Pearson correlation coefficients among sow performance parameters during gestation and lactation. Additionally, the REG procedure was used to establish the simple linear regressions and determine the effects of sow BW gain during gestation on sow BW change during lactation, sow BF change

during gestation on sow BF loss during lactation, and sow BF post-farrowing on lactation average daily feed intake.

The LIFETEST procedure was used to examine the retention rate of sows among the 4 feeding levels during gestation periods. Logrank test was used to compare the retention rate among the 4 feeding levels.

RESULTS

Effects of feeding levels on sow performance

At the initiation of the experiment (d 27 of gestation), there were no differences ($P = 0.80$ and 0.56, respectively) for sow BW and BF thickness (Table 3-2). There were also no differences for sow BF thickness on d 55 and 83 of gestation ($P = 0.70$ and 0.29, respectively). However, sows on 2.0M feeding level had higher ($P = 0.05$) BW at d 55 of gestation than those on 0.5M feeding level, and sows on 1.5M and 2.0M feeding levels had greater ($P < 0.01$) BW on d 83 of gestation compared with those on 0.5M feeding level. On d 109 of gestation, post-farrowing and at weaning, both BW and BF thickness were greater ($P < 0.05$) for sows on 1.0M, 1.5M and 2.0M feeding levels compared with those on 0.5M feeding level. Additionally, sow BW and BF thickness on d 83, 109 of gestation, at post-farrowing and weaning increased linearly ($P < 0.05$) with the rise of feeding levels.

From d 27 to 109 of gestation, sow BW gains on 1.0M, 1.5M and 2.0M feeding levels were higher ($P < 0.01$) than sows on 0.5M feeding level, and sows on 1.5M and 2.0M feeding levels had greater ($P < 0.01$) BF thickness change in comparison with those on 0.5M feeding level. Both gestation BW gain (16.12, 24.74, 30.62 and 36.71 kg,

respectively) and BF change (-0.27, 0.99. 1.49 and 2.45 mm, respectively) from d 27 to 109 of gestation increased linearly ($P < 0.01$) with the rise of feeding levels during the 3 short periods. In contrast, sows on 0.5M feeding level during 3 short periods of gestation gained more weight during lactation compared with those on the other three feeding levels, and sows on 2.0M feeding level during 3 short periods of gestation lost more BF during lactation than those on 0.5M feeding level. Lactation weight gain (14.31, 9.84, 7.09 and 3.50 kg, respectively) decreased linearly ($P < 0.01$), while BF loss during lactation (-0.79, -0.92, -1.12 and -1.57 mm, respectively) increased linearly ($P = 0.05$) with the increase of feeding levels during 3 short periods of gestation. Additionally, ADFI during lactation tended ($P = 0.10$) to be higher for sows on 0.5M feeding level during 3 short periods of gestation than those on 2.0M feeding level. With the rise of feeding levels during gestation, ADFI during lactation (7.05, 7.00, 6.91 and 6.52 kg/d, respectively) tended to decrease linearly ($P = 0.09$). Furthermore, both net BW gains and BF changes from d 27 of gestation to weaning were greater ($P < 0.01$) in sows fed 1.0M, 1.5M and 2.0M during gestation in comparison with these counterparts fed 0.5M. Both net BW gains and BF changes from d 27 of gestation to weaning increased linearly ($P < 0.01$) with the rise of feeding levels during 3 short periods of gestation. There were also no differences ($P = 0.78$) among 4 different feeding levels in terms of wean to estrus interval. Survival analysis revealed that there were no differences among the 4 feeding levels in terms of sow retention rate from d 27 until farrowing (Figure 3-1).

The results of feeding levels during 3 short periods of gestation on sow performance during these 3 periods are presented in Table 3-3. For all the 3 periods, sow performance parameters were greater in sows on 1.0M, 1.5M and 2.0M feeding levels in comparison

with those on 0.5M feeding level in terms of BW change, BF change, ADG, feed intake and gain to feed ratio. Additionally, sows fed 1.5M and 2.0M feeding levels had higher BW change, BF change, ADG, feed intake and gain to feed ratio than sows fed 1.0M feeding level. With the rise of feeding levels, sow performance parameters increased linearly ($P < 0.01$) in terms of BW change, BF change, ADG, feed intake and gain to feed ratio. Furthermore, sow BW change, ADG, feed intake and gain to feed ratio increased significantly ($P < 0.01$, data not shown) with the advancement of gestation periods. However, there was no period effect ($P = 0.22$, data not shown) on sow BF change.

Effect of feeding levels on litter performance

There were no differences ($P > 0.10$) among 4 feeding levels in terms of numbers of liveborn, stillborn, total born, after cross-fostering, death and weaning, and litter weight at birth and weaning (Table 3-4). Number of mummies was higher ($P = 0.01$) in sows fed 1.0M feeding level than sows fed 2.0M feeding level. Gestation length was shorter ($P = 0.02$) in sows on 0.5M feeding level in comparison with sows on 2.0M feeding level. As a result of weaning at same day, lactation length was longer ($P < 0.01$) in sows on 0.5M feeding level in comparison with sows on 2.0M feeding level. Additionally, average weight of liveborn piglets at birth from sows on 1.0M, 1.5M and 2.0M feeding levels were higher ($P = 0.05$) than sows on 0.5M feeding level. After adjusting using gestation length, average weight of liveborn piglets at birth from sows on 1.0M, 1.5M and 2.0M feeding levels also tended to be higher ($P = 0.08$) than sows on 0.5M feeding level. Furthermore, no differences ($P > 0.10$) were found among the 4 feeding levels in terms of average daily gain and pre-weaning mortality of piglets. There were also no differences

($P > 0.10$) among the 4 feeding levels in terms of coefficient of variation of piglet weights within litter at birth and weaning (Table 3-5).

In terms of subsequent litter performance (Table 3-6), increasing feeding levels during 3 short periods of gestation did not ($P > 0.10$) affect the litter size, litter weight and average weight of piglets at birth and weaning, as well as average daily gain of piglets, in the subsequent reproductive cycles.

Predicted sow body compositions during gestation and lactation

At the initiation of the experiment (d 27), there were no differences ($P > 0.10$) among 4 different feeding levels in terms of predicted protein and fat mass (Table 3-7). At the end of gestation (d 109) and post-farrowing, sows on 1.0M, 1.5M and 2.0M feeding levels had greater ($P < 0.01$) protein and fat mass than those on 0.5M feeding level. However, sow predicted protein mass at weaning was similar ($P > 0.10$) among the 4 feeding level, while predicted fat mass continued to be higher ($P < 0.05$) in sow on 1.5M and 2.0M feeding levels compared with those on 0.5M feeding level. Additionally, gains of sow protein (2.94, 4.05, 4.93 and 5.63 kg, respectively) and fat (3.12, 6.65, 8.75 and 11.23 kg, respectively) mass from d 27 to 109 of gestation increased linearly ($P < 0.01$) with the rise of gestation feeding levels. In contrast, protein mass gain (2.24, 1.73, 1.04 and 0.62 kg, respectively) during lactation decreased linearly ($P < 0.01$), while fat mass change (0.80, -0.18, -0.72 and -2.36 kg, respectively) during lactation increased linearly ($P < 0.01$) with the rise of feeding levels during 3 short periods of gestation.

Relationship among sow performance parameters

Gestation BW gain was negatively (r = -0.52, $P < 0.01$, Figure 3-2) correlated with lactation BW gain (Table 3-8). Gestation BF change was inversely (r = -0.49, $P < 0.01$, Figure 3-3) correlated with lactation BF loss. Additionally, ADFI during lactation was negatively (r = -0.35, $P < 0.01$, Figure 3-4) correlated with sow BF thickness at post-farrowing.

For an extra increase of 1 kg sow BW gain during gestation (from d 27 to 109 of gestation), lactation BW gain decreased by 0.51 kg (Table 3-9, Equation 1), while for an extra increase of 1 mm sow BF change during gestation, sow BF loss during lactation increased by 0.27 mm (Equation 2). Additionally, for an extra increase of 1 mm sow BF at post-farrowing, ADFI during lactation decreased by 80 g (Equation 3).

DISCUSSION

Effects of feeding levels on sow performance

Sow BW and BF changes during gestation and lactation

The current experiment demonstrated that increasing feeding levels during 3 short periods of gestation caused a dramatic increase of BW and BF changes during these 3 short periods and from the initiation of the study (d 27 of gestation) to farrowing. The greater BW and BF gains during gestation resulted in less BW gain and higher BF loss during lactation, which was consistent with the previous literature (Baker et al., 1969; Hoppe et al., 1990; YOUNG et al., 1990; Dourmad et al., 1991). Interestingly, most of the aforementioned literature reported that sows lost considerable amount of BW and BF

during lactation. In the present experiment, however, sows from all the gestation feeding levels gained different amount of BW during lactation and the amount of BW gain during lactation was inversely proportional to BW gain during gestation. It was estimated from the current study that sow BW gain during lactation decreased by 0.51 kg for an extra kg of BW gain during gestation. Similarly, Dourmad et al. (1991) also illustrated an inverse relationship between gestation BW gain and lactation BW loss and found that every extra kg of BW gain during gestation was associated with 0.46 kg of lactation BW loss. It should also be noted that lactation BF loss increased linearly with the rise of feeding levels during 3 short periods of gestation, despite the fact the lactation BW increased in all dietary treatment, which indicated the limitation of the feeding strategy based only on the target of BW gain (Dourmad et al., 1991).

An apparent reduction of slope in the gestation BW gain from d 27 to 109 of gestation (8.62 kg/0.5M change vs. 5.88 kg/0.5M change) occurred at 1.0M feeding levels. This suggests that feed utilization for BW gain was more efficient at 1.0M feeding level than higher feeding levels. One possible explanation for the apparent decrease of feed utilization for sow BW gain in higher feeding levels may be that maternal fat synthesis may have increased relative to protein synthesis when feeding levels exceeded 1.0M.

BW changes during 3 short periods increased linearly with the rise of feeding level. By extrapolation of BW changes to zero based on the equations from Table 3, 1.20M, 0.66M and 0.65M feeding levels were needed to maintain a constant BW during these 3 short periods, respectively. These results indicate that the current maintenance energy requirement of gestation sows may be underestimated or overestimated depending on

gestation periods and the maintenance energy requirement may not be constant during gestation periods. More detailed research is needed to warrant this finding.

Lactation feed intake

Numerous studies have demonstrated the negative relationship between gestation feeding levels and lactation feed intake (Baker et al., 1969; Dourmad et al., 1991; Weldon et al., 1994). It was suggested that the decrease of lactation feed intake was associated with the increased body composition, especially BF thickness at farrowing (Dourmad et al., 1991). It was estimated from the present study that for 1 mm more BF thickness at farrowing, average daily feed intake during lactation decreased by 80 g. Dourmad et al. (1991) reported that the reduction of lactation feed intake in response to BF thickness at farrowing was most pronounced during the first week of lactation and estimated that the relationship between backfat thickness at farrowing and lactation feed intake to be -95 $g \cdot d^{-1} \cdot mm^{-1}$ during the first week of lactation and -63 $g \cdot d^{-1} \cdot mm^{-1}$ during the entire lactation period. Similarly, it was reported that the inverse relationship between average daily feed intake and BF thickness at farrowing was remarkable for multiparous sows (-129 $g \cdot d^{-1} \cdot mm^{-1}$), while the inverse relationship was not evident in the primiparous sows (-18 $g \cdot d^{-1} \cdot mm^{-1}$), suggesting that the relationship between lactation feed intake and BF thickness at farrowing may be dependent on the parity. Indeed, a recent publication from our lab confirmed this hypothesis and revealed that with the increase of parity, the inverse relationship between average daily feed intake and BF thickness at farrowing was 60-120 $g \cdot d^{-1} \cdot mm^{-1}$ (Kim et al., 2015). The mechanism regarding the inverse relationship between lactation feed intake and BF thickness at farrowing is not well understood. It was suggested by Weldon et al. (1994a) that reduction of lactation feed intake may be

attributed to the low plasma insulin concentration. Indeed, exogenous insulin administration in lactation increased lactation feed intake during the infusion period, and this effect was more pronounced for sows fed generously during gestation than sows fed restrictedly (Weldon et al., 1994a). Another explanation for the lower lactation feed intake could be the higher non-esterified fatty acid (NEFA) in the fat sows compared with thin sows (Weldon et al., 1994a; Weldon et al., 1994b). It was reported that plasma NEFA concentration at d 1 postpartum was negatively correlated with lactation feed intake at d 1 postpartum (Trottier and Easter, 1995). Increased insulin concentration in sows fed restrictedly in gestation may attenuate the release of NEFA from adipose tissue. It was known that insulin could decrease lipolysis and increase lipogenesis (Hadley, 1988), as well as reducing the activity of carnitine palmitoyltransferase I (Gamble and Cook, 1985), suggesting that oxidation of NEFA may be reduced. Therefore, insulin could increase lactation feed intake in two ways: the first way could be that higher circulating insulin may increase the peripheral glucose usage and thus more feed intake was required for maintaining blood glucose concentration; the other one could be the inhibition of mobilization of adipose tissue and oxidation of NEFA. In contrast with the aforementioned literature and the current study, Cromwell et al. (1989) reported that lactation feed intake was not affected by gestation feeding levels, even though the sows receiving more feed during gestation gained more BW during gestation and lost more BW during lactation in comparison with the sows receiving less feed during gestation. The inconsistent results may be ascribed to different feeding strategies. In the study conducted by Cromwell et al. (1989), additional feed was only provided during the last 23 d of gestation and the results showed that sows receiving extra feed had more live pigs

at farrowing and the piglets were heavier at birth, indicating that the increase of BW during the last 23 d of gestation for sows receiving extra feed was mainly occurred in the fetal tissues (Elsley, 1968). Therefore, maternal body reserve, especially BF at farrowing, was not affected by additional feed during the last 23 d of gestation, possibly rendering the lactation feed intake not affected by gestation treatments.

Wean to estrus interval

In the present study, wean to estrus interval was not affected by feeding levels during 3 short periods of gestation. Yang et al. (1989) and Whittemore (1996) suggested that both the amount of body reserves at farrowing and weaning and their mobilization during lactation affected return to estrus. It was probable that the differences of BF thickness at farrowing and weaning among 4 feeding levels were not dramatic enough to trigger different activity of ovarian. Indeed, the existence of a critical amount of adipose and/or muscle tissue was necessary for the normal ovarian activity (Mullan and Williams, 1989; Dourmad et al., 1991). There was good evidence that, in the present study, predicted body protein mass of sows all increased during lactation, which may render similar wean to estrus intervals among the 4 feeding treatments. Additionally, it was likely that the degrees of BF mobilization during lactation among the 4 feeding treatments were not severe enough to differentiate its effect on return to estrus.

Effects of feeding levels on litter performance

Litter performance in the first reproductive cycle

The current experiment showed that the numbers of piglets born total, alive and at weaning were not different among different feeding levels during 3 short periods of gestation, which agreed with the reported literature (Lodge et al., 1966; Baker et al., 1969; Whittemore et al., 1988; Dourmad et al., 1991; Weldon et al., 1994a). However, some researchers have reported that increased gestation feeding levels (or energy intake) had adverse effects on the number of live born piglets at birth and/or weaning (Buitrago et al., 1974; Libal and Wahlstrom, 1977; Gonçalves et al., 2016). It could be speculated that higher energy intake or feeding levels during gestation may increase the clearance rate of progesterone and thus resulted in lower circulating progesterone concentration (Prime and Symonds, 1993), which may be responsible for the reduction of embryo survival and eventually fewer liveborn piglets.

Being consistent with the results of Lodge et al. (1966), Baker et al. (1969), Elsley et al. (1969) and Cromwell et al. (1989), the current experiment demonstrated a linear increase of piglet birth weight in response to the rise of feeding levels during 3 short periods of gestation. Interestingly, gestation length was reduced in the lowest feeding level. One may wonder the reduced gestation length in the lowest feeding level may be responsible for the reduced piglet birth weight. When adjusted for the gestation length, however, birth weight of piglets from sows on the lowest feeding level still tended to be lower compared with the piglets from sows on the other three feeding levels, indicating that gestation feeding levels exerted its effects on fetal development. It was reported that malnutrition could elevate cortisol concentration in both maternal and fetal serum (Dwyer and Stickland, 1992). It was likely that sows on the lowest feeding level had higher maternal and fetal serum cortisol concentrations, which may stimulate the placenta to secrete

relatively more estrogen and less progesterone, resulting in the decrease of gestation length (Wood and Keller-Wood, 1991). However, piglet weaning weight was not different among the 4 gestation feeding levels, indicating that milking capacity was not affected by gestation feeding levels.

In this present study, within-litter variations of piglets born alive at birth and weaning were similar among the 4 feeding levels. With the genetic selection progress in litter size of sows, the variation of piglet birth weight within litter has been increased (Merks, 2000). It was also reported that the increased percentage of low birth weight piglets, due to the increased heterogeneity of piglet weight within-litter, was responsible for the higher mortality rate of piglets (Lund et al., 2002). Therefore, nutritional strategies attempting to improve uniformity of piglets within litter is promising in terms of enhanced economic return. The results of the current experiment suggested that different feeding levels during 3 short periods of gestation was not able to differentiate the fetal development, probably affected by placental vascularization and efficiency (Ford, 1997; Biensen et al., 1998).

Subsequent reproductive performance

There were no differences among the 4 previous gestation feeding levels in terms of subsequent reproductive performance. This suggests that there is no evidence for the long-term impact or carry-over effect of previous gestation feeding levels on the subsequent reproductive performance, as in the subsequent reproductive cycle, sows were managed under standard farm procedures.

To our best knowledge, this was the first study evaluating different feeding levels during 3 short periods of gestation on sow and litter performance and its impact on the subsequent reproductive performance. It was found, in the current experiment, that 1.20M, 0.66M and 0.65M feeding levels were needed to maintain a constant BW during these 3 short periods, respectively, suggesting that the current NRC (2012) maintenance energy requirement may be underestimated or overestimated depending on the gestation periods and the maintenance energy requirement may not be constant during gestation periods. This hypothesis was further supported by the fact that sows on 1.0M feeding level throughout gestation gained considerable amount of BW with limited increase of BF thickness.

CONCLUSION

Increasing feeding levels during 3 short periods of gestation increased BW and BF gains during gestation and caused less BW gain and more BF loss during lactation due to the reduction of lactation feed intake in response to increasing gestation feeding levels. Increasing feeding levels during 3 short periods of gestation increased piglet birth weight, but did not affect piglet weaning weight. The feeding strategies in the current reproductive cycle did not impact subsequent reproductive performance. The data indicated that the current maintenance energy requirement of gestation sows may be underestimated or overestimated depending on gestation periods.

Table 3-1. Ingredient and nutrient composition of experimental diets for gestation and lactation (as-fed basis)

Item	Gestation	Lactation
Ingredient, %		
Corn	65.22	61.15
Soybean meal	10.00	17.20
cDDGS[1]	20.00	15.00
Choice white grease	1.50	3.00
Limestone	1.00	0.88
Dicalcium phosphate	1.20	1.15
Lysine HCl (78%)	0.10	0.46
DL-Methionine	-	0.01
L-Threonine	-	0.13
L-Tryptophan	-	0.04
Salt	0.35	0.35
Premix[2]	0.50	0.50
Tylan[3]	0.13	0.13
Nutrient composition		
ME, [4] kcal/kg	3,310	3,424
CP, [5] %	15.71	17.92
Total Ca, [5] %	0.72	0.68
STTD[6] P, [4] %	0.35	0.35
SID[7] Lys, [4] %	0.57	1.01
SID Met + Cys, [4] %	0.47	0.52
SID Thr, [4] %	0.44	0.64
SID Trp, [4] %	0.12	0.19

[1]cDDGS = corn distillers dried grains with solubles.

[2]Supplied the following nutrients per kilogram of diets: vitamin A, 12,114 IU; vitamin D, 2,753 IU; vitamin E, 66 IU; vitamin K, 4.4 mg; thiamine, 1 mg; riboflavin, 10 mg; niacin, 55 mg; pantothenic acid, 33 mg; pyridoxine, 2.2 mg; folic acid, 1.6 mg; vitamin B_{12}, 0.06 mg; I, 0.5 mg from ethylenediamine dihydriodide; Se, 0.3 mg from sodium selenite; choline, 548 mg from choline chloride; and metal polysaccharide complexes of zinc sulfate (125 mg of Zn), iron sulfate (125 mg of Fe), manganese sulfate (40 mg of Mn), and copper sulfate (15 mg of Cu).

[3]Tylan™ 40 (Tylosin phosphate 40), Elanco Animal Health, Indianapolis, IN.

[4]Calculated values according to NRC (2012).

[5]Analyzed values.

[6]STTD = standardized total tract digestible; [7]SID = standardized ileal digestible.

Table 3-2. Effects of different feeding levels during three short periods of gestation on sow performance at different time points and during gestation and lactation

	Feeding levels[1]					*P* values[2]			
	0.5M	1.0M	1.5M	2.0M	SEM	Treatment	Linear	Quadratic	Cubic
Number of sows	38	36	43	39					
Average parity	5.32	5.57	5.51	5.21					
Sow BW, kg									
d 27	220.88	221.29	222.32	222.31	4.35	0.80	0.40	0.81	0.88
d 55	224.54	226.94	228.16	229.90	4.02	0.05	<.01	0.74	0.75
d 83	229.85	234.55	236.71	240.32	4.06	<.01	<.01	0.82	0.51
d 109	236.94	245.93	252.72	258.35	4.18	<.01	<.01	0.42	0.82
Post-farrowing	227.13	237.09	241.28	248.10	4.33	<.01	<.01	0.57	0.34
Weaning	241.43	246.80	248.72	251.46	4.35	0.01	<.01	0.73	0.64
Sow BF, mm									
d 27	14.95	14.58	14.61	15.49	0.58	0.56	0.40	0.19	0.90
d 55	15.16	15.51	15.27	16.08	0.66	0.70	0.19	0.58	0.58
d 83	15.30	16.44	16.15	17.10	0.72	0.29	0.03	0.90	0.50
d 109	14.76	15.85	16.03	17.85	0.77	0.02	<.01	0.42	0.76
Post-farrowing	13.98	15.55	15.78	17.53	0.74	<.01	<.01	0.64	0.51
Weaning	13.14	14.32	14.84	15.95	0.60	<.01	<.01	0.94	0.80
Gestation BW change[3], kg	16.12	24.74	30.62	36.71	2.30	<.01	<.01	0.34	0.62
Gestation BF change[4], mm	-0.27	0.99	1.49	2.45	0.93	<.01	<.01	0.69	0.48
Lactation BW change, kg	14.31	9.84	7.09	3.50	1.84	<.01	<.01	0.77	0.70
Lactation BF change, mm	-0.79	-0.92	-1.12	-1.57	0.40	0.10	0.05	0.50	0.19
Lactation ADFI[5], kg	7.05	7.00	6.91	6.52	0.22	0.10	0.09	0.20	0.25

Net BW change[6], kg	21.16	25.36	26.17	29.66	1.86	<.01	<.01	0.82	0.39
Net BF change[7], mm	-1.79	-0.31	0.27	0.56	0.50	<.01	<.01	0.03	0.62
Wean to estrus interval, d	4.98	4.96	4.96	4.85	0.12	0.78	0.38	0.63	0.76

[1]0.5M, 1.0M, 1.5M and 2.0M represented 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (100 × $BW^{0.75}$ kcal $ME \cdot d^{-1}$), respectively.

[2] Probability of effect of feeding levels using analysis of variance and probability of linear, quadratic and cubic effects of increasing feeding levels using orthogonal polynomial contrasts.

[3]Weight change from d 27 to d 109 of gestation.

[4]Backfat change from d 27 to d 109 of gestation.

[5]Lactation length was used as a covariate in the statistical model.

[6]Weight change from d 27 of gestation to weaning.

[7]Backfat change from d 27 of gestation to weaning.

Table 3-3. Effects of different feeding levels during three short periods of gestation on sow performance during three periods of gestation

	Feeding levels[1]					*P* values[2]			
Item	0.5M	1.0M	1.5M	2.0M	SEM	Treatment	Linear	Quadratic	Cubic
Number of sows	38	36	43	39					
Average parity	5.32	5.57	5.51	5.21					
Period 1 (d 27-34)									
BW change, kg[3]	-6.29	-1.16	2.60	8.22	0.79	<.01	<.01	0.80	0.20
BF change, mm	-0.08	0.63	0.68	0.93	0.24	0.01	<.01	0.37	0.41
ADG, kg	-0.88	-0.16	0.36	1.15	0.10	<.01	<.01	0.74	0.20
Feed intake, kg	6.43	12.59	18.66	24.64	0.52	<.01	<.01	0.61	0.98
Gain to Feed, kg:kg	-0.99	-0.10	0.14	0.34	0.08	<.01	<.01	<.01	0.04
Period 2 (d 55-62)									
BW change, kg[4]	-1.45	2.79	6.81	10.31	1.06	<.01	<.01	0.82	0.93
BF change, mm	-0.55	0.01	0.68	1.07	0.20	<.01	<.01	0.75	0.73
ADG, kg	-0.22	0.37	0.94	1.44	0.14	<.01	<.01	0.84	0.92
Feed intake, kg	6.52	12.83	19.02	25.27	0.52	<.01	<.01	0.98	0.77
Gain to Feed, kg:kg	-0.26	0.22	0.37	0.42	0.08	<.01	<.01	<.01	0.29
Period 3 (d 83-90)									
BW change, kg[5]	-1.70	3.56	8.25	12.56	0.75	<.01	<.01	0.46	0.90
BF change, mm	-0.17	0.15	0.50	0.98	0.20	<.01	<.01	0.71	0.83
ADG, kg	-0.23	0.47	1.10	1.68	0.10	<.01	<.01	0.50	0.88
Feed intake, kg	7.18	13.72	20.04	26.61	0.56	<.01	<.01	0.60	0.55
Gain to Feed, kg:kg	-0.24	0.26	0.42	0.48	0.06	<.01	<.01	<.01	0.21

[1]0.5M, 1.0M, 1.5M and 2.0M represented 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (100 × $BW^{0.75}$ kcal $ME \cdot d^{-1}$), respectively.

[2] Probability of effect of feeding levels using analysis of variance and probability of linear, quadratic and cubic effects of increasing feeding levels using orthogonal polynomial contrasts.

[3]BW change during period 1 = -10.97 + 4.71 × Feeding level (R^2 = 0.64, MSE = 15.78)

[4]BW change during period 2 = -5.19 + 3.92 × Feeding level (R^2 = 0.37, MSE = 31.60)

[5]BW change during period 3 = -6.15 + 4.73 × Feeding level (R^2 = 0.67, MSE = 13.57)

Table 3-4. Effects of different feeding levels during three short periods of gestation on litter performance

	Feeding levels[1]					*P* values[2]			
Item	0.5M	1.0M	1.5M	2.0M	SEM	Treatment	Linear	Quadratic	Cubic
Number of litters	38	36	43	39					
Litter size									
Liveborn	13.25	12.86	12.94	12.66	0.56	0.86	0.44	0.92	0.71
Stillborn	0.92	1.26	0.97	1.06	0.30	0.58	0.82	0.52	0.22
Mummy	0.42	0.64	0.39	0.15	0.18	0.01	0.01	0.01	0.66
Total born	14.69	15.09	14.46	14.08	0.59	0.58	0.28	0.45	0.58
After cross-fostering	12.85	12.72	12.35	12.45	0.40	0.69	0.30	0.74	0.64
Death	2.26	2.23	1.95	1.71	0.35	0.49	0.13	0.69	0.84
Weaning	10.72	10.57	10.56	10.67	0.26	0.93	0.87	0.53	0.96
Litter wt, kg									
Liveborn	17.51	17.94	18.22	17.86	0.79	0.86	0.62	0.51	0.85
Weaning	67.54	67.32	67.35	68.59	1.86	0.92	0.64	0.63	0.89
Gain	48.46	50.43	49.67	51.10	1.88	0.70	0.32	0.87	0.49
Piglet wt, kg									
Average birth wt	1.32	1.42	1.42	1.44	0.04	0.05	0.02	0.29	0.42
Average birth wt, adjusted[3]	1.33	1.41	1.42	1.44	0.04	0.08	0.02	0.36	0.49
Average wean wt	6.32	6.39	6.40	6.46	0.12	0.82	0.36	0.97	0.78
Piglet ADG, g	244.31	256.52	253.49	255.23	5.47	0.26	0.16	0.27	0.34
Piglet pre-weaning mortality	0.18	0.18	0.16	0.14	0.02	0.31	0.07	0.53	0.86
Gestation length, d	114.92	115.82	115.40	115.44	0.23	0.02	0.19	0.03	0.05
Lactation length, d	20.49	19.44	19.72	19.79	0.24	<0.01	0.04	0.01	0.08

[1]0.5M, 1.0M, 1.5M and 2.0M represented 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (100 × $BW^{0.75}$ kcal ME·d^{-1}), respectively.

[2] Probability of effect of feeding levels using analysis of variance and probability of linear, quadratic and cubic effects of increasing feeding levels using orthogonal polynomial contrasts.

[3]Gestation length was used as a covariate in the statistical model.

Table 3-5. Effects of different feeding levels during three short periods of gestation on piglet weight variation within litter at birth and weaning

	Feeding levels					
Item	0.5M	1.0M	1.5M	2.0M	SEM	*P* values
Number of litters	6	6	6	6		
Coefficient of variation of piglet weights within litter, %						
Piglets born alive	23.68	21.48	22.87	23.30	2.99	0.96
Piglets at weaning	13.03	15.56	17.73	15.83	2.30	0.44

[1]0.5M, 1.0M, 1.5M and 2.0M represented 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (100 × $BW^{0.75}$ kcal $ME \cdot d^{-1}$), respectively.

[2] Probability of effect of feeding levels using analysis of variance and probability of linear, quadratic and cubic effects of increasing feeding levels using orthogonal polynomial contrasts.

Table 3-6. Effects of different feeding levels during three short periods of gestation on subsequent litter performance

	Feeding levels					*P* values			
Item	0.5M	1.0M	1.5M	2.0M	SEM	Treatment	Linear	Quadratic	Cubic
Number of litters	33	25	35	32					
Litter size									
Liveborn	12.40	12.82	13.19	12.46	0.58	0.63	0.81	0.25	0.65
Weaning	10.36	10.13	10.59	10.39	0.35	0.73	0.66	0.96	0.30
Litter wt, kg									
Liveborn	17.30	18.43	19.04	17.93	0.73	0.21	0.36	0.08	0.68
Weaning	64.35	65.16	66.20	66.24	2.62	0.21	0.48	0.86	0.90
Piglet wt, kg									
Liveborn	1.41	1.47	1.46	1.46	0.04	0.64	0.39	0.38	0.75
Weaning	6.21	6.41	6.20	6.33	0.16	0.62	0.80	0.81	0.20
Piglet ADG, g	248	259	245	253	7.41	0.43	0.99	0.79	0.10

[1]0.5M, 1.0M, 1.5M and 2.0M represented 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (100 × $BW^{0.75}$ kcal ME·d^{-1}), respectively.

[2] Probability of effect of feeding levels using analysis of variance and probability of linear, quadratic and cubic effects of increasing feeding levels using orthogonal polynomial contrasts.

Table 3-7. Effects of different feeding levels during three short periods of gestation on predicted sow body compositions

	Feeding levels[1]					*P* values[2]			
	0.5M	1.0M	1.5M	2.0M	SEM	Treatment	Linear	Quadratic	Cubic
Number of sows	38	36	43	39					
Average parity	5.32	5.57	5.51	5.21					
Estimated protein mass, kg[3]									
d 27	35.01	35.36	35.23	35.01	0.58	0.54	0.88	0.15	0.66
d 109	37.95	39.48	40.04	40.59	0.68	<.01	<.01	0.13	0.50
Post-farrowing	36.29	37.77	38.03	38.80	0.66	<.01	<.01	0.22	0.20
Weaning	38.74	39.52	39.30	39.61	0.70	0.20	0.10	0.44	0.28
Change from d 27 to 109	2.94	4.05	4.93	5.63	0.31	<.01	<.01	0.39	0.96
Change during lactation	2.24	1.73	1.04	0.62	0.29	<.01	<.01	0.85	0.66
Estimated fat mass, kg[4]									
d 27	40.98	40.36	40.61	41.88	1.49	0.64	0.46	0.28	0.97
d 109	44.36	46.99	49.70	53.27	2.39	<.01	<.01	0.68	0.88
Post-farrowing	41.27	44.77	46.81	51.04	2.22	<.01	<.01	0.73	0.47
Weaning	42.08	44.60	46.10	48.68	1.67	<.01	<.01	0.95	0.65
Change from d 27 to 109	3.12	6.65	8.75	11.23	1.66	<.01	<.01	0.42	0.54
Change during lactation	0.80	-0.18	-0.72	-2.36	0.86	<.01	<.01	0.52	0.69

[1]Feeding levels included 0.5, 1.0, 1.5 and 2.0 × maintenance energy intake level (100 × $BW^{0.75}$ kcal ME·d^{-1}).

[2] Probability of effect of feeding levels using analysis of variance and probability of linear, quadratic and cubic effects of increasing feeding levels using orthogonal polynomial contrasts.

[3]Protein mass was estimated using the equation from Dourmad et al. (1997): 2.3 + 0.178 × empty BW (kg) − 0.33 × BF depth (mm); empty BW = 0.905 × $(BW)^{1.013}$.

[4]Fat mass was estimated using the equation from Dourmad et al. (1997): -26.40 + 0.221 × empty BW (kg) + 1.33 × BF depth (mm); empty BW = 0.905 × $(BW)^{1.013}$.

Table 3-8. Pearson correlation coefficients among sow performance parameters

	Gestation BW gain	Gestation BF change	Lactation BW change	Lactation BF loss	BF at farrowing	ADFI during lactation
Gestation BW gain	1.00					
Gestation BF change	0.48**	1.00				
Lactation BW change	-0.52**	-0.36**	1.00			
Lactation BF loss	-0.27*	-0.49**	0.54**	1.00		
BF at farrowing	0.46**	0.53**	-0.52**	-0.67**	1.00	
ADFI during lactation	-0.19*	-0.11	0.37**	0.31*	-0.35**	1.00

**represented probability of < 0.001, *represented probability of < 0.01.

Table 3-9. Relationship between BW (kg) and BF (mm) changes during gestation and BW change and BF loss during lactation, and effect of BF at farrowing on lactation ADFI (kg)

Equation number	Equations	R^2	Root MSE
1	Lactation BW change = 22.36 - 0.51 × Gestation BW gain	0.26	9.57
2	Lactation BF loss = -0.76 - 0.27 × Gestation BF change	0.23	1.38
3	Lactation ADFI = 8.18 - 0.08 × BF at farrowing	0.12	1.02

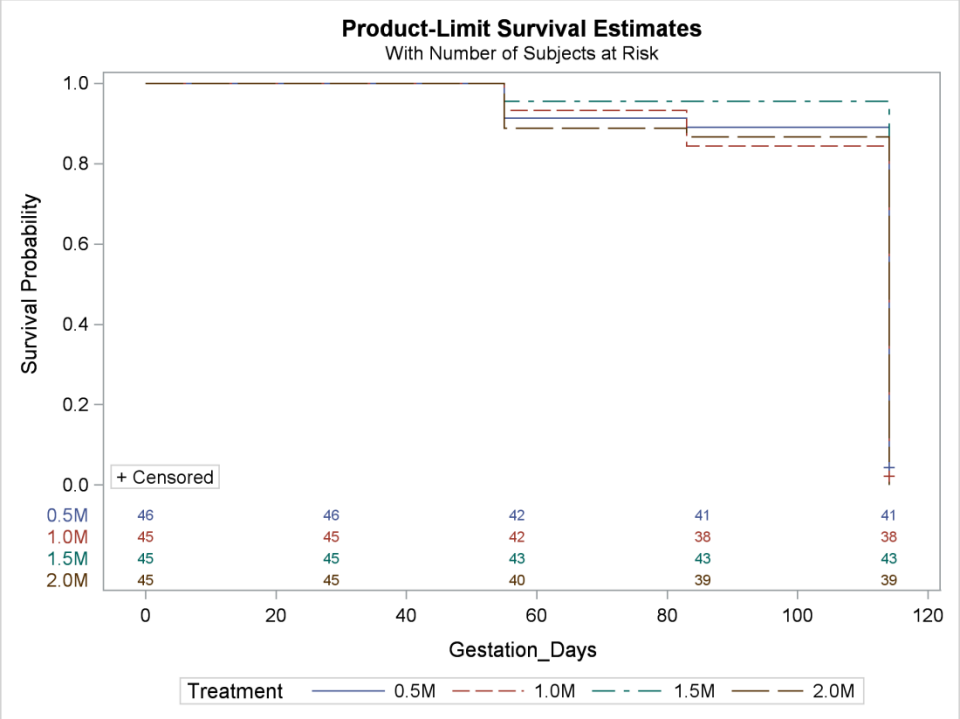

Figure 3-1. Estimated survival curves for sows on 4 different feeding levels (0.5M, 1.0M, 1.5M and 2.0M) during 3 short periods of gestation. Multiple comparison among 4 feeding levels showed no significant differences ($P = 0.50$).

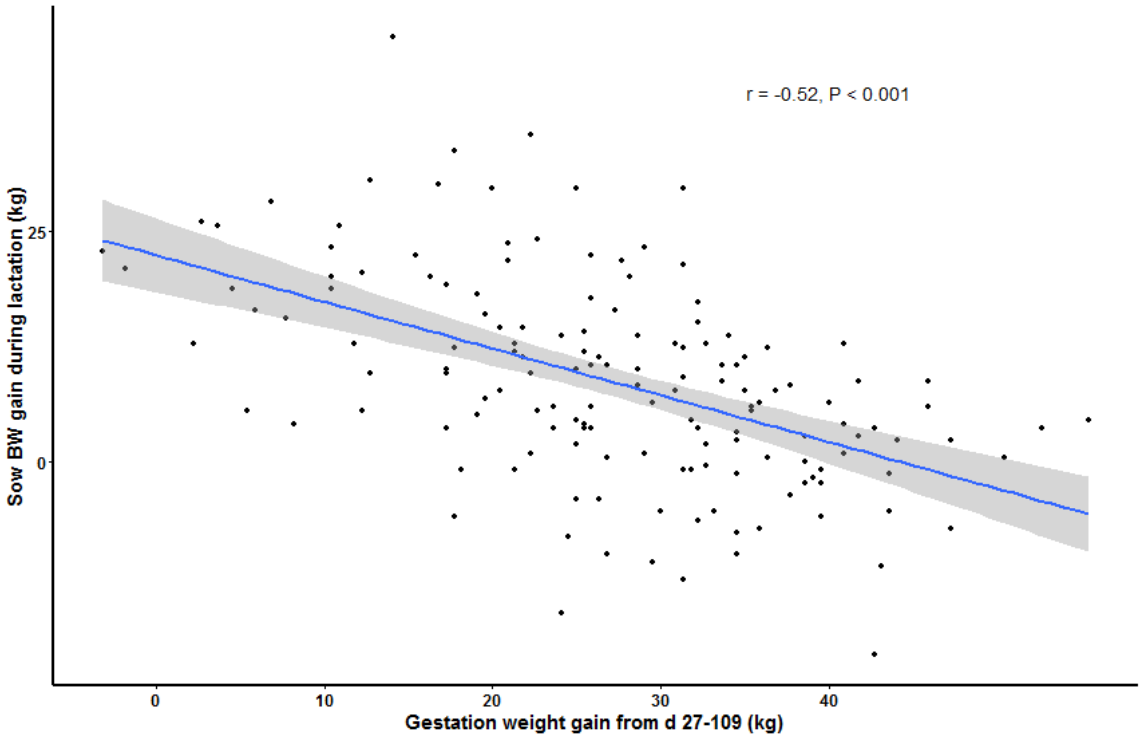

Figure 3-2. Relationship between gestation weight gain from d 27 to 109 of gestation and sow BW gain during lactation (r = -0.52, *P* < 0.001). The blue line indicated the linear relationship and the gray area represented the 95% confidence interval.

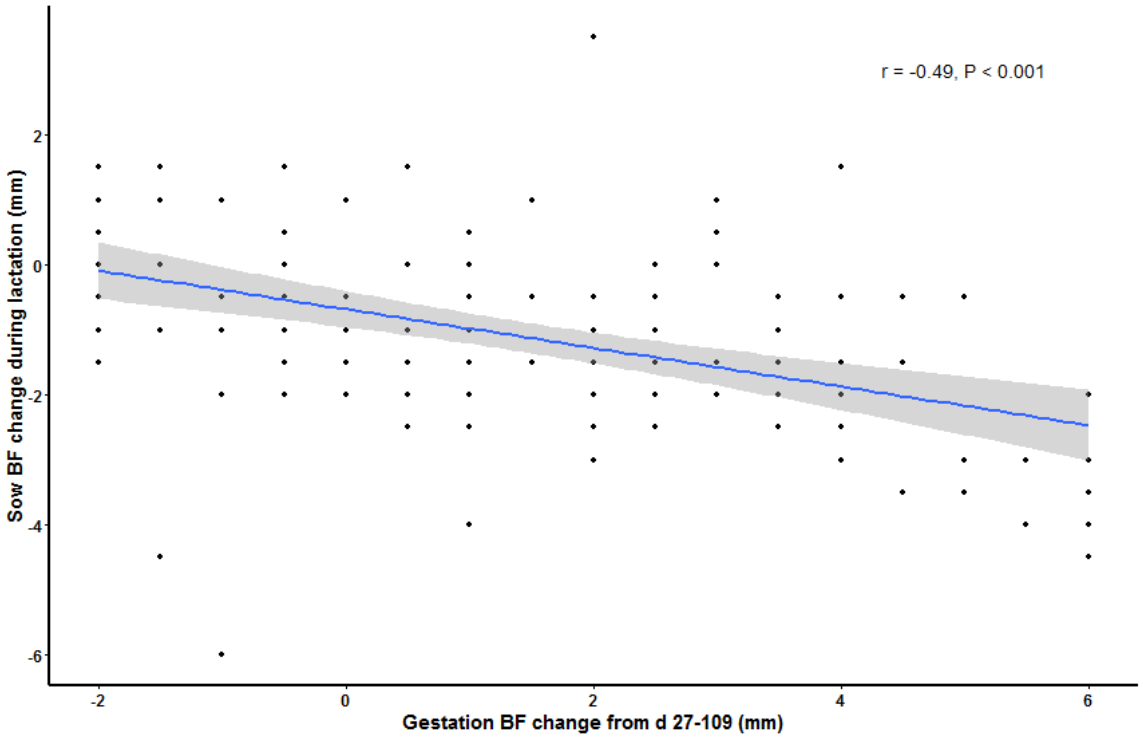

Figure 3-3. Relationship between gestation BF change from d 27 to 109 of gestation and sow BF change during lactation (r = -0.49, *P* < 0.001). The blue line indicated the linear relationship and the gray area represented the 95% confidence interval.

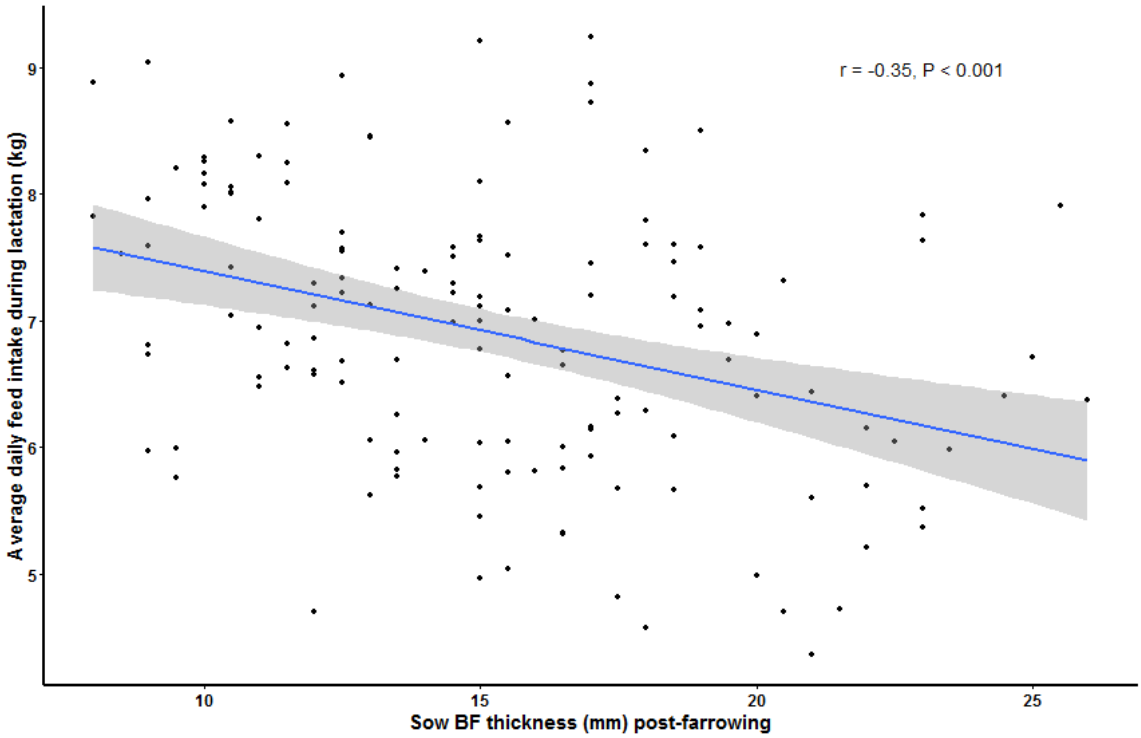

Figure 3-4. Relationship between sow BF thickness post-farrowing and average daily feed intake during lactation (r = -0.35, *P* < 0.001). The blue line indicated the linear relationship and the gray area represented the 95% confidence interval.

Chapter 4. Effects of different feeding levels during three short periods of gestation on gilt and litter performance, nutrient digestibility and plasma hormones related to energy homeostasis in gilts

SUMMARY

The present study investigated the effects of different feeding levels during 3 short periods of gestation on gilt and litter performance, apparent total tract digestibility (**ATTD**) of energy and nutrients, and plasma hormones related to energy homeostasis in gilts. A total of 18 gilts were allotted to 1 of 3 dietary treatments using a completely randomized design. All gilts were fed one common corn-soybean meal-based diet with the amount of 1.0 × maintenance energy intake (100 × BW $(BW)^{0.75}$ kcal ME/d) throughout gestation except 3 periods of 7 d when dietary treatments were imposed on d 27, d 55 and d 83 of gestation. During the 3 short periods, gilts were fed 1 of 3 different feeding levels: 0.5, 1.0 and 2.0 × maintenance energy level (0.5M, 1.0M and 2.0M, respectively). Results showed that gilts on 2.0M feeding level had higher ($P < 0.05$) weight gain from d 27 to 109 of gestation (37.05 vs. 15.34 kg) and greater ($P < 0.05$) BW change, average daily gain and gain to feed ratio during gestation periods 1 (d 27-34) and 3 (d 83-90) when compared with gilts on 0.5M feeding level. No differences ($P > 0.10$) in litter performance were observed among the 3 feeding levels. The slopes of BW change in response to feeding levels in period 1 were 4.32 kg/0.5M change from 0.5M to 1.0M feeding level and 3.72 kg/0.5M change from 1.0M to 2.0M feeding level, respectively. There were quadratic ($P < 0.05$) effects of feeding levels on ATTD of dry matter and gross energy during periods 1 and 2 (d 55-62). In addition, there were significant

interactions between feeding levels and gestation periods for ATTD of dry matter (P = 0.02), gross energy (P = 0.01) and neutral detergent fiber (P = 0.04), which, for the 0.5M and 1.0M feeding levels, decreased with the advancement of gestation periods, but, for the 2.0M feeding level, reduced in period 2 and then increased in period 3 to levels greater than period 1. Furthermore, fasting plasma concentrations of acyl ghrelin and non-esterified fatty acid (NEFA) in period 1 were greater (P < 0.01) in gilts on 0.5M feeding level than those on 2.0M feeding level. In conclusion, increasing feeding levels during 3 short periods increased primiparous sow performance during these short periods but did not affect litter performance. ATTD of energy and nutrients, and BW change efficiency were maximized for gilts on 1.0 M feeding level. The data also indicated that sows on the lowest feeding level were exposed to negative energy balance as evidenced by the higher plasma acyl ghrelin and NEFA concentrations.

KEYWRODS: Feeding levels, gilt, nutrient, digestibility, energy homeostasis

INTRODUCTION

Two-thirds of sows' lifetime are spent in gestation, which indicates that a better understanding of nutrient utilization and the mechanism how nutritional strategies could improve nutrient utilization would guarantee an improved reproductive efficiency and better economic return. Among the nutritional strategies, changing feeding levels during gestation could be an easy management practice which does not need more labor input. In the past several decades, numerous studies have been conducted to evaluate the effects of feeding levels during certain period of gestation (Cromwell et al., 1989; Heo et al., 2008; Hoving et al., 2011) or whole gestation (Dourmad, 1991; Mahan, 1998) on gilt/sow and

litter performance in one or several reproductive cycles. However, we are not aware of any research of investigating effect of imposing different feeding levels during several short periods of gestation on gilt and litter performance. Therefore, one objective of this study was to determine the effects of feeding levels during 3 short periods of gestation on gilt and litter performance.

Previous research have yielded inconsistent results concerning the effect of feeding levels on the apparent digestibility of energy and nutrients (Mroz et al., 1994; Smits et al., 1994; Morel et al., 2006; García-Valverde et al., 2008; Goerke et al., 2014). These inconsistent finding may be attributed to the factors such as feeding level, level and source of dietary fiber and animal body size (Van Es, 1982). In our current experiment, we aimed to identify a relationship between apparent energy and nutrient digestibility and gilt BW change caused by different feeding levels.

Plasma acyl ghrelin is believed to serve as both a short-term and long-term indicator of energy homeostasis (Ariyasu et al., 2001; Toshinai et al., 2001; M. Tschop et al., 2001; Wren et al., 2001). Leptin and insulin are proportional to animal body fat mass, which plays a critical role in long-term food regulation (Polonsky et al., 1988; Zhang et al., 1994). To our best knowledge, there was limited research concerning the effect of feeding levels on these plasma hormones related to energy homeostasis in pigs and other animals. Therefore, the third objective of this study was to investigate the effect of feeding levels on the plasma hormones related to energy homeostasis.

MATERIALS AND METHODS

Institutional Animal Care and Use Committee of University of Minnesota approved the experimental protocol of this study.

Animals and Management

The present experiment was conducted at the University of Minnesota - Southern Research and Outreach Center, Waseca, MN. Eighteen Large White x Danish Landrace crossbred gilts (TOPIGS 20, TOPIGS Inc., Winnipeg, Manitoba, Canada) were used in this study and kept in the individual stalls (2.1 m length x 0.6 m width x 0.6 m height) throughout gestation. All gilts were fitted with cephalic vein catheters according to procedures described by Moehn et al. (2004). Briefly, a catheter was tunneled under the skin from the incision site to a point of exit on the shoulder where an access port was connected with the catheter. After surgery, gilts were treated with analgesic and antibiotics, allowing 2 wk for recovery. Then all gilts were fed a small portion of feed mixed with 6.8 ml (15 mg Altrenogest) Matrix (Merck Animal Health, NJ, USA) each day; after finishing the small portion of feed, the rest of feed were delivered to the gilts. The Matrix feeding regime was imposed for 2 wks in order to synchronize estrus in the experimental gilts. After withdrawing Matrix, all gilts came to heat in 1 wk. All gilts were bred twice via artificial insemination in 2 consecutive days. After breeding, gilts were randomly allotted to 1 of 3 dietary treatments. Pregnancy check was conducted in

all these bred gilts around d 35 of gestation. Another pregnancy check was conducted 2 wk later on these gilts to confirm the pregnancy. During gestation, all gilts were fed their respective gestation diets with different amounts of feed on different periods of gestation. On d 109 of gestation, gilts were moved into the farrowing rooms with environment controlled systems and housed in individual farrowing crates (2.13 m length × 0.66 m width × 0.97 m height). All gilts were fed 2.27 kg lactation diets beginning from d 109 to the date of farrowing. After parturition, the amount of feed was increased gradually to allow for *ad libitum* feed intake from d 5 until weaning at about d 19 of lactation. After weaning, gilts were moved to the environmental controlled gestation room with individual stalls. Estrus was checked on the daily basis.

Dietary Treatments, Experimental Design and Sample Collection

At d 27 of gestation, gilts were randomly allotted to 1 of 3 experimental treatments. The experiment started from d 27 of gestation throughout the gestation and lactation period. All gilts were fed one common corn-soybean meal-based basal diet (Table 4-1) with the amount of 1.0 × maintenance energy intake (100 × $BW^{0.75}$ kcal ME/d, NRC, 2012) throughout the gestation period except 3 periods of 7 d dietary treatments imposing at d 27, d 55 and d 83 gestation. During these 3 periods, gilts were fed 1 of 3 different feeding levels based on maintenance energy intake: 1) 0.5 × maintenance level (0.5M); 2) 1.0 × maintenance level (1.0M); 3) 2.0 × maintenance level (2.0M). Gestation diet and lactation diet (Table 4-1) met or exceeded NRC (2012) nutrient recommendations.

On each of the 3 short periods, all experimental gilts were fed the same gestation diet containing 0.3% titanium dioxide. The first 5 d was considered as adaptation period and

followed by 2 d for fecal sample collection. Grab sampling for the feces was conducted on the last 2 d of each period. The fecal samples were stored at -20 ^{o}C immediately after collection. At the end of sample collection, fecal samples within each gilt within each period were thawed and pooled together and a subsample was taken for chemical analysis. Fecal samples were dried in the oven (Thermo Scientific Precision, Thermo Fisher Scientific Inc., Hampton, New Hampshire**)** with the temperature of 65 ^{o}C for 48 h, and then ground through 1 mm screen, and thoroughly mixed before a subsample was collected for chemical analysis.

Gilt and Litter Data Collection

Gilt BW was recorded and BF thickness was measured using ultrasonic detection machine (Preg-Alert Pro, Renco Corp., Minneapolis, USA) on both the left and right sides at the P2 position (6.5 cm from the dorsal mid-line at the level of the last rib) on d 27, 34, 55, 62, 83, 90, 109 of gestation, within 24 h after farrowing and at weaning to measure the BW and BF change during gestation and lactation periods. During lactation, litter size (number of total piglets born, born alive, after cross-fostering and at weaning) and piglet deaths were recorded. Litter weight at birth, after cross-fostering and at weaning was also recorded. Feed intake was recorded on daily basis until weaning. Preweaning mortality of piglets within litter was calculated using the live born piglets died before weaning divided by the number of live born piglets. Litter weight gain and piglet average daily gain (**ADG**) were also calculated. Average daily feed intake (**ADFI**) was calculated using the summation of daily feed intake divided by the length of lactation period.

Chemical Analysis

All analyses were conducted in duplicate. The gestation diet and fecal samples were analyzed for dry matter (DM, method 934.01; AOAC, 2006), ether extract (EE, method 920.39; AOAC, 2006), Crude protein (CP, method 984.13; AOAC, 2006), neutral detergent fiber (**NDF**, method 973.18; AOAC, 2006) and acid detergent fiber (**ADF**, method 973.18; AOAC, 2006) at University of Minnesota's Southern Research and Outreach Center. Gestation diet and fecal samples were analyzed for gross energy (**GE**) via adiabatic oxygen bomb calorimeter (Parr Instruments, Moline, IL). Concentrations of calcium (method 958.01; AOAC, 2006), phosphorus (method 958.01; AOAC, 2006) and amino acid (method 982.30; AOAC, 2006) were analyzed in Experiment Station Chemical Laboratories (University of Missouri, Columbia, MO). Titanium concentration in the gestation diet and fecal samples was analyzed according to the procedures described by Myers et al. (2004).

Blood Collection and Plasma Analysis

During period 1 (d 27-34 of gestation), blood samples for all gilts were collected via cephalic vein catheters right before feeding (7:30 am) on the 7th day of each period. Before blood collection, 50 µl dipeptidyl peptidase-IV inhibitor (EMD Millipore, MA, US) and 180 µl 4-(2-Aminoethyl) benzenesulfonyl fluoride hydrochloride (AEBSF) (100 mM, Sigma-Aldrich, MO, USA) were added to the blood collection tubes. Blood samples (6 ml) were added to the chilled collection tubes containing K_3EDTA as an anticoagulant and the contents were gently mixed to make sure the added chemicals were equally distributed in the blood. After gentle mixing, the tubes were centrifuged at 2500 rpm for

15 min. After centrifugation, each plasma sample was carefully alloquated to 6 Self-Lock Eppendorf microtubes with 0.5 ml in each microtube. In the microtube for acyl-ghrelin analysis, 10 µl of 6N HCl was added to acidify the plasma to provide additional protection. The plasma samples were snap frozen in the liquid nitrogen and then stored at -80 ^{o}C until analysis for acyl ghrelin, glucaogon-like peptide 1 (**GLP-1**), leptin, insulin, and non-esterified fatty acids (**NEFA**).

Commercial ELISA kits were used for analysis of acyl-ghrelin (EZRGRA-90K, EMD Millipore, MA, USA) and leptin (BG-POR11464, Novateinbio, MA, USA) in plasma. Plasma GLP-1 (7-36) was measured using a commercial fluorescent immunoassay kit (FEK-028-11, Phoenix Pharmaceuticals, Inc., CA, USA). Plasma insulin was analyzed using a commercial radioimmunoassay kit (PI-12K, EMD Millipore, MA, USA). Plasma NEFA was analyzed using the enzymatic colorimetric method (NEFA HR(2), Wako Life Sciences, Inc., VA, USA). The intra-assay CV for the assays were 5.1, 4.5, 2.0 and 7.5% for acyl-ghrelin, GLP-1, leptin and insulin, respectively.

Calculations

The apparent total tract digestibility (**ATTD**) of energy, ether extract, crude protein, NDF and ADF for each gilt in each period was calculated using the equation described by Adeola (2001):

$$\mathrm{ATTD} = \left[1 - \left(\frac{\mathrm{Nutr\ f}}{\mathrm{Nutrd}}\right) \times \left(\frac{\mathrm{Tid}}{\mathrm{Tif}}\right)\right] \times 100\%,$$

where $\mathrm{Nutr_f}$ is the concentration of nutrients (energy, ether extract, crude protein, NDF and ADF) in the fecal samples, $\mathrm{Nutr_d}$ is the concentration of nutrients in the gestation diet,

Ti_d represents titanium concentration in the gestation diet, and Ti_f denotes titanium concentration in the fecal samples.

Statistical Analysis

SAS 9.4 (SAS Inst. Inc., Gary, NC) was used in all data analysis. Individual gilt served as the experimental unit. The LSMEANS statement was used to calculate the least squares means. Tukey-Kramer adjustment was used for multiple comparisons of the least squares means. Covariates was used to adjust the least square means of response and presented as a footnote for each table. Pooled SEM was calculated for each measurement. A probability of $P < 0.05$ was considered as significant and $0.05 < P < 0.1$ was declared as a trend.

The GLIMMIX procedure was used to analyze all the data. Dietary treatment was considered as the fixed effect. Gilt BW and BF measured on d 27, 55, 83, 109, post-farrowing and at weaning were considered as repeated measurements in time. Different covariance structure candidate models were examined and the best fit model was selected for each measurement based on Akaike Information Criterion (**AIC**) and Bayesian Information Criterion (**BIC**) values. Model examination results indicated that first-order ante-dependence (ante(1)) was the best covariance model for either gilt BW or BF measurement. The SLICE option by time was used to test the effect of dietary treatments at each of the different time points.

Gilt BW change, BF change, ADG, feed intake and gain to feed ratio during the 3 short periods were also considered as repeated measurements. The best covariance structure

models selected using the aforementioned technique for gilt BW change, BF change, ADG and gain to feed ratio were all heterogenous first-order autoregressive (arh(1)), while Toeplitz (toep) was the best model for feed intake. The SLICE option by period was used to test the effect of dietary treatments at the 3 short periods.

For litter performance, the data of litter weight and average piglet weight at birth and weaning, and average daily gain of piglets were analyzed with the default assumption of normal distribution. Count data, such as number of liveborn, total born, after cross-fostering, death and wean piglets were analyzed using Poisson regression model, while zero-inflated Poisson regression model was used to analyze the numbers of stillborn and mummies. Furthermore, the binomial regression model was used to analyze pre-weaning piglet mortality.

ATTD of energy and nutrients during the 3 short periods were also considered as repeated measurements. The best covariance structure models selected using the aforementioned technique for ATTD of dry matter, gross energy, neutral detergent fiber and acid detergent fiber were all first-order autoregressive (ar(1)), while arh(1) was the best model for ATTD of crude protein and ether extract. The SLICE option by period was used to test the effect of dietary treatments at the 3 short periods. For plasma hormone parameters, the data were analyzed with the default assumption of normal distribution.

RESULTS

Effect of feeding levels on gilt and litter performance

At the initiation of the experiment (d 27 of gestation), there were no differences in gilt BW and BF thickness ($P = 0.75$) among the 3 different feeding levels (Table 4-2). Throughout gestation and lactation periods, gilt BW and BF measurements at d 55, 83, 109, post-farrowing and weaning were not significant different ($P > 0.10$) among the 3 different feeding levels. However, gilt BW gain from d 27 to 109 of gestation for gilts on 2.0M feeding level was higher ($P < 0.05$) than gilts on 0.5M feeding level, while there was no difference ($P > 0.10$) between gilts on 0.5M and 1.0M feeding levels in terms of gilt BW gain from d 27 to 109 of gestation. No differences ($P > 0.10$) existed among gilts fed the 3 different feeding levels in terms of gilt BF change from d 27 to 109 of gestation, lactation BW and BF losses, lactation average daily feed intake, gilt net BW and BF changes from d 27 of gestation to weaning and wean to estrus interval.

The results of feeding levels during 3 short periods of gestation on gilt performance during these 3 periods are presented in Table 4-3. For period 1 (d 27-34), BW change, BF change, ADG, feed intake and gain to feed ratio were greater ($P < 0.01$) for gilts on 2.0M feeding level compared with gilts on 0.5M and 1.0M feeding levels. There were no differences ($P > 0.10$) between gilts on 0.5M and 1.0M feeding levels in terms of BW change, BF change and ADG. In contrast, feed intake and gain to feed ratio were all greater ($P < 0.01$) for gilts on 1.0M feeding level in comparison with gilts on 0.5M feeding level. For period 2 (d 55-62), BW change and ADG tended ($P = 0.09$) to be higher for gilts on 2.0M feeding level than gilts on 0.5M feeding level. However, there were no differences among the 3 feeding levels in terms of BF change ($P = 0.14$) and gain to feed ratio ($P = 0.20$). For period 3 (d 83-90), BW change, ADG, feed intake, and gain to feed ratio were greater ($P < 0.01$) for gilts on 1.0M and 2.0M feeding levels

compared with gilts on 0.5M feeding level, while there were no differences ($P > 0.10$) between gilts on 1.0M and 2.0M feeding levels in terms of the aforementioned parameters. BF change during period 3 was similar ($P = 0.27$) among the 3 feeding levels.

There were no differences ($P > 0.10$) among the 3 different feeding levels in terms of numbers of liveborn, stillborn, mummy, total born, after cross-fostering, death and weaning (Table 4-4). Additionally, litter weight at birth and weaning, litter gain, average piglet weight at birth and weaning, piglet ADG and piglet pre-weaning mortality were similar ($P > 0.10$) among the 3 different gestation feeding levels. Furthermore, lactation length was similar ($P = 0.23$) among the 3 feeding level treatments, although gilts on 2.0M feeding level tended ($P = 0.09$) to farrow later than gilts on 0.5M feeding level.

Effect of feeding levels and gestation periods on energy and nutrient digestibilities

The results of different feeding levels during 3 short periods on ATTD of energy and nutrients are presented in Table 4-5. For period 1 (d 27-34), gilts on 0.5M and 1.0M feeding levels had greater ATTD of dry matter ($P < 0.01$), gross energy ($P < 0.01$), crude protein ($P = 0.01$), neutral detergent fiber ($P = 0.05$) and acid detergent fiber ($P < 0.01$) compared with gilts on 2.0M feeding level, while there were no differences ($P > 0.10$) between gilts on 0.5M and 1.0M feeding levels in terms of these parameters. In contrast, ATTD of ether extract was similar ($P = 0.34$) among gilts on the 3 feeding levels. Additionally, there were quadratic effects for ATTD of dry matter ($P = 0.01$), gross energy ($P < 0.01$) and crude protein ($P = 0.05$) with the increase of feeding levels.

For period 2 (d 55-62), gilts on 1.0M feeding level had higher ATTD of dry matter (P = 0.03), gross energy (P = 0.03), neutral detergent fiber (P = 0.01) and acid detergent fiber (P < 0.01) than gilts on 2.0M feeding level, whereas there were no differences (P > 0.10) between gilts on 0.5M and 1.0M feeding levels, as well as between gilts on 0.5M and 2.0M feeding levels, in terms of ATTD of dry matter, gross energy and neutral detergent fiber. Additionally, ATTD of crude protein and ether extract were similar (P = 0.36 and 0.66, respectively) among gilts on the 3 feeding levels. Furthermore, quadratic effects existed for ATTD of dry matter (P = 0.03), gross energy (P = 0.03), neutral detergent fiber (P = 0.02) and acid detergent fiber (P = 0.05) with the rise of feeding levels.

For period 3 (d 83-90), gilts on 1.0M feeding level tended (P = 0.10) to have greater ATTD of acid detergent fiber than gilts on 0.5M feeding level. There were, however, no differences (P > 0.10) among gilts on the 3 feeding levels in terms of ATTD of dry matter, gross energy, crude protein, ether extract and neutral detergent fiber. Additionally, there was quadratic (P = 0.05) effect for ATTD of acid detergent fiber with the increase of feeding levels.

There were significant interactions between feeding levels and gestation periods in terms of ATTD of dry matter (P = 0.02, Figure 4-1), gross energy (P = 0.01, Figure 4-2) and neutral detergent fiber (P = 0.04, Figure 4-3). For gilts on 0.5M and 1.0M feeding levels, ATTD of dry matter, gross energy and neutral detergent fiber decreased with the advancement of gestation periods, while for gilts on 2.0M feeding level, ATTD of the aforementioned measurements decreased during period 2 (d 55-62), but increased during period 3 (d 83-90), and reached the values greater than those found during period 1 (d 27-

34). No interactions (data not shown) between feeding levels and gestation periods existed for ATTD of crude protein ($P = 0.39$) and acid detergent fiber ($P = 0.22$).

Effect of feeding levels on plasma hormones related to energy homeostasis

Fasting plasma acyl ghrelin concentration was higher ($P < 0.01$) in gilts on 0.5M feeding level compared with those on 2.0M feeding level (Table 4-6), while there were no differences ($P > 0.10$) between gilts on 0.5M and 1.0M feeding levels, as well as between gilts on 1.0M and 2.0M feeding levels. Additionally, fasting plasma NEFA concentration was greater ($P < 0.01$) in gilts on 0.5M and 1.0M feeding levels compared with gilts on 2.0M feeding level, and gilts on 0.5M feeding level also had higher ($P < 0.01$) plasma NEFA concentration than those on 1.0M feeding level. There were no differences ($P > 0.10$) among the 3 feeding levels in terms of fasting plasma concentrations of GLP-1, leptin and insulin.

DISCUSSION

The present study demonstrated that increasing feeding levels during 3 short periods of gestation led to an increase of BW change during these 3 short periods and from the initiation of the experiment (d 27) to d 109 of gestation. The greater BW gain during gestation did not result in more BW loss during lactation, which was in contrast with the results reported by Cromwell et al. (1989), Dourmad et al. (1991), Whittemore et al. (1988), Xue et al. (1997) and Young et al. (1990). Even though the lactation BW loss of gilts seemed to increase numerically with the rise of gestation feeding levels, the large variation within treatments rendered the results non-significant, indicating that relatively large number of animals are needed to draw a definite conclusion.

It should be noted that the slopes of the BW change for period 1 were 4.32 and 3.72 kg/0.5M change from 0.5M to 1.0M feeding level and from 1.0M to 2.0M feeding level, respectively, indicating that an apparent reduction of slope at 1.0M feeding level. This suggested that the efficiency of feed utilization for BW change was maximized at 1.0M feeding level. One possible reason for the apparent decrease of feed utilization efficiency for gilt BW change in 2.0M feeding level may be that maternal fat synthesis may have increased relative to protein synthesis when feeding level was higher than 1.0M. Another possible explanation could be that energy and nutrient digestibilities were maximized at 1.0M feeding level. This hypothesis was confirmed in the current experiment, which showed that ATTD of dry matter, gross energy and crude protein in period 1 increased qudratically in response to the rise of feeding levels, reaching the greatest values at 1.0M feeding level.

In the current experiment, ATTD of gross energy and major nutrients were greater in two lower feeding levels (0.5M and 1.0M) than the highest feeding level (2.0M) in period 1 and 2. In the past several decades, numerous studies have been conducted to investigate the effect of feeding levels on ATTD of energy and nutrients in pigs at different stages. It was reported that with the increase of feeding levels, ATTD of energy and nutrients reduced in weaning piglets (Ball and Ahernet, 1987; Goerke et al., 2014), growing pigs (Haydon et al., 1984; Smits et al., 1994), finishing pigs (Smits et al., 1994) and sows (Everts and Smits, 1987), which was also confirmed in African catfish (Henken et al., 1985). In contrast, other researchers observed no differences of ATTD of energy and nutrients in response to feeding levels (Mroz et al., 1994; Morel et al., 2006; García-Valverde et al., 2008), while Dourmad et al. (1996) even found that ATTD of dry matter,

organic matter and gross energy increased linearly with the increase of energy intake. The inconsistent findings concerning the effect of feeding levels on digestibility of energy and nutrients could be attributed to several factors, such as feeding levels, level and source of dietary fiber and age of pigs (Van Es, 1982). It was found that an enhanced feeding level led to a faster passage rate in the gastrointestinal tract (Henken et al., 1985), which caused a decreased retention time in the large intestine, allowing less fermentation in the hindgut, thus reducing the digestibility of energy and nutrients (Van Es, 1982). However, it should not be overlooked that the apparent digestibility of energy and nutrients were subjected to the influence of endogenous excretions whose contribution to the fecal output may be expected to vary according to both feeding level, the chemical composition and nature of the feed, as well as the animal body size. Sugimoto (1985) further suggested that apparent digestibility of energy and nutrients may depend on the quality of the feed fed to animals, i.e. diets containing less digestible nutrients could be influenced to a large extent by feeding levels than diets containing more digestible nutrients. It was possible that the interaction among these factors could generate different results in different experimental settings.

Numerous studies have investigated the effect of gestation periods on digestibility of energy and nutrients. Noblet and Etienne (1987) reported that digestibility of energy and nitrogen was not affected by gestation periods when sows were fed a standard gestation diet (3.4% crude fiber). In contrast, digestibility of nutrients increased between early and middle gestation when sows were fed a fibrous feed (Nuzback et al., 1984). This was not confirmed in the study conducted by Olesen et al. (2001), which reported that no effect of stage of pregnancy on the digestibility of nutrients was found. Calvert et al. (1985) found

that the digestibility of nutrients decreased in the late period of pregnancy, which could be supported by the evidence that increased passage rate was associated with advancing pregnancy (Forbes, 1970; Singh and Singh, 1990). These findings indicated that digestibility of energy and nutrients in pregnant sows were related to both feed characteristics and physiological stage of pregnancy.

Interestingly, in our present experiment, we noted that interaction effect between feeding level and gestation periods was evident in terms of ATTD of dry matter, gross energy and neutral detergent fiber. For gilts on 0.5M and 1.0M feeding levels, ATTD of dry matter, gross energy and neutral detergent fiber decreased with the advancement of gestation periods, while for gilts on 2.0M feeding level, ATTD of the aforementioned measurements decreased during period 2 (d 55-62), but increased during period 3 (d 83-90), and reached the values greater than those found during period 1 (d 27-34). The definite mechanism concerning this interaction was not clear. It was probable that at 0.5M and 1.0M feeding levels, increased passage rate was more pronounced with the advancement of pregnancy, resulting in the decrease of digestibility of these aforementioned nutrients with the advancing pregnancy. However, at 2.0M feeding level, during the late pregnancy, high energy and nutrient requirement may drive the body to more effectively utilize the energy and nutrients in the diet. Additionally, the proportion of endogenous losses of nutrients in late gestation may be reduced in comparison with early and middle gestation. Further research is needed to confirm this finding and well-controlled mechanistic studies are needed to fully understand the mechanism regarding the interaction effect between feeding levels and physiological stages of pregnancy on apparent digestibility of energy and nutrients.

The current experiment showed that feeding levels did not have effect on litter performance in terms of numbers of piglets born total, alive, at weaning and the weight of piglet and litter at birth and weaning. It was reported that feeding levels did not impact number of piglet at birth and weaning (Dourmad et al., 1991; Weldon et al., 1994; Whittemore et al., 1988). However, others have reported that numbers of liveborn piglets at birth and/or weaning were adversely affected by gestation feeding levels (or energy intake) (Libal and Wahlstrom, 1977; Gonçalves et al., 2016). In contrast with the results reported by Baker et al. (1969) and Cromwell et al. (1989) and our large scale study in sows, the current experiment did not show a linear increase of piglet birth weight in response to the rise of gestation feeding levels during 3 short periods of gestation. It is possible that a relatively large number of gilts are needed to reduce the variation within each feeding level and draw a confident conclusion regarding litter performance.

Our current study demonstrated that acyl ghrelin concentration in the gilts on the lower feeding level was higher than the gilts on the higher feeding level. Data gleaned over the last decade demonstrated that plasma ghrelin concentration elevated under conditions of negative energy balance such as starvation and anorexia, whereas it declined under conditions of positive energy balance such as feeding and obesity (Ariyasu et al., 2001; Tschöp et al., 2001). It was also reported that intracerebroventricular administration of acyl ghrelin inhibited the secretion of thyroid stimulating hormone (Wren et al., 2000). It was probable that in times of energy deficiency, elevated plasma acyl ghrelin may function as an inhibitory factor to avoid excessive metabolic drain, thus saving energy expenditure.

NEFA is an indicator of fat mobilization and its concentration would increase in the negative energy balance (Weldon et al., 1994c). As expected, gilts on the lower feeding level had higher plasma NEFA concentration than gilts on the higher feeding level, indicating that gilts eating less were exposed to a negative energy balance and thus mobilize more fat reserve to meet the daily energy requirement, which was further supported by the evidence that gilts on 0.5M and 1.0M feeding levels lost backfat during d 27 to 34 of gestation.

CONCLUSION

In conclusion, increasing feeding levels during 3 short periods increased primiparous sow performance during these short periods. ATTD of energy and nutrients, and BW change efficiency were maximized for gilts on the medium feeding level (1.0M). Feeding strategies during 3 short periods of gestation did not impact litter performance. The data also indicated that sows on the lowest feeding level were exposed to negative energy balance as evidenced by the higher fasting plasma acyl ghrelin and NEFA concentrations.

Table 4-1. Ingredient and nutrient composition of experimental diets for gestation and lactation (as-fed basis)

Item	Gestation	Lactation
Ingredient, %		
Corn	65.22	61.15
Soybean meal	10.00	17.20
cDDGS[1]	20.00	15.00
Choice white grease	1.50	3.00
Limestone	1.00	0.88
Dicalcium phosphate	1.20	1.15
Lysine HCl (78%)	0.10	0.46
DL-Methionine	-	0.01
L-Threonine	-	0.13
L-Tryptophan	-	0.04
Salt	0.35	0.35
Premix[2]	0.50	0.50
Tylan[3]	0.13	0.13
Nutrient composition		
ME, [4] kcal/kg	3,310	3,424
CP, [5] %	15.71	17.92
Total Ca, [5] %	0.72	0.68
STTD[6] P, [4] %	0.35	0.35
SID[7] Lys, [4] %	0.57	1.01
SID Met + Cys, [4] %	0.47	0.52
SID Thr, [4] %	0.44	0.64
SID Trp, [4] %	0.12	0.19

[1]cDDGS = Corn distillers dried grains with solubles (containing 27.3% CP, 5.47% EE, 0.05% Ca, 0.94% P and 0.77% Lys).

[2]Supplied the following nutrients per kilogram of diets: vitamin A, 12,114 IU; vitamin D, 2,753 IU; vitamin E, 66 IU; vitamin K, 4.4 mg; thiamine, 1 mg; riboflavin, 10 mg; niacin, 55 mg; pantothenic acid, 33 mg; pyridoxine, 2.2 mg; folic acid, 1.6 mg; vitamin B_{12}, 0.06 mg; I, 0.5 mg from ethylenediamine dihydriodide; Se, 0.3 mg from sodium selenite; choline, 548 mg from choline chloride; and metal polysaccharide complexes of zinc

sulfate (125 mg of Zn), iron sulfate (125 mg of Fe), manganese sulfate (40 mg of Mn), and copper sulfate (15 mg of Cu).

[3]Tylan™ 40 (Tylosin phosphate 40), Elanco Animal Health, Indianapolis, IN.

[4]Caculated values according to NRC (2012).

[5]Analyzed values.

[6]STTD = standardized total tract digestible.

[7]SID = standardized ileal digestible.

Table 4-2. Effects of different feeding levels during three short periods of gestation on gilt performance at different time points during gestation and lactation

	Feeding levels[1]				
Items	0.5M	1.0M	2.0M	SEM	*P* value
Number of gilts	6	6	6		
Gilt BW, kg					
d 27	201.71	199.66	193.33	8.14	0.70
d 55	210.68	213.18	193.33	8.14	0.97
d 83	215.11	216.82	220.23	8.78	0.90
d 109	217.05	228.86	230.38	9.40	0.54
Post-farrowing	203.18	214.20	211.49	9.60	0.70
Weaning	190.91	200.91	192.84	16.02	0.88
Gilt BF, mm					
d 27	22.88	22.63	23.92	1.34	0.75
d 55	23.63	23.88	25.83	1.52	0.51
d 83	22.63	24.50	26.17	1.93	0.42
d 109	22.50	23.25	25.58	1.68	0.37
Post-farrowing	22.38	22.75	25.49	1.77	0.32
Weaning	20.00	19.75	21.31	2.70	0.84
Gestation weight change[2], kg	15.34[a]	29.21[ab]	37.05[b]	4.81	0.02
Gestation BF change[3], mm	-0.38	0.63	1.67	0.85	0.22
Lactation weight change, kg	-11.60	-13.30	-17.27	10.20	0.87
Lactation BF change, mm	-2.25	-3.00	-4.20	1.94	0.67
Lactation ADFI[4], kg	5.14	4.76	4.03	1.01	0.63
Net weight change[5], kg	-6.37	1.25	5.27	13.66	0.78
Net BF change[6], mm	-2.75	-2.88	-1.80	2.12	0.85
Wean to estrus interval, d	6.00	5.33	5.40	0.44	0.41

[1]0.5M, 1.0M and 2.0M represented 0.5, 1.0 and 2.0 × maintenance energy intake level ($100 \times BW^{0.75}$ kcal $ME \cdot d^{-1}$), respectively.

[2]Weight change from d 27 to 109 of gestation.

[3]BF change from d 27 to 109 of gestation.

[4]Lactation length was used as a covariate in the statistical model.

[5]Weight change from d 27 of gestation to weaning.

[6]BF change from d 27 of gestation to weaning.

Table 4-3. Effects of different feeding levels during three short periods of gestation on gilt performance during the three periods of gestation

	Feeding levels[1]				
Items	0.5M	1.0M	2.0M	SEM	*P* value
Number of gilts	6	6	6		
Period 1 (d 27-34)					
BW change, kg	-6.14[a]	-1.82[a]	5.61[b]	1.18	<.01
BF change, mm	-0.75[a]	-0.38[a]	0.25[b]	0.27	<.01
ADG, kg/d	-0.88[a]	-0.36[a]	0.80[b]	0.17	<.01
Feed intake, kg	5.65[a]	11.30[b]	21.95[c]	0.43	<.01
Gain to Feed, kg/kg	-1.09[a]	-0.21[b]	0.26[c]	0.13	<.01
Period 2 (d 55-62)					
BW change, kg	-2.28	-0.57	4.43	2.29	0.09
BF change, mm	-0.25	0.38	0.83	0.41	0.14
ADG, kg/d	-0.33	-0.08	0.63	0.33	0.09
Feed intake, kg	5.89[a]	11.85[b]	23.44[c]	0.57	<.01
Gain to Feed, kg/kg	-0.38	-0.07	0.20	0.23	0.20
Period 3 (d 83-90)					
BW change, kg	-1.82[a]	3.53[b]	5.53[b]	1.14	<.01
BF change, mm	0.13	0.25	0.50	0.18	0.27
ADG, kg/d	-0.26[a]	0.50[b]	0.79[b]	0.16	<.01
Feed intake, kg	7.32[a]	12.01[b]	19.55[c]	1.42	<.01
Gain to Feed, kg/kg	-0.25[a]	0.29[b]	0.20[b]	0.06	<.01

[1]0.5M, 1.0M and 2.0M represented 0.5, 1.0 and 2.0 × maintenance energy intake level ($100 \times BW^{0.75}$ kcal ME·d^{-1}), respectively.

[a,b,c] Least squares means within a row without common letters differ ($P < 0.01$)

Table 4-4. Effects of different feeding levels during three short periods of gestation on litter performance

Items	Feeding levels[1]			SEM	*P* value
	0.5M	1.0M	2.0M		
Number of litters	6	6	6		
Litter size					
Liveborn	12.75	13.00	13.20	0.86	0.93
Stillborn	0.50	1.00	0.40	0.42	0.42
Mummy	0.75	0.25	0.50	0.61	0.79
Total born	14.00	14.25	14.20	1.25	0.99
After cross-fostering	13.33	13.00	13.60	0.90	0.85
Death	2.50	1.50	2.33	0.85	0.63
Weaning	11.33	11.50	11.00	0.61	0.77
Litter weight, kg					
Liveborn	16.22	16.08	16.20	2.40	1.00
Weaning	66.50	61.41	67.74	6.18	0.67
Gain	49.13	45.33	49.16	5.69	0.82
Piglet weight, kg					
Average birth weight	1.27	1.24	1.35	0.07	0.49
Average wean weight	5.85	5.36	6.17	0.46	0.36
Piglet ADG, g	231.00	216.75	259.63	23.48	0.32
Piglet pre-weaning mortality, %	15.00	11.54	19.12	5.94	0.58
Gestation length	113.75	115.25	116.50	0.87	0.09
Lactation length	19.67	19.00	18.40	0.55	0.23

[1]0.5M, 1.0M and 2.0M represented 0.5, 1.0 and 2.0 × maintenance energy intake level ($100 \times BW^{0.75}$ kcal ME·d^{-1}), respectively.

Table 4-5. Effects of different feeding levels during three short periods of gestation on apparent total tract digestibility (ATTD) of energy and nutrients

	Feeding levels[1]				
Items	0.5M	1.0M	2.0M	SEM	*P* value
Number of gilts	6	6	6		
ATTD[2], %					
Period 1 (d 27-34)					
DM[3]	88.33[b]	89.03[b]	85.90[a]	0.49	<.01
GE[3]	88.03[b]	88.71[b]	85.11[a]	0.50	<.01
CP[3]	87.13[b]	87.57[b]	85.18[a]	0.48	0.01
EE	62.98	63.03	60.95	1.15	0.34
NDF	72.24[ab]	74.87[b]	64.83[a]	2.94	0.05
ADF	77.96[b]	75.93[b]	62.33[a]	2.84	<.01
Period 2 (d 55-62)					
DM[3]	86.16[ab]	87.93[b]	84.66[a]	0.90	0.03
GE[3]	85.63[ab]	87.57[b]	83.69[a]	1.03	0.03
CP	85.48	86.71	84.46	1.10	0.36
EE	57.15	60.45	61.69	3.88	0.66
NDF[3]	66.57[ab]	72.34[b]	56.96[a]	3.21	0.01
ADF[3]	69.31[b]	71.13[b]	54.75[a]	3.13	<.01
Period 3 (d 83-90)					
DM	85.51	85.82	86.62	0.56	0.39
GE	84.54	84.88	86.05	0.77	0.39
CP	85.34	86.08	86.38	0.92	0.72
EE	59.94	54.35	64.29	4.03	0.27
NDF	60.73	65.02	64.50	1.79	0.24
ADF[3]	57.20	64.84	61.44	2.22	0.10

[1]0.5M, 1.0M and 2.0M represented 0.5, 1.0 and 2.0 × maintenance energy intake level (100 × $BW^{0.75}$ kcal ME·d^{-1}), respectively.

[2]ATTD = apparent total tract digestibility; DM, GE, CP, EE, NDF and ADF represent dry matter, gross energy, crude protein, ether extract, neutral detergent fiber and acid detergent fiber, respectively.

[3]Qudratic effect ($P < 0.05$) of feeding levels.

[a,b] Least squares means within a row without common letters differ ($P < 0.05$)

Table 4-6. Effects of different feeding levels on fasting plasma hormones related to energy homeostasis during period 1 (d 27-34)

	Feeding levels[1]				
Items	0.5M	1.0M	2.0M	SEM	*P* value
Acyl ghrelin, pg/ml	211.32[b]	174.37[ab]	87.64[a]	19.69	<.01
GLP-1, pg/ml	174.13	186.15	279.44	49.43	0.19
Leptin, ng/ml	0.90	0.86	1.09	0.09	0.18
Insulin, μU/ml	8.85	8.17	9.60	1.52	0.80
NEFA, mmol/l	0.47[c]	0.21[b]	0.13[a]	0.03	<.01

[1]0.5M, 1.0M and 2.0M represented 0.5, 1.0 and 2.0 × maintenance energy intake level ($100 \times BW^{0.75}$ kcal $ME \cdot d^{-1}$), respectively.

[a,b,c] Least squares means within a row without common letters differ ($P < 0.01$)

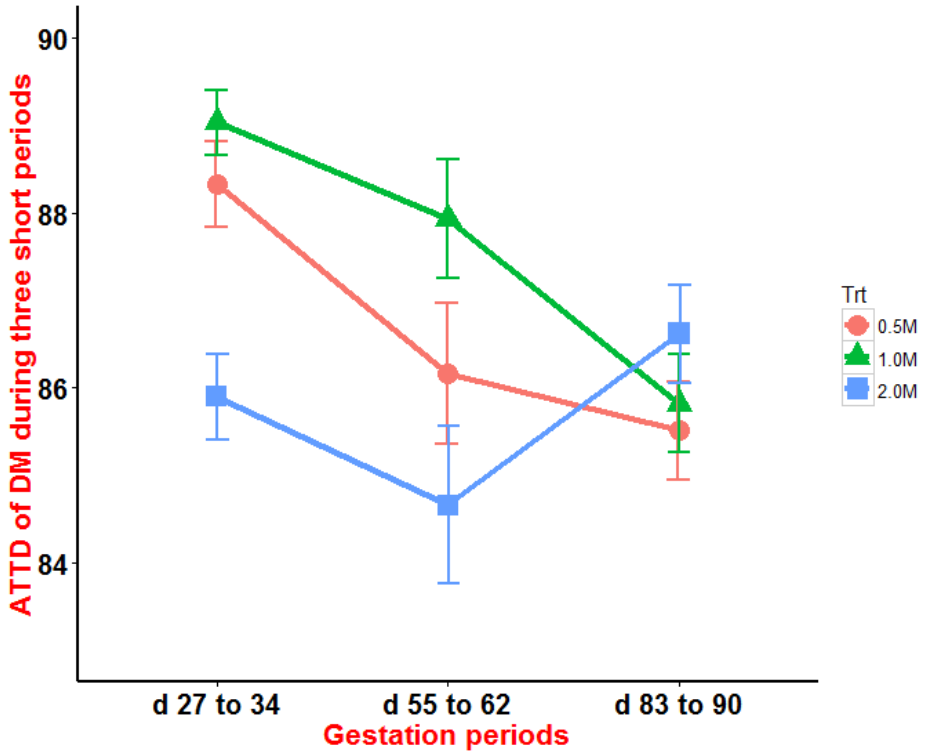

Figure 4-1. Interaction between gestation feeding levels and gestation phase for apparent total tract digestibility (ATTD, %) of dry matter (DM)

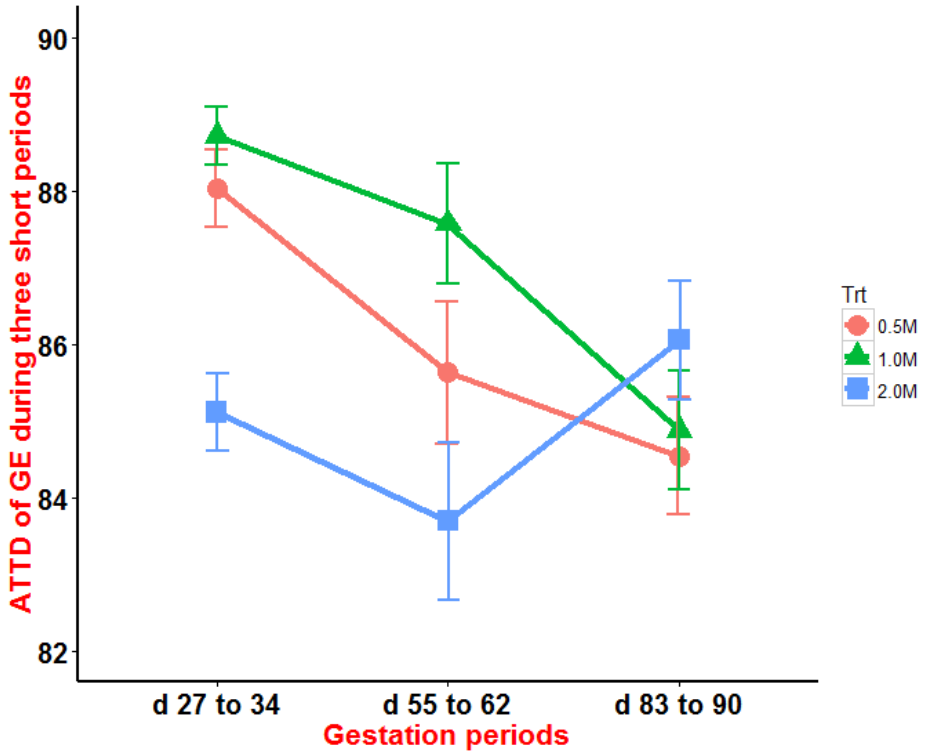

Figure 4-2. Interaction between gestation feeding level and gestation phase for apparent total tract digestibility (ATTD, %) of gross energy (GE)

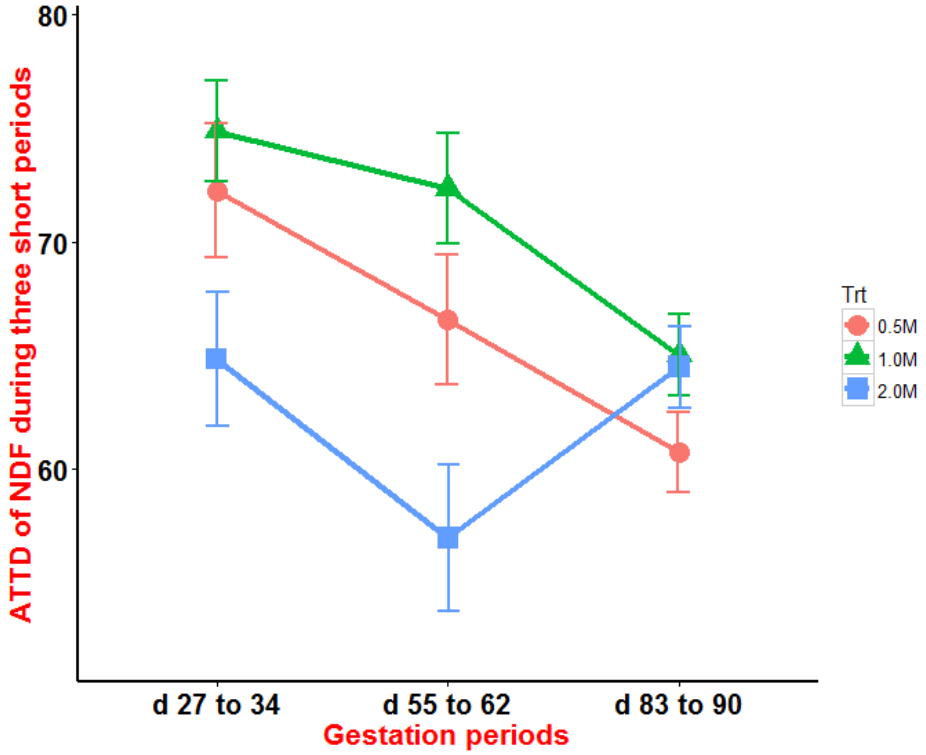

Figure 4-3. Interaction between gestation feeding level and gestation phase for apparent total tract digestibility (ATTD, %) of neutral detergent fiber (NDF)

Chapter 5. Plasma acyl ghrelin and non-esterifified fatty acids are the best predictors for hunger status in pregnant gilts

SUMMARY

In the present study, 3 different feeding levels were generated to create different hunger status in pregnant gilts and plasma hormones related to energy homeostasis and non-esterified fatty acids (**NEFA**) were analyzed to quantify their response to different feeding levels. A total of 18 gilts were allotted to 1 of 3 dietary treatments using a completely randomized design. All gilts were fed one common corn-soybean meal-based diet with the amount of 1.0 × maintenance energy intake (100 × BW (BW)$^{0.75}$ kcal ME/d) throughout gestation except 3 periods of 7 d when dietary treatments were imposed on d 27, d 55 and d 83 of gestation. During the 3 short periods, gilts were fed 1 of 3 different feeding levels: 0.5, 1.0 and 2.0 × maintenance energy level (0.5M, 1.0M and 2.0M, respectively). During period 1 (d 27-34), serial blood samples were collected at the last day after 6 d adaptation. Results showed that during gestation period 1, BW and backfat (BF) changes were higher ($P < 0.01$) for gilts on 2.0M than gilts on 0.5M feeding level. Plasma acyl ghrelin concentrations showed a relatively flat pattern during the 24 h period. Generally, plasma acyl ghrelin and NEFA concentrations and area under curves (**AUC**) were greater ($P < 0.05$) in gilts on 0.5M feeding level than those on 2.0M feeding level. No differences ($P > 0.10$) in AUC of plasma GLP-1 and leptin concentrations were observed among the 3 feeding levels. Additionally, consumption time for 1.82 kg feed at d 35 of gestation was longer ($P < 0.01$) in gilts fed 2.0M feeding level during d 27 to 34 of gestation than those on 0.5M feeding level. Simple linear regression results showed

that AUC of acyl ghrelin was the best predictor for prediction of consumption time, whereas AUC of NEFA was the best predictor for prediction of BW or BF change during d 27 to 34 of gestation. In conclusion, our data suggested that a relative flat pattern existed in pregnant gilts in terms of diurnal plasma profile of acyl ghrelin and that feed intake of pregnant gilts was negatively correlated with plasma concentrations of acyl ghrelin and NEFA, which in turn were negatively associated with feed consumption time. Therefore, AUC of acyl ghrelin and NEFA seemed to be the best predictors for hunger status of pregnant gilts.

KEYWORDS: feeding level, gilt, acyl ghrelin, NEFA, consumption time

INTRODUCTION

Numerous studies have shown that ghrelin may serve as both a short-term and long-term indicator of energy homeostasis. It was well-documented that ghrelin secretion was up-regulated in the conditions of negative energy balance, such as fasting and anorexia nervosa, and down-regulated in the case of positive energy balance, such as feeding and obesity (Ariyasu et al., 2001; Toshinai et al., 2001; M. Tschop et al., 2001; Wren et al., 2001).

The diurnal profile of ghrelin concentrations have been investigated in both non-pregnant rodents (Tschöp et al., 2000; Sánchez et al., 2004) and humans (Ariyasu et al., 2001; Cummings et al., 2001; M Tschop et al., 2001; Liu et al., 2008b). These studies clearly demonstrated that ghrelin concentrations increased before feeding and declined after feeding, indicating ghrelin functions as a physiological meal initiator. However, to our best knowledge, we are not aware of any study investigating the diurnal profile of acyl

ghrelin concentrations in pregnant animals. Additionally, it was reported that ghrelin plays important roles in fertilization, implantation and embryo/fetal development (Fuglsang, 2007; Luque et al., 2014). Therefore, the first objective of this study was to characterize the diurnal plasma profile of acyl ghrelin concentrations in pregnant gilts.

Leptin and insulin are proportional to animal body fat mass, which plays a critical role in long-term food regulation and energy homeostasis (Polonsky et al., 1988; Zhang et al., 1994). However, intraventricular administration of GLP-1 could reduce short-term but not long-term food intake or body weight in both lean and obese rats (Donahey et al., 1998), indicating that GLP-1 may exhibit its function in the short-term regulation of food intake and energy homeostasis. Additionally, non-esterified fatty acids (NEFA) is an indicator of fat mobilization and its concentration would be increased in the negative energy balance (Weldon et al., 1994c). Therefore, the second objective of this study was to examine the correlations among the plasma hormones and NEFA, and select the best predictors for hunger status or energy homeostasis in pregnant gilts.

MATERIALS AND METHODS

Institutional Animal Care and Use Committee of University of Minnesota approved the experimental protocol of this study.

Animals and Management

The present experiment was conducted at the University of Minnesota's Southern Research and Outreach Center in Waseca, MN. Eighteen Large White x Danish Landrace crossbred gilts (TOPIGS 20, TOPIGS Inc., Winnipeg, Manitoba, Canada) were used in

this study and kept in the individual stalls (2.1 m length x 0.6 m width x 0.6 m height) throughout gestation. All gilts were fitted with cephalic vein catheters according to procedures described by Moehn et al. (2004). Briefly, a catheter was tunneled under the skin from the incision site to a point of exit on the shoulder where an access port was connected with the catheter. After surgery, gilts were treated with analgesic and antibiotics, allowing 2 wk for recovery. Then all gilts were fed a small portion of feed mixed with 6.8 ml (15 mg Altrenogest) Matrix (Merck Animal Health, NJ, USA) each day; after finishing the small portion of feed, the rest of feed were delivered to the gilts. The Matrix feeding regime was imposed for 2 wks in order to synchronize estrus in the experimental gilts. After withdrawing Matrix, all gilts came to heat in 1 wk. All gilts were bred twice via artificial insemination in 2 consecutive days. After breeding, gilts were randomly allotted to 1 of 3 dietary treatments. Gilts were fed once a day at 7:30 am during the gestation period before moving to farrowing rooms. Pregnancy check was conducted in all these bred gilts around d 35 of gestation. Another pregnancy check was conducted 2 wk later on these gilts to confirm the pregnancy. During gestation, all gilts were fed their respective gestation diets with different amounts of feed on different periods of gestation. On d 109 of gestation, gilts were moved into the farrowing rooms with environment controlled systems and housed in individual farrowing crates (2.13 m length × 0.66 m width × 0.97 m height). All gilts were fed 2.27 kg lactation diets beginning from d 109 to the date of farrowing.

Dietary Treatments, Experimental Design and Data Collection

At d 27 of gestation, gilts were randomly allotted to 1 of 3 experimental treatments. The experiment started from d 27 of gestation throughout the gestation and lactation period. All gilts were fed one common corn-soybean meal-based basal diet (Table 5-1) with the amount of 1.0 × maintenance energy intake (100 × $BW^{0.75}$ kcal ME/d, NRC, 2012) throughout the gestation period except 3 periods of 7 d dietary treatments imposing at d 27, d 55 and d 83 gestation. During these 3 periods, gilts were fed 1 of 3 different feeding levels based on maintenance energy intake: 1) 0.5 × maintenance level (0.5M); 2) 1.0 × maintenance level (1.0M); 3) 2.0 × maintenance level (2.0M). Gestation and lactation diets (Table 5-1) met or exceeded NRC (2012) nutrient recommendations.

Gilt BW was recorded and BF thickness was measured using ultrasonic detection machine (Preg-Alert Pro, Renco Corp., Minneapolis, USA) on both the left and right sides at the P2 position (6.5 cm from the dorsal mid-line at the level of the last rib) on d 27, 34, 55, 62, 83 and 90 of gestation for calculation of the BW and BF change during the 3 short periods of gestation. After the first dietary imposing period (d 27-34), a feed consumption test was conducted to record the consumption time of the same amount of feed (1.82 kg) for each experimental gilt on d 35 of gestation.

Chemical Analysis

All analyses were conducted in duplicate. The gestation and lactation diets were analyzed for DM (method 934.01; AOAC, 2006), ether extract (method 920.39; AOAC, 2006), crude protein (method 984.13; AOAC, 2006), neutral detergent fiber (**NDF**, method 973.18; AOAC, 2006) and acid detergent fiber (**ADF**, method 973.18; AOAC, 2006) at the University of Minnesota's Southern Research and Outreach Center. Gestation diet and

fecal samples were analyzed for gross energy (GE) via adiabatic oxygen bomb calorimeter (Parr Instruments, Moline, IL). Concentrations of calcium (method 958.01; AOAC, 2006), phosphorus (method 958.01; AOAC, 2006) and amino acid (method 982.30; AOAC, 2006) were analyzed in Experiment Station Chemical Laboratories (University of Missouri, Columbia, MO).

Blood Collection and Plasma Analysis

During d 27 to 34 of gestation, the first 6 d was considered as period of adaptation to the diets and the blood collection was conducted on the 7th day. Blood samples for all gilts were collected via cephalic vein catheters right before feeding (0 h), then every 15 min for 2 h and then every 2 h until the completion of 24 h. Before blood collection, 50 µl dipeptidyl peptidase-IV inhibitor (EMD Millipore, MA, US) and 180 µl 4-(2-Aminoethyl) benzenesulfonyl fluoride hydrochloride (**AEBSF**) (100 mM, Sigma-Aldrich, MO, USA) were added to the blood collection tubes. Blood samples (6 ml) were added to the chilled collection tubes containing K_3EDTA as an anticoagulant and the contents were gently mixed to make sure the added chemicals were equally distributed in the blood. After gentle mixing, the tubes were centrifuged at 2500 rpm for 15 min. After centrifugation, each plasma sample was carefully transferred to 6 Self-Lock Eppendorf microtubes with 0.5 ml in each microtube. In the microtube for acyl-ghrelin analysis, 10 µl of 6N HCl was added to acidify the plasma to provide additional protection. The plasma samples were

snap frozen in liquid nitrogen and then stored at -80 ^{o}C until analysis for acyl ghrelin, glucagon-like peptide 1 (**GLP-1**), leptin, insulin, and non-esterified fatty acid (**NEFA**). For blood samples collected during period 1 (d 27 to 34 of gestation), acyl ghrelin concentrations in plasma sampled at every 2 h time point were measured, whereas blood samples collected at specific time points were analyzed for GLP-1 (0, 0.5 and 1 h post-prandial), leptin (0, 4 and 8 h post-prandial), insulin (0, 15 min, 30 min, 45 min, 60 min, 75 min, 90 min, 2 h and 4 h post-prandial), and NEFA (0, 4 and 8 h post-prandial).

Commercial ELISA kits were used for analysis of plasma acyl-ghrelin (EZRGRA-90K, EMD Millipore, MA, USA) and leptin (BG-POR11464, Novateinbio, MA, USA). Plasma GLP-1 (7-36) was measured using a commercial fluorescent immunoassay kit (FEK-028-11, Phoenix Pharmaceuticals, Inc., CA, USA). Plasma insulin was analyzed using a commercial RIA kit (PI-12K, EMD Millipore, MA, USA). Plasma NEFA was analyzed using the enzymatic colorimetric method (NEFA HR(2), Wako Life Sciences, Inc., VA, USA). The intra-assay CV for the assays were 5.1, 4.5, 2.0 and 7.5% for acyl-ghrelin, GLP-1, leptin and insulin, respectively.

Statistical Analysis

SAS 9.4 (SAS Inst. Inc., Gary, NC) was used in all data analysis. Individual gilt served as the experimental unit. The LSMEANS statement was used to calculate the least squares means. Tukey-Kramer adjustment was used for multiple comparisons of the least squares means. Pooled SEM was calculated for each measurement. A probability of $P < 0.05$ was considered as significant and $0.05 < P < 0.1$ was declared as a trend.

Proc GLIMMIX was used for the data analysis. Gilt BW change, BF change, ADG, feed intake and gain to feed ratio during the 3 short periods were considered as repeated measurements. Different covariance structure candidate models were examined and the best fit model was selected for each measurement based on Akaike Information Criterion (**AIC**) and Bayesian Information Criterion (**BIC**) values. After model testing, the best covariance structure models selected using the aforementioned technique for gilt BW change, BF change, ADG and gain to feed ratio were all heterogenous first-order autoregressive (arh(1)), while Toeplitz (toep) was the best model for feed intake. The SLICE option by period was used to test the effect of dietary treatments at the 3 short periods.

Plasma hormones and NEFA concentrations analyzed at different time points were considered as repeated measurements. Model testing results indicated that the best covariance structure models selected for acyl ghrelin, GLP-1, leptin, insulin and NEFA were toep, toep, compound symmetry (c)s, arh(1) and first order ante-dependence (ante(1)), respectively. Area under curve (**AUC**) for each plasma parameters were calculated using trapezoidal method and analyzed using default linear regression model if normal assumption was met.

Proc Corr was used to examine correlation coefficients among feed consumption time, BW and BF change during period 1 (d 27-34 of gestation) and plasma parameters. Consumption time, BW and BF change during period 1 were considered as dependent variables. If the plasma parameters were significantly correlated or tended to correlate

with the dependent variables, simple linear regression models were built using the Proc Reg procedure.

RESULTS

Gilt performance

The results of feeding levels during 3 short periods of gestation on gilt performance during period 1 (d 27-34) are presented in Table 5-2. BW change, BF change, ADG, feed intake and gain to feed ratio were greater ($P < 0.01$) for gilts on 2.0M feeding level compared with gilts on 0.5M and 1.0M feeding levels. There were no differences ($P > 0.10$) between gilts on 0.5M and 1.0M feeding levels in terms of BW change, BF change and ADG. In contrast, feed intake and gain to feed ratio were all greater ($P < 0.01$) for gilts on 1.0M feeding level in comparison with gilts on 0.5M feeding level.

Plasma hormones

Plasma acyl ghrelin concentrations of gilts with each feeding level did not decrease post-prandially and maintained at a constant level except an abrupt increase at 10 h postprandial during the 24 h sample collection period (Table 5-3; Figure 5-1). However, gilts on 0.5M feeding level had greater ($P < 0.05$) acyl ghrelin concentration at the majority of time points and AUC compared with those on 2.0M feeding level.

Fasting plasma insulin concentrations were similar ($P = 0.80$) among gilts on the 3 feeding levels (Table 5-4; Figure 5-2). However, gilts on 1.0M feeding level tended ($P =$

0.07) to have higher insulin concentration at 45 min postprandially compared with gilts on 0.5M feeding level. Gilts on 2.0M feeding level had greater insulin concentration at 60 min post-prandially than those on 0.5M and 1.0M feeding levels, as well as at 75 min post-prandially than those on 0.5M feeding level. Additionally, the insulin concentrations decreased to the similar levels among 3 feeding levels at 90 min (P = 0.60) and 2 h (P = 0.30) post-prandially. However, plasma insulin concentrations were greater for gilts on 1.0M and 2.0M feeding levels at 4 h postprandially compared with those on 0.5M feeding level. Furthermore, Insulin concentrations reached the maximum of 39.17 and 78.35 μU/ml at 45 min postprandially for gilts on 0.5M and 1.0M feeding levels, respectively, while insulin concentration reached a maximum of 72.62 μU/ml at 60 min postprandially for gilts on 2.0M feeding level. AUC of plasma insulin concentrations tended (P = 0.06) to be greater for 1.0M and 2.0M feeding levels than 0.5M feeding level.

Plasma concentrations of GLP-1 at fasting (0 h) and AUC of GLP-1 were not different (P > 0.10) among feeding levels, but gilts on 2.0M feeding level tended to have higher levels of GLP-1 at time points 0.5 h (P = 0.07) and 1 h (P = 0.08) post-prandially compared with gilts on 0.5M and 1.0M feeding levels (Table 5-5). No differences (P > 0.10) were found among gilts on the 3 feeding levels in terms of plasma concentrations of leptin at different time points post-prandially and AUC. However, fasting NEFA concentration was greater (P < 0.01) in gilts on 0.5M feeding level than those on 1.0M and 2.0M feeding levels. Additionally, fasting NEFA concentration was also greater (P < 0.01) in gilts on 1.0M feeding level than their counterparts on 2.0M feeding level. Furthermore, NEFA concentrations at 4 h and 8h post-prandially and AUC were greater (P < 0.01) in gilts fed 0.5M feeding level than those on 1.0M and 2.0M feeding level.

Consumption time and Pearson correlations

After dietary feeding levels imposing period (d 27-34 of gestation), feed consumption test revealed that gilts on 2.0M feeding level spent more ($P < 0.01$) time to finish the 1.82 kg feed than gilts on 0.5M feeding level at d 35 of gestation (Figure 5-3). Pearson correlation results showed that consumption time of 1.82 kg feed at d 35 of gestation was strongly and negatively correlated with AUC of acyl ghrelin (r = -0.91, $P < 0.01$) and NEFA (r = -0.71, $P < 0.01$) (Table 5-6). Acyl ghrelin AUC positively correlated with NEFA AUC (r = 0.72, $P < 0.01$).

Pearson correlation results also revealed that BW change during d 27 to 34 of gestation was inversely (r = -0.77, $P < 0.01$) correlated with AUC of NEFA, while it tended to negatively and positively correlated with AUC of acyl ghrelin (r = -0.50; $0.05 < P < 0.10$) and insulin ($P = 0.48$; $0.05 < P < 0.10$), respectively (Table 7). In terms of BF change during d 27 to 34 of gestation, it was inversely correlated with both AUC of acyl ghrelin (r = -0.64; $P < 0.05$) and NEFA (r = -0.69; $P < 0.01$). Additionally, AUC of GLP-1 tended (r = 0.49; $0.05 < P < 0.10$) to positively correlated with BF change during d 27 to 34 of gestation (Table 5-7).

Simple linear regression models selected for prediction of feed consumption time, BW change, or BF change in pregnant gilts are shown in Table 5-8. If feed consumption time was considered as a dependent variable, AUC of acyl ghrelin was the best predictor based on R^2 and root mean square error (**MSE**). For predicting changes of gilt BW or BF during the period of d 27 to 34 of gestation, AUC of NEFA was the best predictor.

DISCUSSION

The present study investigated the impact of feeding levels during gestation on energy homeostasis and hunger status as measured by the hormones involved in feed intake regulation and consumption time of certain amount of feed in pregnant gilts.

Several studies on rodents (Sánchez et al., 2004; Tschöp et al., 2000), growing pigs (Reynolds et al., 2010), and humans (Ariyasu et al., 2001; Cummings et al., 2001; Tschop et al., 2001; Liu et al., 2008) have supported the notion that ghrelin is a physiological meal initiator, which concentrations rise before feeding and decline after feeding. However, our experiment demonstrated that acyl ghrelin concentrations did not increase pre-prandially nor decrease post-prandially, which was similar to previous reports on plasma acyl ghrelin in finishing pigs fed *ad libitum* (Reynolds et al., 2010) and total ghrelin in finishing pigs fed *ad libitum*, once or twice a day (Scrimgeour et al., 2008). This surprising results may be related to different physiological stages of animals. In fact, to our best knowledge, this was the first study investigating the diurnal profile of acyl ghrelin concentrations in pregnant animals. Considering that ghrelin mRNA is expressed in hypothalamus, pituitary, placenta and ovary (Gnanapavan et al., 2001; Gualillo et al., 2001) in addition to stomach, we propose that a stable acyl ghrelin concentration may be vital for fetal development and maintaining pregnancy. Indeed, it was reported that maternal ghrelin played an important role in rat fetal development during pregnancy, as evidenced by the fact that chronic administration of ghrelin in mothers resulted in a significant increase in birth weight of offspring (Nakahara et al., 2006). Additionally, Luque et al. (2014) reported that either hypoghrelinemia and hyperghrelinemia exerted

negative effects on the fertilization, implantation and embryo/fetal development. It was demonstrated *in vitro* that 100-500 pg/ml human ghrelin inhibited secretion of progesterone and estradiol by ovarian follicles from mature pigs, whereas 20 pg/ml ghrelin, a concentration in porcine follicular fluid, did not inhibit secretion of the two hormones (Rak-Mardyła et al., 2015). Therefore, we suggest that acyl ghrelin has a physiological role in pregnancy and a constant level may be responsible for fetal development and maintaining pregnancy.

Interestingly, abrupt increase of acyl ghrelin concentrations were observed at 10 h postprandial, which may be related to the regular light management in the research facility. It was reported that sleeping enhanced nocturnal plasma ghrelin concentration in healthy human subjects and the nocturnal increase was blunted during sleep deprivation (Dzaja et al., 2004). The nocturnal increase of acyl ghrelin concentrations were also observed by Liu et al. (2008). It was possible, in the current experiment, the abrupt increase of acyl ghrelin concentrations were attributed to sleep, due to the fact that the light in the facility was turned off around 9 h postprandial.

Even though the acyl ghrelin concentrations did not vary pre- and post-prandially, its concentrations were higher in the gilts on lower feeding level compared with the higher feeding level, which was in agreement with a previous report on changes of plasma concentrations of total ghrelin as affected by amount of feed intake in pigs (Scrimgeour et al., 2008). Data gleaned over the last decade demonstrated that plasma ghrelin concentration elevated under conditions of negative energy balance such as starvation and anorexia, whereas it declined under conditions of positive energy balance such as

feeding and obesity (Ariyasu et al., 2001; Tschöp et al., 2001; Govoni et al., 2005). In keeping with this, it was reported that fasting plasma ghrelin was negatively correlated with body mass index (Tschöp et al., 2001). The results of the aforementioned literature were related to observations in non-pregnant animals or humans. In our current experiment, however, the animals were in the pregnant status, which may yield different results. Our current experiment also showed that AUC of acyl ghrelin was negatively correlated with backfat change. Cools et al. (2013) found no association between ghrelin and backfat thickness in sows during the peripartum period. Nevertheless, sow blood was only collected once a day for analysis of ghrelin in their study. In consistent with the findings of the present experiment, Gualillo et al. (2002) demonstrated that plasma ghrelin levels and gastric ghrelin mRNA expression were up-regulated during under nutrition in pregnant rats. It was further supported by the evidence that intravenous administration of ghrelin resulted in the inhibition of the thyroid stimulating hormone (Wren et al., 2000), which may be responsible for the reduction of energy expenditure in times of limited nutrition. It was possible that ghrelin may function as a signal for energy insufficiency during pregnancy, acting as an inhibitory factor to avoid excessive metabolic drain. Collectively, these findings confirmed that acyl ghrelin may serve as a long-term physiological indicator of energy homeostasis in both non-pregnant and pregnant animals and humans.

Our present study showed that plasma insulin concentrations responded differently among gilts fed 3 different feeding levels. An early study conducted in sheep showed that ingestion of a low amount of food was followed by a rapid increase in plasma insulin concentrations, with maximum values being reached 1-3 h after feeding, while ingestion

of a high amount of food resulted in a higher insulin concentration for longer duration (Bassett, 1974). It was also demonstrated that a maximum concentration of insulin was reached at 60 min post-prandially after a carbohydrate rich meal (Erdmann et al., 2003). In consistent with the results reported in the two aforementioned reports, the current experiment showed that plasma insulin concentrations responded differently among gilts fed 3 different feeding levels. For the gilts fed the lowest feeding level, insulin concentrations reached the maximum level in a rapid manner with attenuated values, while for gilts fed the highest feeding level, maximum insulin concentration was postponed with a higher value compared with the lowest feeding level.

NEFA is an indicator of fat mobilization and its concentration would be increased in the negative energy balance (Weldon et al., 1994c). As expected, gilts on the lower feeding level had higher plasma NEFA concentration than gilts on the higher feeding level, indicating that gilts eating less were exposed to a negative energy balance and thus mobilized more fat reserve to meet the daily energy requirement, which was further supported by the evidence that gilts on 0.5M and 1.0M feeding levels lost backfat during d 27 to 34 of gestation.

In the current experiment, we evaluated the effect of feeding levels during d 27 to 34 of gestation on consumption time of same amount feed (1.82 kg) on d 35 of gestation. We noted that gilts on 0.5M feeding level consumed feed much faster than gilts on 2.0M feeding level, suggesting that gilts on 0.5M feeding level were hungrier than gilts on 2.0M feeding level. Therefore, we proposed the idea of using consumption time as the dependent variable to examine its relationship with plasma hormones related to energy

homeostasis. The results indicated that AUC of acyl ghrelin was best single predictor for consumption time. Similarly, Lents et al. (2016) reported that plasma concentrations of acyl ghrelin were negatively correlated with meal length and positively associated with the number of meals for growing-finishing pigs. Due to the fact that NEFA and acyl ghrelin was significantly correlated, these two factors could not be incorporated in the same equation to estimate the consumption time.

Alternatively, BW and backfat changes during d 27 to 34 of gestation may indicate the status of energy homeostasis of gilts. Using these two parameters as the dependent variables, the results showed that AUC of NEFA was the best single predictor.

CONCLUSION

In conclusion, our data suggested that feed intake of pregnant gilts was negatively correlated with plasma concentrations of acyl ghrelin and NEFA, which in turn were negatively related to feed consumption time. There was no apparent pre- and post-prandial changes in plasma concentrations of acyl ghrelin during the period of early pregnancy in gilts. AUC of acyl ghrelin and NEFA seemed to be the best predictors for hunger status of pregnant gilts.

Table 5-1. Ingredient and nutrient composition of experimental diets for gestation and lactation (as-fed basis)

Item	Gestation	Lactation
Ingredient, %		
Corn	65.22	61.15
Soybean meal	10.00	17.20
cDDGS[1]	20.00	15.00
Choice white grease	1.50	3.00
Limestone	1.00	0.88
Dicalcium phosphate	1.20	1.15
Lysine HCl (78%)	0.10	0.46
DL-Methionine	-	0.01
L-Threonine	-	0.13
L-Tryptophan	-	0.04
Salt	0.35	0.35
Premix[2]	0.50	0.50
Tylan[3]	0.13	0.13
Nutrient composition		
ME, [4] kcal/kg	3,310	3,424
CP, [5] %	15.71	17.92
Total Ca, [5] %	0.72	0.68
STTD[6] P, [4] %	0.35	0.35
SID[7] Lys, [4] %	0.57	1.01
SID Met + Cys, [4] %	0.47	0.52
SID Thr, [4] %	0.44	0.64
SID Trp, [4] %	0.12	0.19

[1]cDDGS = Corn distillers dried grains with solubles (containing 27.3% CP, 5.47% EE, 0.05% Ca, 0.94% P and 0.77% Lys).

[2]Supplied the following nutrients per kilogram of diets: vitamin A, 12,114 IU; vitamin D, 2,753 IU; vitamin E, 66 IU; vitamin K, 4.4 mg; thiamine, 1 mg; riboflavin, 10 mg; niacin, 55 mg; pantothenic acid, 33 mg; pyridoxine, 2.2 mg; folic acid, 1.6 mg; vitamin B_{12}, 0.06 mg; I, 0.5 mg from ethylenediamine dihydriodide; Se, 0.3 mg from sodium selenite; choline, 548 mg from choline chloride; and metal polysaccharide complexes of zinc

sulfate (125 mg of Zn), iron sulfate (125 mg of Fe), manganese sulfate (40 mg of Mn), and copper sulfate (15 mg of Cu).

[3]Tylan™ 40 (Tylosin phosphate 40), Elanco Animal Health, Indianapolis, IN.

[4]Caculated values according to NRC (2012).

[5]Analyzed values.

[6]STTD = standardized total tract digestible.

[7]SID = standardized ileal digestible.

Table 5-2. Effects of different feeding levels during three short periods of gestation on gilt performance during gestation period 1 (d 27-34)

	Feeding levels[1]				
Items	0.5M	1.0M	2.0M	SEM	*P* value
Number of gilts	6	6	6		
BW change, kg	-6.14[a]	-1.82[a]	5.61[b]	1.18	<.01
BF change, mm	-0.75[a]	-0.38[a]	0.25[b]	0.27	<.01
ADG, kg/d	-0.88[a]	-0.36[a]	0.80[b]	0.17	<.01
Feed intake, kg	5.65[a]	11.30[b]	21.95[c]	0.43	<.01
Gain to Feed, kg/kg	-1.09[a]	-0.21[b]	0.26[c]	0.13	<.01

[1]0.5M, 1.0M and 2.0M represented 0.5, 1.0 and 2.0 × maintenance energy intake level ($100 \times BW^{0.75}$ kcal ME·d^{-1}), respectively.

[a,b,c]Least squares means within a row without common letters differ ($P < 0.01$).

Table 5-3. Effect of different feeding levels on the diurnal change of plasma concentrations of acyl ghrelin (pg/ml) during d 27-34 of gestation in gilts

	Time points[2]													
Feeding levels[1]	0 h	2 h	4 h	6 h	8 h	10 h	12 h	14 h	16 h	18 h	20 h	22 h	24 h	AUC[3]
0.5M	211.32	262.11	206.56	227.49	238.02	296.33	205.78	201.37	247.24	169.45	183.54	172.97	169.16	5162.35
1.0M	174.37	137.82	137.82	178.81	178.33	233.88	171.67	180.61	154.54	126.08	154.48	172.05	159.09	4040.69
2.0M	87.64	128.52	106.52	141.66	133.53	215.55	106.23	132.21	151.30	98.70	130.77	132.94	121.46	3251.14
SEM	19.69	33.60	23.43	29.28	21.19	13.30	24.17	31.58	21.42	17.64	15.40	10.24	38.45	411.60
P value	<.01	0.01	0.01	0.10	<.01	<.01	0.01	0.24	<.01	0.01	0.04	<.01	0.61	0.02

[1]0.5M, 1.0M and 2.0M represented 0.5, 1.0 and 2.0 × maintenance energy intake level (100 × $BW^{0.75}$ kcal ME·d^{-1}), respectively.

[2]Gilts were fed once daily at 7:30 am; 0 h represented right before feeding and the other time points represented the hours post-feeding.

[3]AUC = area under curve.

Table 5-4. Effect of different feeding levels on the postprandial plasma concentrations of insulin (μU/ml) during d 27-34 of gestation in gilts

	Time points[2]									
Feeding levels[1]	0 h	15 min	30 min	45 min	60 min	75 min	90 min	2 h	4 h	AUC[3]
0.5M	8.85	11.42	24.00	39.17	26.65	22.83	26.37	17.55	11.47	75.41
1.0M	8.17	17.28	31.70	78.35	50.25	47.40	39.00	20.02	19.68	116.60
2.0M	9.60	21.48	25.00	48.16	72.62	59.63	37.52	25.70	18.03	122.31
SEM	1.52	3.80	6.19	13.41	8.80	10.76	9.59	3.77	2.28	13.75
P value	0.80	0.18	0.63	0.07	<.01	0.05	0.60	0.30	0.03	0.06

[1]0.5M, 1.0M and 2.0M represented 0.5, 1.0 and 2.0 × maintenance energy intake level (100 × $BW^{0.75}$ kcal ME·d^{-1}), respectively.

[2]Gilts were fed once daily at 7:30 am; 0 h represented right before feeding and the other time points represented the minutes or hours post-feeding.

[3]AUC = area under curve.

Table 5-5. Effect of different feeding levels on plasma concentrations of GLP-1 (pg/ml), leptin (ng/ml) and non-esterified fatty acid (mmol/l) during d 27-34 of gestation in gilts

	GLP-1				Leptin				NEFA			
Feeding levels[1]	0 h	0.5 h	1 h[2]	AUC[3]	0 h	4 h	8 h	AUC	0 h	4 h	8 h	AUC
0.5M	174.13	207.47	218.52	201.90	0.90	1.43	0.96	9.42	0.47	0.29	0.17	2.43
1.0M	186.15	242.38	245.16	229.02	0.86	1.50	0.89	9.50	0.21	0.09	0.04	0.87
2.0M	279.44	351.44	355.95	334.57	1.09	1.55	1.04	10.46	0.13	0.09	0.03	0.68
SEM	49.43	49.43	49.43	52.77	0.09	0.09	0.09	0.62	0.03	0.02	0.02	0.15
P value	0.19	0.07	0.08	0.14	0.18	0.64	0.54	0.41	<.01	<.01	<.01	<.01

[1]0.5M, 1.0M and 2.0M represented 0.5, 1.0 and 2.0 × maintenance energy intake level (100 × $BW^{0.75}$ kcal $ME \cdot d^{-1}$), respectively.

[2]Gilts were fed once daily at 7:30 am; 0 h represented right before feeding and the other time points represented the hours post-feeding.

[3]AUC = area under curve.

Table 5-6. Pearson correlation matrix among consumption time, plasma hormones and free fatty acids concentrations

	Consumption time[1]	Ghrelin_AUC[1]	GLP-1_AUC[1]	Leptin_AUC[1]	Insulin_AUC[1]	NEFA_AUC[1]
Consumption time	1.00					
Ghrelin_AUC	-0.91**	1.00				
GLP-1_AUC	0.32	-0.64*	1.00			
Leptin_AUC	-0.15	-0.07	0.60*	1.00		
Insulin_AUC	0.43	-0.45	0.38	0.25	1.00	
NEFA_AUC	-0.71**	0.72**	-0.55*	-0.04*	-0.68	1.00

[1]Consumption time represents the least squares means of feed consumption time when all gilts were offered 1.82 kg of feed on d 35 of gestation. Ghrelin_AUC, GLP-1_AUC, Leptin_AUC, Insulin_AUC and NEFA_AUC represented the area under curve calculated for each parameter.

**$P < 0.01$; *$0.01 < P < 0.05$.

Table 5-7. Pearson correlation matrix among BW and backfat change during period 1 (d 27-34), plasma hormones and free fatty acids concentrations

	BW_change[1]	BF_change[1]	Ghrelin_AUC[1]	GLP-1_AUC[1]	Leptin_AUC[1]	Insulin_AUC[1]	NEFA_AUC[1]
BW_change	1.00						
BF_change	0.84***	1.00					
Ghrelin_AUC	-0.50*	-0.64**	1.00				
GLP-1_AUC	0.27	0.49*	-0.64**	1.00			
Leptin_AUC	-0.01	0.24	-0.07	0.60**	1.00		
Insulin_AUC	0.48*	0.52*	-0.45	0.38	0.25	1.00	
NEFA_AUC	-0.77***	-0.69***	0.72***	-0.55**	-0.04	-0.68**	1.00

[1]BW and BF change represent changes of gilt BW and backfat, respectively, during gestation period 1 (d 27-34 of gestation). Ghrelin_AUC, GLP-1_AUC, Leptin_AUC, Insulin_AUC and NEFA_AUC represented the area under the curve calculated for each parameter.

***$P < 0.01$, **$0.01 < P < 0.05$, and *$0.05 < P < 0.10$.

Table 5-8. Simple linear relationships between consumption time and plasma parameters, and between gilt BW or BF change during period 1 (d 27-34 of gestation) and plasma parameters

Equation number	Equations	R^2	Root MSE
1	Consumption time = $40.38 - 2.88 \times 10^{-2} \times$ ghrelin_AUC	0.82	1.52
2	Consumption time = $32.31 - 2.81 \times$ NEFA_AUC	0.46	2.59
3	BW_change = $10.40 - 2.67 \times 10^{-2} \times$ ghrelin_AUC	0.18	5.38
4	BW_change = $-8.77 - 0.07 \times$ Insulin_AUC	0.16	5.43
5	BW_change = $6.27 + 5.14 \times$ NEFA_AUC	0.55	3.97
6	BF_change = $2.47 - 5.48 \times 10^{-4} \times$ ghrelin_AUC	0.36	0.76
7	BF_change = $-1.23 - 5.80 \times 10^{-3} \times$ GLP-1_AUC	0.17	0.87
8	BF_change = $-1.19 - 0.01 \times$ Insulin_AUC	0.21	0.85
9	BF_change = $1.19 - 0.73 \times$ NEFA_AUC	0.42	0.72

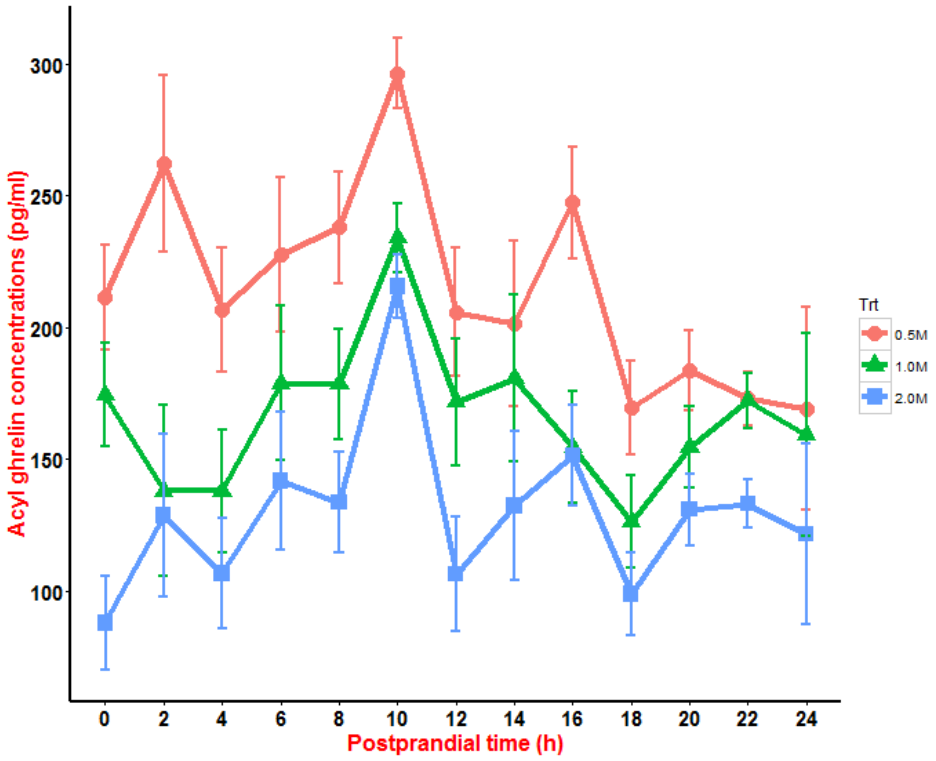

Figure 5-1. Effect of different feeding levels on the diurnal change of plasma acyl ghrelin concentrations during d 27-34 of gestation in gilts

Note: Gilts were fed once daily at 7:30 am; 0 h represented right before feeding and the other time points represented the hours post-feeding.

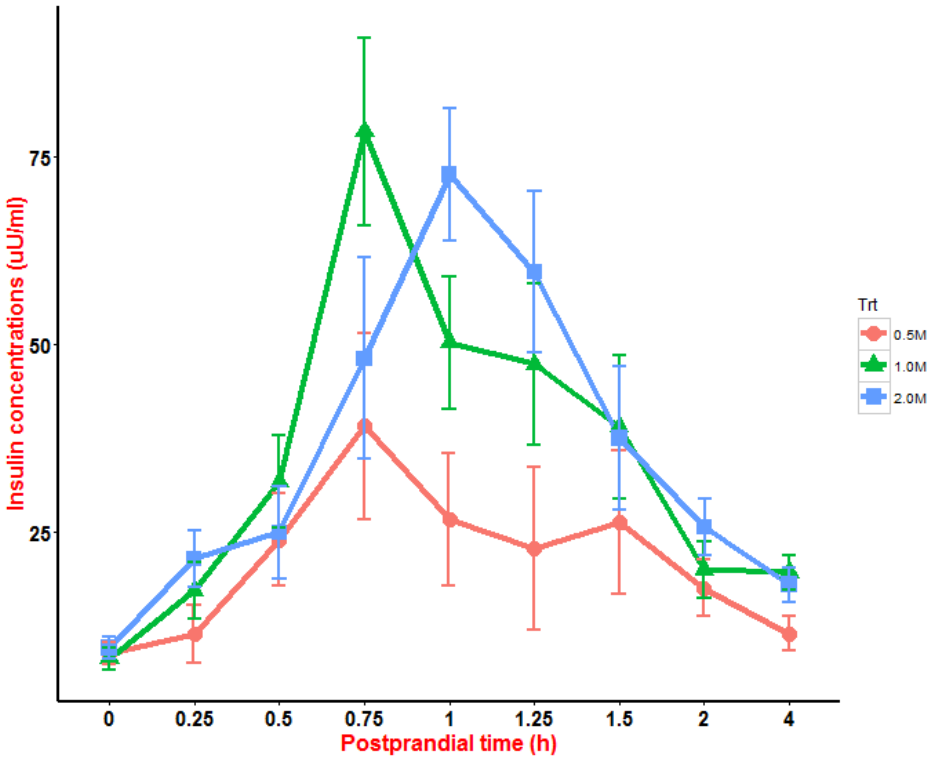

Figure 5-2. Effect of different feeding levels on the postprandial plasma insulin concentrations during d 27-34 of gestation in gilts

Note: Gilts were fed once daily at 7:30 am; 0 h represented right before feeding and the other time points represented the hours post-feeding.

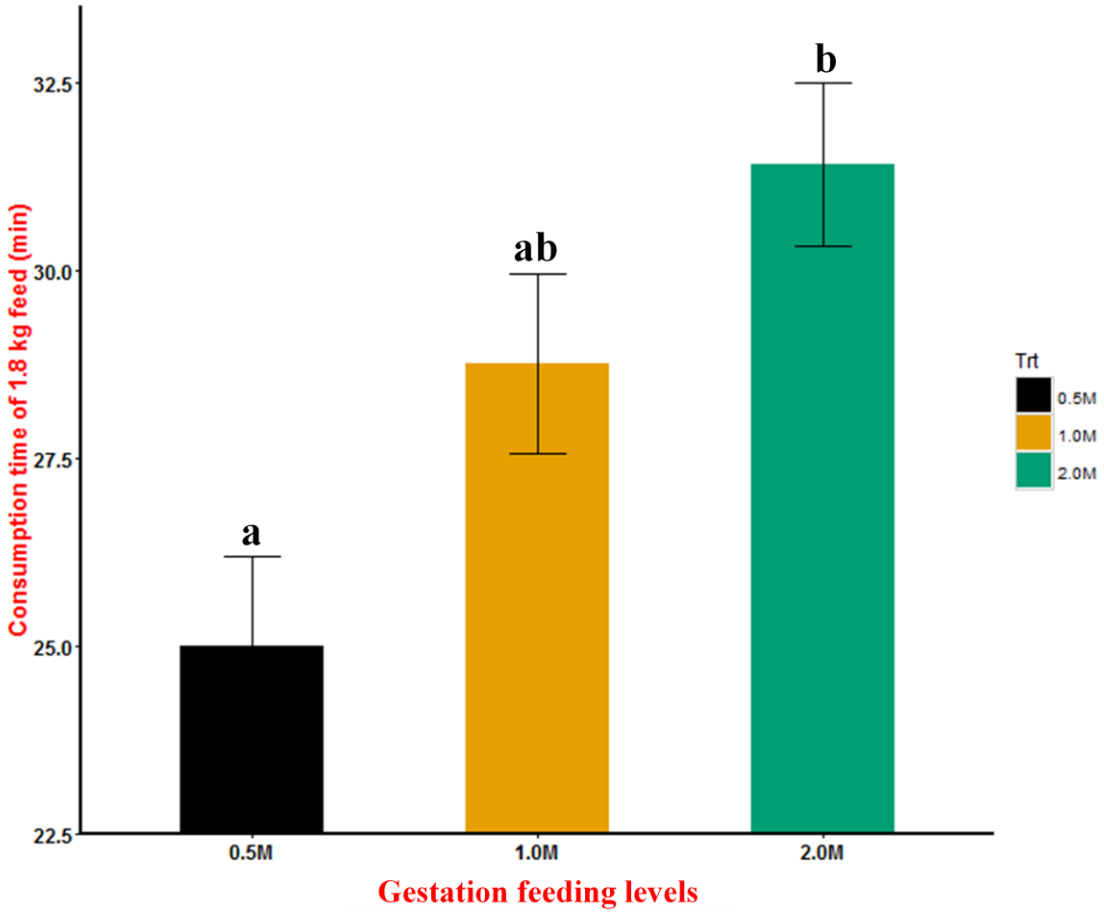

Figure 5-3. Effect of feeding levels on the consumption time (min) of gilts offered 1.82 kg of feed at d 35 of gestation.

Note: Values were least squares means of 6 animals per feeding level, with their standard errors represented by vertical bar. Significant difference ($P < 0.01$) existed between 0.5M and 2.0M feeding levels.

Chapter 6. Overall summary and implications

Enhancing reproductive performance through nutritional strategies in gestation and lactation sows has been the research of interest for several decades. It has been proposed that maintaining an ideal body condition, especially BF, throughout a sow lifetime is essential for maximizing reproductive performance and sow longevity (Young et al., 2004). Therefore, nutritional strategies which aim to maintain a constant sow BF throughout the reproductive cycle, would be successful in improving reproductive performance and sow longevity.

The aim of this dissertation was to determine the effect of imposing different feeding levels during several short periods of gestation on sow and litter performance, and its impact on subsequent reproductive performance. The interactive effect between feeding levels and housing systems was also examined in terms of reproductive performance. Additionally, effect of feeding levels during 3 short periods of gestation on apparent digestibility of energy and nutrients was assessed in order to understand the energy and nutrient utilization in response to different feeding levels. Furthermore, effect of different feeding levels on diurnal profile of plasma hormones and metabolites related to feed intake regulation and energy homeostasis was evaluated in pregnant gilts.

In Chapter 2 and 3, two experiments were conducted to determine the effects of feeding levels during 4 or 3 short periods of gestation on sow and litter performance, and its impact on subsequent reproductive performance. Interactive effect between feeding levels and housing systems on sow and litter performance was also evaluated in Chapter 2. Results from these two experiments showed that increasing feeding levels during either 4 or 3 short periods of gestation increased sow BW and BF gain during gestation, but led to

less BW gain and more BF loss during lactation. In addition, lactation ADFI was linearly reduced with the increase of gestation feeding levels during either 4 or 3 short periods of gestation. Both feeding levels during 4 or 3 short periods of gestation and housing systems did not affect reproductive performance. Subsequent reproductive performance was also not affected by feeding levels during 3 short periods of gestation. Furthermore, group pen housing system may be beneficial in terms of increased overall BW gain throughout gestation and lactation.

It was noted that sows on the 4 feeding levels during the 4 or 3 short periods of gestation all gained considerable amount of BW during whole gestation and lactation cycle, but only sows on 2.0M feeding level had limited BF gain during the whole reproductive cycle. These results indicated that feeding gestation sows at two times maintenance energy intake level for only 3 or 4 wks with the maintenance energy intake level during the rest of the gestation period was able to meet the energy and nutrient requirement of gestation sows for optimal reproductive performance. These two experiments also indicated that the current maintenance energy requirement of gestation sows may be underestimated or overestimated depending on gestation stage.

In Chapter 4, effect of feeding levels on apparent energy and nutrient digestibility was investigated using pregnant gilts. The finding showed that apparent digestibility of energy and nutrients were maximized for gilts on 1.0M feeding level. Interestingly, the slopes of BW change for period 1 (d 27 to 34 of gestation) were 4.32 and 3.72 kg/0.5M change from 0.5M to 1.0M feeding level and from 1.0M to 2.0M feeding level, respectively, indicating that an apparent reduction of slope at 1.0M feeding level, which was in correspondence with the findings of apparent digestibility of energy and nutrients. These

findings demonstrated that energy and nutrient utilization was maximized at 1.0M feeding level.

In Chapter 5, effect of different feeding levels on the diurnal profile of plasma hormones and metabolites related to energy homeostasis was assessed in pregnant gilts. The findings suggested that a relatively flat pattern existed in pregnant gilts in terms of diurnal profile of plasma acyl ghrelin concentration and that feed intake of pregnant gilts was negatively correlated with plasma concentrations of acyl ghrelin and NEFA, which in turn was negatively associated with feed consumption time of a certain amount of feed (1.8 kg) and BW/BF change. Therefore, we proposed that AUC of acyl ghrelin and NEFA were the best physiological predictors for hunger status or energy homeostasis of pregnant gilts.

The first two experiments from this dissertation implicated that modification of feeding levels during gestation could optimize reproductive performance and reduce the feed cost to a greater extent. The findings from these two experiments could serve as the guideline of the application of feeding levels during gestation for pork producers to improve reproductive performance and maximize economic returns. In addition, the third experiment underlined the mechanism regarding how the feeding levels affected energy and nutrient utilization. Furthermore, the fourth experiment suggested stable acyl ghrelin concentrations may be responsible for fetal development and maintaining pregnancy. The fact that acyl ghrelin and NEFA were the best physiological indicators for hunger status or energy homeostasis could serve as a reference to evaluate the hunger status of gestation sows due to the public concern of welfare of gestation sows. The findings from

this dissertation will facilitate future research to find solutions to improve the welfare of gestation sows without compromising reproductive performance.

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