# A review of heavy weight market pigs: status of knowledge and future needs assessment[1]

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**ABSTRACT:** Marketing weight is an important economic variable that impacts the productivity and profitability of finishing pig production. Marketing weight has been increasing worldwide over the past decades driven by the dilution of fixed production cost over more weight per pig and the improvement of genetic selection of lean-type pigs. This review was aimed to summarize current knowledge and assess the future research needs on producing finishing pigs with marketing weight greater than 130 kg. Based on a thorough literature review, increasing marketing weight affected overall pig growth; in particular, cumulative average daily gain (ADG) decreased by 4.0 g, average daily feed intake (ADFI) increased by 78.1 g, and gain-to-feed ratio (G:F) decreased by 0.011 for every 10 kg increase of marketing weight. Increasing marketing weight by 10 kg increased carcass yield by 0.41% units, backfat by 1.8 mm, longissimus muscle (LM) area by 1.9 cm$^2$, carcass length by 2.2 cm, and belly yield by 0.32% units, but decreased percentage of fat-free-lean by 0.78 units and decreased loin, shoulder, and ham yields by 0.13, 0.16, and 0.17% units, respectively. Studies that inves-tigated the effects of marketing weight on pork quality observed decreased pH by 0.02 and 0.01 at 45 min and 24 h postmortem, respectively, and increased a* value by 0.28 per 10 kg marketing weight increase. Heavier market pigs had increased concentrations of saturated fatty acids and intramuscular fat. However, studies reported conflicting results for L* and b* values, drip loss, Warner-Bratzler shear force, and sensory proper-ties of pigs in response to increasing marketing weight. A limited amount of research has been conducted to estimate nutrient requirements for pigs greater than 140 kg. Increased weight and size of heavy pigs can create challenges to farm and packer facilities and equipment. Discussions and recommendations are provided concerning the adjustments for floor and feeder space, barn design, ventilation, disease con-trol, transportation, and carcass processing needed for increasing marketing weight. In conclusion, increas-ing marketing weight creates both opportunities and challenges to current finishing pig production, and future research is needed to provide nutritional and management guidelines and improve feed efficiency and meat quality of heavy weight market pigs.

**Key words:** carcass quality, growth, heavy pig, marketing weight, meat quality

## INTRODUCTION

Marketing weight is an important variable that affects the profitability of finishing pig production due to its impact on pig growth, efficiency, and the quantity and quality of pork produced. Average marketing weight in the U.S. has been steadily increasing for over 80 yr and increased from 121.1 kg in 2004 to 125.6 kg in 2013 (NASS, 2014). A dilution of fixed production cost is a major force that drives the increase of market-ing weight because the total number of pigs required to produce a given quantity of pork is reduced (Park and Lee, 2011). A drawback of the increased market-ing weight is reduced gain-to-feed ratio (G:F) result-ing from accelerated fat accretion and a declining rate

of lean deposition during in the late finishing phase (Shields et al., 1983; Gu et al., 1991; Piao et al., 2004). In addition, increased weight and size of heavy pigs creates challenges to farm facilities and equipment, such as floor and feeder space, ventilation, and transportation systems, which in turn affects pig growth performance.

Some additional factors that require consideration when increasing marketing weight include genetic selection and nutritional requirements. Lean-genotype pigs are needed to prolong the period of efficient weight gain, while the selection for lean gain rate should also be balanced with the requirements of meat quality and animal health attributes. From a nutritional prospective, nutrient requirements are established for pigs less than 140 kg (NRC, 2012); however, pigs with further increased body weight (BW) have greater maintenance needs than lighter BW and therefore, additional research is needed to provide nutritional guidelines. Finally, information regarding the impact of meat quality with increasing marketing weight, such as color, primal cut yields, and intramuscular fatness of heavy pigs and its subsequent impact on consumer preference are needed. This review evaluated published studies involving genetic selection, nutritional requirements, health, welfare, and pork quality of heavy weight market pigs and assessed future research needs.

## MATERIALS AND METHODS

Examination of published studies was conducted via the Kansas State University Libraries, using databases including AGRICOLA, CAB International, MEDLINE, National Pork Board Research Database, and SCOPUS. No yr of publication limits was set in any of the electronic database searches. Additional search of literature was performed within the following journals: *Journal of Animal Science*, *Animal*, *Animal Feed Science and Technology*, *Meat Science*, *Livestock Science*, and *Livestock Production Science*. Key words used for the above databases included: "heavy pig*", "heavy hog*", "heavy weight", "finishing pig*", "finishing hog*", "late finishing pig*", "late finishing hog*", "slaughter weight", "harvest weight", "marketing weight", along with the key words associated with the aspects of selection/genetics, nutrition, pork/meat quality, pork safety, and swine health and well-being. In addition, non-peer-reviewed publications (i.e., university extension and company reports) were also collected, closely scrutinized for accuracy and quality, and served as valuable resources of information for this review. Conference proceedings and abstracts that were not included in the peer-reviewed databases were searched using Searchable Proceedings of Animal Conferences (S-PAC) and Google Scholar

search engine. Additionally, personal communication with genetic and production companies, university researchers, and packing plant personnel were performed for the collection of internally-generated information that had application for this review.

In this review, heavy weight market pigs refer to pigs with marketing weight greater than 130 kg. For the summary of marketing weight effects on pig growth performance, carcass characteristics, and pork quality, the data set excluded studies in which the greatest marketing weight used was less than 125 kg and pigs did not have ad libitum access to feed during the experiment. The screening threshold of 125 kg was adopted to obtain data from pigs marketed slightly lighter than the definition of heavy pig to improve the modeling quality. Sensitivities of growth, carcass, and pork quality traits in response to increasing marketing weight by 10 kg were generated using simple linear regression. These analyses were based on the assumption that traits had linear responses to the increase in marketing weight and there were no interactive effects between marketing weight and other factors (i.e., gender, inclusion of growth promoters). Such assumptions could be challenged; however, a simple linear regression approach was adopted because of the limited number of observations available for many of the response criteria. Average responses were reported as the mean among studies. In the calculation of average responses, studies by Latorre et al. (2004 and 2008) were excluded for average daily gain (ADG),average daily feed intake (ADFI), and G:F, because pigs were reported to be under heat stress, and a study by Serrano et al. (2008) was excluded for growth and carcass traits due to the use of Iberian obese pig breed that is typically not used in North America pig production. A study by Piao et al. (2004) was excluded in the calculation for drip loss due to the abnormally high value reported (greater than 3 standard deviations from the mean of all values).

## RESULTS AND DISCUSSION

### *Impact of Marketing Weight on Growth Performance, Carcass Characteristics, and Meat Quality*

***Growth Performance.*** Numerous studies have been conducted to investigate the effects of increasing marketing weight on growth performance (i.e., ADG, ADFI, and G:F) of growing-finishing or finishing pigs. A total of 14 experiments involving pigs harvested at weights greater than 125 kg were summarized in Table 1. Although instantaneous gain rate and feed intake of pigs follow allometric patterns as BW increases (sigmoid growth curve; Schinckel et al., 2006; Shull, 2013), we plotted the cumulative ADG and ADFI values against marketing weight

**Table 1.** Summary of studies investigating the effects of market weight on overall growth performance (changes per 10 kg marketing weight increase)[1]

| Reference | Initial wt, kg | Marketing wt, kg | Pigs/pen | Space/pig, m$^2$ | Total pigs | ADG[3], g | ADFI[3], g | G:F[3] |
|---|---|---|---|---|---|---|---|---|
| Neely et al. (1979) | 15 | 100,113,127 | 6 | - | 200 | 8.7 | 52.7 | -0.004 |
| Sather et al. (1980) | 2 | 73,84,98,109,123,134 | 4 | 1.44 | 288 | -16.0 | 102.0 | -0.015 |
| Kanis et al. (1990) | 60 | 100,140 | 1 | - | 96 | -19.5 | 56.3 | -0.012 |
| Johnston et al. (1993) | 59 | 105,127 | 3 | 2.30 | 120 | 8.0 | 54.0 | -0.003 |
| Cisneros et al. (1996) | 60 | 100,115,130,145,160 | 4 | 1.17 | 160 | 4.0 | 100.0 | -0.006 |
| Leach et al. (1996) | 40 | 110,125,140 | 4 | 1.20 | 144 | -18.6 | - | -0.010 |
| Weatherup et al. (1998)[2] | 50 | 92,103,113,125 | 1 | 6.00 | 96 | -9.2 | 111.3 | -0.017 |
| Weatherup et al. (1998)[4] | 50 | 92,103,113,125 | 6 | 1.00 | 288 | 2.8 | 91.9 | -0.014 |
| Latorre et al. (2003) | 25 | 122,136 | 5 | 1.10 | 240 | 7.1 | 78.6 | -0.009 |
| Latorre et al. (2004) | 75 | 116,124,133 | 8 | 1.00 | 192 | -38.0 | -3.0 | -0.010 |
| Piao et al. (2004) | 27 | 100,110,120,130 | 4 | 1.01 | 224 | -7.3 | 76.4 | -0.014 |
| Latorre et al. (2008) | 107 | 120,125,130,135,140 | 10 | 1.05 | 200 | -54.9 | -78.0 | -0.010 |
| Serrano et al. (2008) | 25 | 145,156 | 15 | 1.50 | 360 | 8.2 | 163.6 | -0.013 |
| Shull (2013) Exp.2 | 6 | 113,125,136,147,159,170,181 | 20 | 1.06 | 2240 | -3.6 | 58.1 | -0.012 |
| Average[5] | - | - | - | - | - | -4.0 | 78.1 | -0.011 |

[1]Generated by simple linear regression analyses by EXCEL.

[2]Individual housing was evaluated.

[3]ADG = Average daily gain, ADFI = Average daily feed intake, and G:F = Gain-to-feed ratio.

[4]Group housing was evaluated.

[5]Studies by Latorre et al. (2004 and 2008) were excluded from the calculation because pigs were reported to be under heat stress; study by Serrano et al. (2008) was excluded from calculation due to the use of Iberian obese pig breed that was uncommonly used in north America pig production.

reported by the reviewed studies and observed linear growth responses to increasing marketing weight. Eight out of the 14 reviewed studies reported a decrease in cumulative ADG of 3.6 to 54.9 g for every 10 kg increase in marketing weight, whereas the remaining studies showed increased ADG of 2.8 to 8.7 g when marketing weight increased by 10 kg. Cumulative ADFI was reported in 13 studies with ADFI increasing by 52.7 to 163.6 g in 11 studies. Conversely, ADFI decreased by 3.0 and 78.0 g in 2 studies [Latorre et al. (2004 and 2008), respectively] where heat stress of pigs under severe summer weather was reported. Reduction in cumulative G:F was observed in all the reviewed studies with the magnitude varying from 0.003 to 0.017 units per 10 kg marketing weight increase. On average (calculation excluded data from Latorre et al. (2004 and 2008) due to suppressed ADFI and data from Serrano et al. (2008) due to the use of an Italian obese pig breed), increasing marketing weight by 10 kg decreased cumulative ADG by 4.0 g, increased ADFI by 78.1 g, and decreased G:F by 0.011.

It is not surprising that pigs marketed at heavy weights have elevated ADFI, because the increased body size and physical capacity of the digestive tract improve the ability of pigs to consume more feed (Suarez-Belloch et al., 2013). Nevertheless, the efficiency of BW gain declines greatly during the late growth stages, which is attributed to accelerated fat accretion and declining rates of water and protein deposition (Shields et al., 1983; Gu et al., 1991; Piao et al., 2004). Increased

maintenance requirements in heavy finishing pigs may also contribute to decreased G:F (Gu et al., 1991). For the ADG response, researchers (Schinckel et al., 2006; Jungst et al. (2012a,b); Shull, 2013) have demonstrated that the instantaneous growth rate of growing-finishing pigs (average between barrow and gilt) reaches a plateau at an average BW of 78 to 85 kg and decreases thereafter. However, evaluating data from the 14 experiments, it is difficult to accurately describe why cumulative ADG was improved in half of the experiments and diminished in the other half. Possible explanations of this discrepancy can be proposed. First, nutritional programs used and, particularly, the dietary energy and protein supply, varied among these studies, which would influence the growth responses of pigs at increasing marketing weight. Second, selection of the initial and terminal BW as well as number of marketing groups differed among studies and could also be a factor. Generally, the greater the initial BW (shorter overall feeding period) and wider range of marketing weight used, the more prominent responses were observed. However, use of wide marketing weight range tended to result in a quadratic response of cumulative ADG to increasing marketing weight (Shull, 2013), which also affected the precision of linear quantification for ADG. Third, housing system and especially the floor and feeder spaces allowance could affect the ADFI and, subsequently, ADG of pigs. Furthermore, dissimilar genetic lines of pigs used in the studies had varied growth

**Table 2.** Summary of studies investigating the effects of marketing weight on carcass characteristics (changes per 10 kg marketing weight increase)[1]

| Reference | Marketing wt, kg | Yield, % | Backfat, mm | Fat-free lean, % | LM[2] area, cm[2] | Length, cm | Subprimal yield, % | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | | | | | | Belly | Loin | Shoulder | Ham |
| Hansson (1975) | 68,88,108,128 | 0.84 | 2.1 | -1.03 | 1.7 | 3.1 | - | - | - | - |
| Carr et al. (1978) | 45,68,91,114,136 | - | 2.0 | -1.00 | 2.2 | 2.4 | - | - | - | -0.09 |
| Neely et al. (1979) | 100,113,127 | - | 1.0 | 0.07 | 2.0 | 1.9 | - | - | - | - |
| Sather et al. (1980) and Martin et al. (1980) | 73,84,98,109,123,134 | - | - | -0.47 | 2.3 | 2.3 | 0.53 | - | -0.48 | -0.20 |
| Shields et al. (1983) | 56,76,90,107,127,146 | 1.05 | 2.8 | - | 1.7 | 2.3 | 0.12 | -0.19 | -0.15 | -0.28 |
| Kanis et al. (1990) | 100,140 | - | 1.1 | -0.55 | - | - | - | - | - | - |
| Gu et al. (1991 and 1992) | 100,114,127 | 0.34 | 3.0 | -1.09 | 1.1 | 2.3 | - | - | - | - |
| Johnston et al. (1993) | 105,127 | 0.05 | 0.9 | -0.18 | 2.7 | - | - | - | - | - |
| Crome et al. (1996) | 107,125 | 0.33 | 2.1 | - | 1.2 | 2.1 | 0.61 | -0.18 | - | 0.14 |
| Cisneros et al. (1996) | 100,115,130,145,160 | 0.32 | 1.6 | - | 1.8 | 1.9 | 0.09 | 0.40 | -0.18 | -0.16 |
| Leach et al. (1996) | 110,125,140 | 0.16 | 1.4 | -1.59 | 0.1 | 1.7 | 0.45 | -0.38 | 0.08 | -0.19 |
| Weatherup et al. (1998)[3] | 92,103,113,125 | 0.68 | 1.6 | -1.28 | - | - | - | - | - | - |
| Weatherup et al. (1998)[4] | 92,103,113,125 | 0.35 | 1.5 | 0.09 | - | - | - | - | - | - |
| Beattie et al. (1999) | 96,108,121,133 | 0.29 | - | - | 2.2 | - | - | - | - | - |
| Wagner et al. (1999) | 25,45,64,84,100,129,152 | 0.67 | 2.3 | -0.77 | 2.3 | 2.7 | - | -0.09 | - | -0.19 |
| Latorre et al. (2003) | 122,136 | 0.29 | 0.5 | - | - | 2.1 | - | -0.21 | -0.21 | -0.36 |
| Virgili et al. (2003) | 144,182 | 0.34 | - | - | 1.5 | - | - | -0.29 | -0.32 | -0.19 |
| Latorre et al. (2004) | 116,124,133 | 0.77 | 2.9 | - | - | 2.4 | - | - | -0.29 | 0.04 |
| Piao et al. (2004) | 100,110,120,130 | -0.49 | 0.9 | 0.05 | 2.3 | 3.1 | - | - | - | - |
| Correa et al. (2008) | 107,115,125 | 0.41 | - | - | - | 2.0 | 0.13 | -0.12 | 0.12 | -0.28 |
| Corino et al. (2008) | 111,160 | 0.38 | 2.0 | -1.85 | - | - | - | -0.06 | - | - |
| Latorre et al. (2008) | 120,125,130,135,140 | 0.48 | 2.5 | - | - | 1.3 | - | -0.18 | -0.02 | -0.34 |
| Serrano et al. (2008) | 145,156 | 0.91 | 1.2 | - | - | - | - | -0.18 | 0.09 | 0.36 |
| Shull (2013) Exp.1 | 75,91,106,121,134,147,168 | - | 1.7 | - | 2.6 | - | - | - | - | - |
| Shull (2013) Exp.2 | 115,124,134, 145,157,166,176 | 0.43 | 1.8 | -1.36 | 1.9 | - | - | - | - | - |
| Average[5] | - | 0.41 | 1.8 | -0.78 | 1.9 | 2.2 | 0.32 | -0.13 | -0.16 | -0.17 |

[1]Generated by simple linear regression analyses by EXCEL.

[2]LM = longissimus muscle.

[3]Individual housing was evaluated.

[4]Group housing was evaluated.

[5]Study by Serrano et al. (2008) was excluded from calculation due to the use of Iberian obese pig breed which was uncommonly used in north America pig production.

patterns at heavy weights. Lean-type pigs are desired for producing pigs marketed at heavy weights (Kim et al., 2005). However, some of the reviewed studies were performed on pigs that were aimed for dry-cured ham production (Latorre et al. (2004 and 2008); Serrano et al., 2008), which were often selected for high fat thickness; discrepant growth responses of these pigs could be expected when compared with modern lean-type pigs. Finally, quantification of growth responses is also determined by the methodology used in the studies. Only studies reporting cumulative growth responses were compared herein because relatively few studies (Carr et al., 1978; Gu et al., 1991; Shull, 2013) in the literature reported instantaneous growth rate and the methodologies utilized to measure instantaneous growth rate differed among these studies.

***Carcass Characteristics.*** Increasing marketing weight greatly affects carcass characteristics of pigs.

For this analysis, 25 studies were reviewed where carcass traits of pigs with increasing market weight were determined (Table 2). Twenty studies evaluated the percentage carcass yield of pigs harvested at heavy weights; increased yield was documented in 19 studies ranging from 0.05 to 1.05% units per 10 kg increase in marketing weight. Across all studies, the mean increase in carcass yield was approximately 0.41% units per 10 kg marketing weight increase. Increased carcass yield was due to a greater allometric growth coefficient of carcass than the whole body (Gu et al., 1992). Shields et al. (1983) suggested that the carcass only represented 70% of the live weight at 56 kg, but 79% by 146 kg; whereas, the relative proportion of the intestinal tract decreased from 5.6% to 4.3%, and that of internal organs also decreased from 4.5% to 3.2%. However, one study reported a reduced yield of 0.49% units per 10 kg increase of marketing weight (Piao et al., 2004). This

study was conducted in Korea where the definition and methodology of calculating carcass yield might have been different from that in North America.

All studies considered in this review observed an increase in backfat thickness with increased marketing weight. However, increases in backfat varied among studies, ranging from 0.5 to 3.0 mm per 10 kg marketing weight increase. Across the studies reviewed, there was an average increase in backfat of 1.8 mm per 10 kg increase in marketing weight. In terms of overall fat deposition, there is little published research evaluating specific areas of deposition, with the exception of the belly and back fat. Correa et al. (2008) reported significant increases in belly fat thickness as marketing weight increased from 107 to 125 kg, though no other studies have evaluated this trait.

Percentage fat-free lean, as provided in the cited studies, decreased with increased marketing weight in most studies. The observed reduction in percentage fat-free lean was most likely due to the increased backfat found in heavy pigs. In contrast, 3 studies found an increase in percentage fat-free lean ranging from 0.05 to 2.28 unit per 10 kg increase in marketing weight. Interestingly, the studies reported an increase in percentage fat-free lean were those that used greater initial BW and narrow ranges between initial and marketing weights than other studies.

As marketing weight increases, there is a general trend of increasing longissimus muscle (LM) area and carcass length, which can be explained by the greater body size of heavy pigs. All the reviewed studies found an increase in LM area ranging from 0.1 to 2.7 cm$^2$, with an average of 1.9 cm$^2$ per 10 kg marketing weight increase. All the reviewed studies observed increasing carcass length with greater marketing weights. However, wide variation of the increase in carcass length was present ranging from 1.3 to 3.1 cm, with an average of 2.2 cm, per 10 kg of additional BW. Increased carcass length may cause issues in processing plants if pigs are too large to fit through typical equipment, such as rails, scalders, carcass splitters, and other mechanized fabrication equipment.

A total of 14 studies evaluated the effects of increasing marketing weight on subprimal cut yields. Belly yield increased with increasing marketing weight in all studies, ranging from only 0.09 to 0.61% units per 10 kg marketing weight increase. In regards to lean primal cuts, yields were generally decreased. Ten studies observed decreased loin yield, ranging from 0.09 to 0.38% units per 10 kg marketing weight increase. However, Cisneros et al. (1996) reported an increase in loin yield of 0.4% yield per 10 kg increase in marketing weight. Of the 10 studies that evaluated shoulder yield, 7 studies reported a decrease ranging from 0.48 to 0.02% units per 10 kg marketing weight increase. However, 3 studies found a slight increase in shoulder yield ranging from 0.08 to 0.09% units per

10 kg marketing weight increase. Ham yield was affected similarly to shoulder and loin yields. As marketing weight increased, ham yield decreased in 10 out of the 13 studies. Decreases in ham yield ranged from 0.09 to 0.36% units per 10 kg increase in marketing weight. However, 3 studies reported slight increases in ham yield; this might be related to how the loin was removed, as Latorre et al. (2004) and Serrano et al. (2008) were studies done with Italian heavy weight pigs. In addition, it is important to note that changes of primal cut yields were affected by whether the data reported trimmed or untrimmed cuts. More prominent responses could be expected for untrimmed cuts because a great amount of fat was deposited on the cuts during the last stages of growth. On average, increasing marketing weight by 10 kg increased belly yield by 0.32% units, but reduced loin, shoulder, and ham yields by 0.13, 0.16, and 0.17% units, respectively.

***Pork Quality.*** Pork quality is important for several reasons, including product functionality, consumer preference, and palatability. Several studies have evaluated pork quality traits as it relates to increased marketing weight (Table 3). These include: pH, drip loss, cooking loss, Warner-Bratzler shear force, intramuscular fat or marbling scores, iodine value, as well as instrumental color scores and sensory panel data.

The majority of published literature has observed a decrease in pH as carcass weight increases. Decreased pH negatively affects drip loss, color, and several other pork quality traits. All the 6 studies reported initial pH measured at 45 min to 1 h postmortem, and 6 out of 8 studies evaluated ultimate pH at 24 h postmortem observed decreased pH values when increasing marketing weights. Beattie et al. (1999) and Martin et al. (1980) showed significant decreases in pH at 1 h postmortem, but no significant differences at 24 h or in ultimate pH when comparing pigs with increasing marketing weight from 92 to 131 kg and 73 to 137 kg, respectively. Additionally, Martin et al. (1980) also reported a negative, but weak, correlation ($r$ = -0.05) between carcass weight and 1 h pH. When comparing pigs at 8 mo of age (143.6 kg BW) versus those 10 mo of age (181.8 kg BW), Virgili et al. (2003) observed a 0.05 unit reduction in pH of the semimembranosus at 1 h as well as at 24 h as marketing weight increased by 10 kg. Moreover, Cisneros et al. (1996) reported a reduction of pH at a rate of 0.01 unit at 45 min and a 0.02 unit reduction at 24 h postmortem per 10 kg of additional BW. Park and Lee (2011) observed a 0.02 unit reduction in 24 h pH per 10 kg increase in marketing weight from 116 to 133 kg. In a study involving pigs with increasing marketing weight from 120 to 170 kg, Durkin et al. (2012) observed a quadratic response of pH at 45 min postmortem. In that study, pH of semimembranosus increased

**Table 3.** Summary of studies investigating the effects of marketing weight on pork quality (changes per 10 kg marketing weight increase)[1]

| Reference | Marketing wt, kg | L* | a* | b* | Initial pH | Ultimate pH | Drip loss, % | WBSF[2], kg |
|---|---|---|---|---|---|---|---|---|
| Beattie et al. (1999) | 92, 105, 118, 131 | 0.52 | -0.02 | 0.18 | - | -0.01 | 0.22 | -0.05 |
| Bertol et al. (2015)[3] | 100, 115, 130, 145 | -0.23 | 0.23 | - | -0.05 | 0.01 | 0.34 | - |
| Bertol et al. (2015)[4] | 100, 115, 130, 146 | 0.04 | 0.16 | - | -0.04 | - | 0.08 | 0.14 |
| Cisneros et al. (1996) | 100, 115, 130, 145, 160 | - | - | - | -0.01 | -0.02 | 0.29 | -0.08 |
| Durkin et al. (2012) | 120, 130, 140, 150, 160, 170 | -0.14 | 0.34 | 0.10 | -0.02 | -0.01 | 0.27 | 0.01 |
| Leach et al. (1996) | 110,125,140 | -1.23 | 0.30 | -0.14 | -0.01 | - | -0.35 | 0.24 |
| Latorre et al. (2004) | 116, 124, 133 | -2.48 | - | -0.24 | - | - | - | 0.11 |
| Moon et al. (2003) | 95, 105, 115, 125 | - | - | - | - | -0.04 | 0.21 | - |
| Piao et al. (2004) | 100, 110, 120, 130 | 1.15 | 1.18 | 0.42 | - | 0.02 | -4.75 | -0.04 |
| Virgili et al. (2003)[5] | 144,182 | -0.01 | 0.10 | -0.17 | -0.01 | -0.05 | - | 0.16 |
| Virgili et al. (2003)[6] | 144,182 | - | - | - | - | - | -0.34 | - |
| Weatherup et al. (1998) | 92,103,113,125 | 0.17 | 0.12 | 0.20 | - | -0.01 | 0.30 | - |
| Average[7] | | -0.25 | 0.30 | 0.05 | -0.02 | -0.01 | -0.11 | 0.06 |

[1]Generated by simple linear regression analyses by EXCEL.

[2]Warner-Bratzler Shear Force.

[3]Ham was evaluated.

[4]Longissimus dorsi was evaluated.

[5]Semimembranosus was evaluated.

[6]Resulted due to 20.7% drip loss in 100 kg pigs; no differences in methodology present.

[7]Study by Piao et al. (2004) was excluded from calculation for drip loss effect due to the abnormally high value reported (greater than 3 standard deviations from the mean of all values).

by 0.01 unit per 10 kg increase in marketing weight from 120 to 140 kg and decreased at a similar rate when marketing weight increased from 140 to 170 kg. In contrast, Piao et al. (2004) and Bertol et al. (2015) observed increases in ultimate pH at 0.02 and 0.01 respectfully per 10 kg marketing weight increase.

With a reduction in pH, especially at 24 h, other pork quality factors, specifically instrumental color and drip loss are affected. Color is the number one factor affecting consumer decisions when purchasing meat, as it is used as an indicator of freshness (Mancini and Hunt, 2005). In regards to color, there are conflicting results related to increased marketing weight.

Overall, 9 studies have evaluated instrumental color in heavy weight carcasses. An example of the conflicting results can be found with L*, an instrumental color measurement used to evaluate the lightness or darkness of a product (greater L* value indicates a lighter color). Durkin et al. (2012) observed no significant differences in L* when comparing 120, 130, 140, 150, 160 kg pigs to those weighing greater than 170 kg. Park and Lee (2011) also observed no significant differences in L* values among pigs weighing 116, 124, and 135 kg. In contrast, Latorre et al. (2004) found a 2.48 unit reduction in L* value with a 10 kg increase in marketing weight when comparing pigs from 116 to 133 kg. In addition, when evaluating differences among pigs slaughtered at 144 and 182 kg, Virgili et al. (2003) determined a 0.01 unit reduction in L* value in the semimembranosus with every 10 kg increase in BW.

In the 8 studies evaluating a* value, an instrumental color measurement used to determine redness of a product (greater a* value indicates a more reddish color), most published literature found an increase or no significant differences as carcass weight increased. Increases in a* value were observed by Durkin et al. (2012) and Latorre et al. (2004). Durkin et al. (2012) found a 0.33 unit increase in CIE (Commission Internationale de l'Eclairage color system) a* values in the semimembranosus muscle when comparing pigs weighing 120, 130, 140, 150, 160 kg to those weighing greater than 170 kg. Latorre et al. (2004) observed a* value increased by 0.43 units per 10 kg marketing weight increase when evaluating the effects of gender on meat quality of pigs weighing 116, 124, and 133 kg. However, other studies found no significant differences in a* value with increasing carcass weights (Park and Lee, 2011; Virgili et al., 2003), thus providing no clear evidence as to the effect of increased carcass weights on a* instrumental color values.

The evaluation of b* is an instrumental determination of yellowness in meat (greater b* value indicates more yellowish color). Much like L* value, the 7 studies that evaluated meat color found contradictory findings, with 4 studies finding increased values and 3 studies finding reduced values. Durkin et al. (2012) reported an increase of 0.1 unit in b* value per 10 kg marketing weight increase. When evaluating the differences in meat quality and carcass characteristics among 8 and 10 mo old Italian pigs weighing 144

and 182 kg, respectively, Virgili et al. (2003) determined there was a 0.17 unit reduction in b* values in the semimembranosus per 10 kg marketing weight increase. Overall as marketing weights increased, there are conflicting results on instrumental color, especially in L* and b* values in published literature. However, such changes in instrumental color values may be of little biological significance, but may result in a minimal impact on consumer preference.

Drip loss, a measurement of water holding capacity, is readily affected by both pH and chilling method. Of the studies evaluating the effects of increasing carcass weight on pork quality, 10 studies evaluated drip loss with conflicting results reported. With increasing BW, drip loss was increased in 6 studies, decreased in 3 studies, and inconsistent response of drip loss to increasing marketing weight was observed in 1 study. Cisneros et al. (1996) and Park and Lee (2011) found a 0.29% unit increase in drip loss per additional 10 kg of BW. In addition, Martin et al. (1980) determined that carcass weight was negatively related ($r$ = -0.31) to percentage expressible juice. As age and carcass weight increased, Virgili et al. (2003) observed a 0.34% unit increase in drip loss for every 10 kg increase in marketing weight from 144 to 182 kg. Durkin et al. (2012) reported that drip loss of pigs marketed at 140 kg was approximately 3% less than pigs marketed at 130, 150, and 160 kg, but was not different from those marketed at 120, 140, and 170 kg. Methodology reported by these studies did not indicate any differences in chilling methods that may have affected drip loss results.

Pork fat quality is important for product functionality and use. Three studies have evaluated the effects of increasing carcass weight on the fatty acid profiles (expressed as the percentage of fatty acid over total fat content) of pork carcasses. All of the studies observed nonsignificant differences in monounsaturated fatty acids (MUFA) among pigs of different BW (Lo Fiego et al., 2005; Correa et al., 2008; Raj et al., 2010). In a study by Raj et al. (2010), where pigs weighing 90, 110, and 130 kg were evaluated for subcutaneous fatty acid profiles, concentrations of polyunsaturated fatty acids (PUFA) were reduced by 0.37% units per 10 kg marketing weight increase from 90 to 130 kg. Conversely, saturated fatty acid (SFA) contents were increased by 0.46% units per 10 kg marketing weight increase when comparing pigs weighing 90 and 130 kg (Raj et al., 2010). When examining the fatty acid profiles of fat coverings of hams in Italian heavy pigs weighing 151, 164, and 176 kg, Lo Fiego et al. (2005) observed similar results to Raj et al. (2010); as BW increased, there was a 0.36% unit increase in SFA content for every 10 kg increase in marketing weight. In addition, these authors reported significant reductions in PUFA concentration

as marketing weight increased; Lo Fiego et al. (2005) reported a 0.52% unit reduction and Raj et al. (2010) observed a 0.37% unit reduction in PUFA concentration per 10 kg increase in marketing weight. Conversely, in a study comparing bellies from heavy weight market pigs intended for cured ham production, Correa et al. (2008) observed a tendency ($P$ = 0.06) for increased PUFA content when comparing pigs weighing 107, 115, and 125 kg. However, Lo Fiego et al. (2005) observed a 0.72 unit decrease in iodine value per 10 kg increase of marketing weight. Iodine value does not affect bellies' functionality when ranging from 70 to 75 g/100g (Benz et al., 2011). Iodine values reported by Correa et al. (2008) and Lo Fiego et al. (2005) did not exceed this acceptance range, suggesting that an increase in marketing weight resulted in minimal reductions in pork product functionality.

Warner-Bratzler shear force (WBSF) results are conflicting in studies evaluating increasing marketing weight. Of the 8 studies that evaluated WBSF, Beattie et al. (1999) and Latorre et al. (2004) observed no significant differences when comparing pigs weighing 70, 80, 90, and 100 kg, as well as 116, 124, and 133 kg, respectfully. On the contrary, Cisneros et al. (1996) observed a slight reduction of 0.08 kg per 10 kg marketing weight increase in WBSF, which may be due to the increased intramuscular fat content associated with increased carcass weights. Martin et al. (1980) also observed a slightly positive, significant relationship between increasing carcass weights and shear force ($r$ = 0.08), which indicated a tougher product with increasing marketing weight. In addition, Durkin et al. (2012) reported a quadratic effect of BW on tenderness; pigs weighing 140 and 160 kg had greater WBSF values and, therefore, were more tender than those weighing 120, 150, and 170 kg.

Marbling or intramuscular fat is a primary driver for both juiciness and tenderness in pork products (Cannata et al., 2010). Multiple studies (Cisneros et al., 1996; Huff-Lonergan et al., 2002; Park and Lee, 2011) demonstrated a concurrent increase in intramuscular fat in the longissimus dorsi muscle as carcass weight increases, with an exception that Martin et al. (1980) observed a weak, negative response ($r$ = -0.02) of marbling to increasing carcass weight from 73 to 137 kg.

There were only 3 studies evaluated the sensory properties of heavy weight market pigs and have produced mixed results. Huff-Lonergan et al. (2002) observed significant, positive responses of juiciness ($r$ = 0.09) and off-flavor presence ($r$ = 0.14) to increasing carcass weight. Increase in off-flavors is likely a result of increased PUFA concentration along with enhanced fat deposition in heavy pigs (Correa et al., 2008). Contrary to those findings, Cisneros et al. (1996) observed decreased tenderness and juiciness by

0.1 and 0.04%, respectively, for every 10 kg increase in marketing weight from 100 to 160 kg. Park and Lee (2011) observed increased presence of off-flavor in raw pork as marketing weight increased from 116 to 133 kg; however, after cooking, there were no significant differences in flavor profiles. Further research is needed to determine the true effects of increasing carcass weight on sensory panel ratings.

After a thorough literature review, it was determined that there has been no research evaluating the impact of chilling rate on meat quality traits with heavy weight market pigs. Research is needed to evaluate if increased wind speeds and decreased cooler temperatures are needed to appropriately chill heavier carcasses to prevent undesirable meat quality traits. Additionally, future study is also in need to determine the effects of heavy marketing weight on pork safety, such as microbiological populations, antimicrobial treatments, or the potential associated dilution of sprayed-on antimicrobials (i.e., organic acids) due to increased cut and carcass size.

### Factors to Consider When Increasing Marketing Weight

*Genetics.* Genetic selection of pigs with high lean-gain potential is essential for the production of heavy pigs. Neely et al. (1979) observed that pigs selected from lean litters (sorted based on backfat) had slower weight gain during the early stages of growth (15 to 86 kg), but gained at a faster rate thereafter compared with pigs from fat litters. During the last finishing period, lean-type pigs have less deposition of fat, thus exhibit better feed efficiency compared with non-lean genotypes (Kim et al., 2005; Park and Lee, 2011). Growth performance and carcass traits of heavy pigs varied considerably when different genetic lines are assessed. In a study where pig growth of 5 genotypes were compared at 3 BW (100, 114, and 127 kg), Gu et al. (1991) observed that there was no genotype × BW interaction and the difference among genotypes could be as large as 11.0, 7.3, and 14.0% for ADG, ADFI, and G:F, respectively. Similarly, Latorre et al. (2003) compared pigs bred from 3 sire lines at 2 marketing weights (122 vs. 136 kg). There were no genotype by marketing weight interactions and differences of 3.3, 1.6, and 4.9% for ADG, ADFI, and G:F, respectively, were observed. More recently, a breeding stock company (PIC, Hendersonville, TN) evaluated 2 different genotypes (PIC280 vs. PIC359) fed to 145 kg; a 2.7 kg difference was observed between lines on final BW, driven by significant differences in ADG (18 g), ADFI (90 g), and G:F (0.006 g/g; personal communication, 2016).

Effects of genetic line on carcass characteristics should also be considered when increasing marketing weight. Using 5 genotypes and 2 marketing weights (130 and 160 kg), Peloso et al. (2010) demonstrated that genetic background was responsible for dissimilar deposition rates of fat and lean during the transition of increasing marketing weight and led to significantly varied hot carcass weight (HCW), backfat thickness, and LM depth of pigs at harvest. Pigs from different genetic lines also exhibit varied patterns in partitioning fat toward intramuscular, subcutaneous (backfat), or internal (kidney) sites at heavy weights, which contributes to a difference in meat quality among genotypes (Franci et al., 2001).

*Nutrition.* In general, heavy pigs have decreased requirements for dietary protein concentration (Crovetto et al., 1999, Galassi et al., 2010), likely due to decreased lean gain compared with lighter finishing pigs. Limited information is available regarding the nutritional requirements of heavy pigs over 140 kg. The NRC (2012) growth model estimates a Standardized Illeal digestible (**SID**) Lys requirement of 0.53% (assuming corn-soybean meal diet which would contain 2350 kcal NE/kg) for finishing pigs with 130 kg BW, which is decreased to 0.49% at 140 kg BW. However, it is important to note that these estimates have not been validated by empirical studies. Using factorial approaches, Manini et al. (1997) predicted that the SID Lys requirement of a 120 kg pig was 0.48%, and the value was reduced to 0.44 and 0.41% of the diet for pigs with 140 and 160 kg BW, respectively. Although the change of SID Lys requirement appears to be marginal, adjustment of diet formulation or an additional feeding phase should be considered as marketing weight increases. This is because a slight decrease in feed cost during late finishing phase can be economically significant due to the increased ADFI of heavy pigs. In addition, tissue turnover rates and maintenance requirements change as the pig grows, the ideal amino acids (AA) to Lys ratios may change with pig weight (Mahan and Shields, 1998a). For example, Thr, Met, and Trp are needed in greater concentrations relative to Lys in older than in younger pigs (Hahn and Baker, 1995), possibly due to a greater requirement for maintenance than for growth purposes. Furthermore, dietary P requirement estimates may decrease during the last feeding phase of heavy pigs. Mahan and Shields (1998b) observed that body Ca:P ratio greatly increased from 75 to 145 kg. This is because body Ca is mainly present in bone tissue, whereas P is present in soft and hard tissues; in heavy pigs, Ca and P deposition largely occurs in skeletal tissue with a declining deposition of P in muscle.

The dietary energy concentration may vary for heavy finishing pigs because of their increased capacity to adjust feed intake to meet energy requirements (Suarez-Belloch et al., 2013). More importantly, increased gut capacity allows heavy pigs to digest and utilize energy from fibrous feedstuffs more efficiently through hindgut

fermentation (Just et al., 1983; Noblet and Shi, 1994; Zanfi and Spanghero, 2012). This provides swine producers with an opportunity to lower feed cost by feeding fibrous feed ingredients. Galassi et al. (2007) compared growth performance of pigs fed 0, 12, and 24% wheat bran diets [11.8, 14.4, and 17.2% neutral detergent fiber (NDF), respectively] over different BW ranges; ADG and feed efficiency were worsened from 44 to 70 kg, numerically impaired from 70 to 98 kg, but were unaffected from 98 to 176 kg when wheat bran was included in the diets. In another study where pigs were fed 0, 15, and 30% sugar beet pulp in diets (14.2, 15.8, and 20.9% NDF, respectively), Galassi et al. (2005) observed that increasing dietary fiber worsened ADG and feed efficiency of pigs from 106 to 120 kg BW, but had no effect on pigs from 120 to 170 kg BW. This observation was supported by the observation that pigs fed the 3 different diets had similar energy digestibility measured at 154 kg. However, pigs fed in the 2 studies above were restrictively fed at approximately 2.25 kg DM/d. Future studies are needed to examine the effects of dietary fiber on growth performance of heavy pigs with ad libitum feeding. In addition, it is important to realize that pigs fed in a university environment may respond differently to the increased dietary fiber compared with pigs raised in a commercial environment because the feed intake of commercial pigs is subject to other restrictive factors, such as stocking density and hygiene (De la Llata et al., 2001). Meanwhile, the negative impact of dietary fiber on carcass yield should also be considered. The magnitude of this effect may be enlarged in heavy pigs due to their increased gut volume.

Feed additives and feeding strategies have been developed to help mitigate the increased fat deposition in heavy finishing pigs. Feeding ractopamine HCl before marketing allows pigs to produce heavier and leaner carcasses with improved gain rate and efficiency compared with untreated pigs (Apple et al., 2007). The efficacy of ractopamine HCl has been confirmed in pigs raised up to 136 kg (Carr et al., 2009; Peterson et al., 2015). Porcine somatotropin is also effective in promoting pig growth performance and carcass leanness (Johnston et al., 1993), and such effects appear to be more prominent in heavy pigs (Kanis et al., 1990). However, somatotropin is not approved to be used in swine in the U.S.

Limiting fat deposition in heavy pigs may also be achieved via feed restriction. Slightly decreased feed intake increases nutrient digestibility, improves the efficiency of energy utilization, and decreases the amount of dietary energy partitioned to fat deposition. Nieto et al. (2012) suggested that pigs allowed to consume 70 and 95% of ad libitum feed intake were able to retain similar amounts of body protein when raised to 150 kg. This finding indicates that heavy pigs may not require ad libitum feeding to attain the maximum protein deposition.

Once pigs reach their genetic potential for maximum protein deposition, feed restriction becomes more effective in decreasing excessive fat gain. Although restricted feeding leads to decreased backfat thickness and slightly improved or unchanged G:F in heavy pigs, reduced ADG is often observed as a consequence of decreased feed intake (Hansson, 1974; Kim et al., 2005; García-Valverde et al., 2008). Moreover, feasibility of restricted feeding is questionable, at least in current U.S. production systems, with regards to the current feeder design and additional labor cost. As an alternative, feeding low-energy diets has been proposed to achieve the goal of restricting energy intake. However, the usefulness of this strategy is challenged by the fact that heavy finishing pigs increase feed intake to compensate for the reduced dietary energy density (Kim et al., 2005). It appeared that early finishing pigs fed low-energy diets had limited ability to adjust feed intake to maintain the same energy intake compared with pigs fed high-energy diets (Smith et al., 1999; Apple et al., 2004; Zhang et al., 2011); whereas heavy finishing pigs were able to maintain high feed and energy intake regardless of energy density of the diets (Suarez-Belloch et al., 2013). Although feeding low-energy diets effectively reduced backfat thickness, impaired ADG was still commonly observed. More importantly, inconsistent responses of caloric efficiency were often obtained when pigs were fed diets with decreased energy densities (Apple et al., 2004; Zhang et al., 2011; Suarez-Belloch et al., 2013), indicating a limited advantage of feeding low-energy diets to heavy finishing pigs.

Another challenge of raising heavy pigs is derived from the interactive effects between increasing marketing weight and gender on pig growth performance (Carr et al., 1978; Sather et al., 1980; Conte et al., 2011). Generally, barrows grow faster than gilts during late finishing phase, because gilts reach puberty at approximately 110 kg BW when declining feed intake and growth rate are commonly observed (Hansson, 1974; Sather et al., 1980). Additionally, barrows have greater reductions of lean gain rate than gilts as BW increase, indicating a different nutritional requirement for barrows and gilts. For instance, the Lys requirement suggested by the NRC (2012) growth model is approximately 0.05% lower for barrows than for gilts at both 130 and 140 kg BW. As a result, different feeding and marketing strategies are potentially needed for barrows and gilts. Through an economic model, Jolly et al. (1980) however argued that marketing both genders at equal weights resulted in negligible income penalty. Immunocastration has been used as an alternative of physical castration to eliminate boar taint while maintaining a pig growth performance similar to intact males. The efficacy of immunocastration has been verified for pigs with heavy marketing weight up to 176 kg (Zamaratskaia et al., 2008). However, as the

**Table 4.** Changes in facility recommendations for pigs based on final marketing weight

| Items | Marketing wt, kg | | | | | |
|---|---|---|---|---|---|---|
| | 125 | 130 | 135 | 140 | 145 | 150 |
| Floor space/pig[1], m² | 0.84 | 0.86 | 0.89 | 0.91 | 0.93 | 0.95 |
| Feeder space[2], cm | 34.6 | 35.1 | 35.5 | 36.0 | 36.4 | 36.8 |
| Drinker height, cm | | | | | | |
|   Right-angled waterer[3] | 73.8 | 74.8 | 75.7 | 76.6 | 77.5 | 78.4 |
|   Downward waterer[4] | 88.6 | 89.7 | 90.8 | 91.9 | 93.0 | 94.1 |
| Heat production[5], kcal/h | 242.1 | 248.1 | 254.0 | 259.7 | 265.5 | 271.1 |
| Pigs/truck[6] | 163 | 156 | 151 | 145 | 140 | 136 |
| Truck space/pig[7], m² | 0.43 | 0.44 | 0.45 | 0.47 | 0.48 | 0.50 |

[1]Estimated using: floor space, m² = k × (BW, kg)$^{0.667}$, where $k$ = 0.0336 (Gonyou et al., 2006).

[2]Estimated using: feeder space = 1.1 × shoulder width (Brumm, 2012), and shoulder width, mm = 64.0 × (BW, kg)$^{0.33}$ (Petherick, 1983).

[3]Estimated using: right-angled waterer height, cm = 15 × (BW, kg)$^{0.33}$ (Gonyou, 1996).

[4]Estimated using: downward waterer height, cm = 18 × (BW, kg)$^{0.33}$ (Gonyou, 1996).

[5]Estimated using: heat production (W/kg) = 14.11 × (BW, kg)$^{-0.38}$ (Brown-Brandt et al., 2004).

[6]Assuming maximum truck load of 20,321.1 kg.

[7]Adapted from recommendation from Grandin (2012).

length of mixed-housing period increases with marketing weight, it is possible that immunocastrated boars may stimulate the onset of puberty in gilts; whereas, no research has been identified to address this question.

*Animal Housing.* One major challenge of housing heavy pigs is the reduced floor space per pig. With a constant stocking density, space allowance becomes a limiting factor for ADFI and, subsequently, ADG of heavy pigs (Edmonds and Baker, 2003; Brumm, 2004; DeDecker et al., 2005). Weatherup et al. (1998) compared the growth performance of pigs housed individually and in groups (6 pigs/pen) and suggested that, with greater space allowance, individually housed pigs had a greater magnitude of increase in ADFI and less degree of reduction in ADG than group-housed pigs when marketing weight was raised. An allometric expression of the floor space required by pigs over a range of weights was proposed by Petherick (1983) and Baxter (1984) using the equation: A, m² = $k$ × (BW, kg)$^{0.667}$, where A represents floor space allowance and $k$ represents a space allowance coefficient. When $k$ is below 0.0336, decreased ADFI and ADG are often observed in pigs housed on fully slated floors (Gonyou et al., 2006). Calculations using the above equation with $k$ = 0.0336, suggest that an average increment of 0.02 m²/pig is required for every 5 kg increase of pig BW from 125 to 150 kg in order not to negatively affect growth performance (Table 4). When adequate floor space cannot be provided, the impact of restricted pen space on pig performance is dependent on the magnitude of the

restriction. A meta-analysis conducted by Flohr (2015) established a set of equations to predict ADG, ADFI, and G:F based on pig BW. From this meta-analysis, for every 0.001 below the critical $k$ value (0.0336), ADG, ADFI, and G:F are expected to decrease by 0.88, 0.58, and 0.31%, respectively, for pigs over 125 kg BW.

A pig removal strategy seems to be a good alternative to provide adequate floor space for heavy pigs in which the heaviest pigs within a pen are harvested first when they reach the target marketing weight, then the remainder pigs in the pen are provided increased floor space for improved growth. DeDecker et al. (2005) removed 25 and 50% of the heaviest pigs (13 or 26 out of 52 pigs/pen) when average pen weight reached 113 kg, which resulted in increased ADG (20.6 and 21.0%), ADFI (10.8 and 7.9%), and G:F (7.7 and 14.3%). Similarly, Jacela et al. (2009) observed that when 8 or 16% of the heaviest pigs (2 or 4 pigs out of a pen of 25) were removed when average pen weight reached 109 kg, pigs remaining in the pen had increased ADG (11.5 and 14.2%), ADFI (7.5 and 4.0%), and G:F (5.2 and 11.5%).

Appropriate feeder space is also essential for heavy pigs to maximize feed intake and gain. Excessive feeder space may increase feed wastage and decrease G:F when ample floor space is provided (Myers et al., 2012); whereas, limiting feeder space negatively affects growth performance especially when pigs have restricted floor space (Jungst et al., 2013). Size of a feeder hole should be 1.1 times the shoulder width (Brumm, 2012; Table 4), which can be estimated using: shoulder width (mm) = 64.0 × (BW, kg)$^{0.33}$ (Petherick, 1983).

Height of waterers also should be adjustable based on the increased height of heavy pigs and the design of waterers. A general guideline for adjusting waterer height has been provided by Gonyou (1996). Nipple waterers pointed straight out from the wall should be placed at shoulder height, which can be predicted using: nipple waterer height, cm = 15 × (BW, kg)$^{0.33}$. Nipple waterers mounted at a downward angle should be placed 5 cm above the back of the pig, which can be estimated using: nipple waterer height, cm = 18 × (BW, kg)$^{0.33}$. Finally, when water bowls are used, pigs should drink water with their head slightly lowered. Capacity of water pipes leading into the barn should also be sized accordingly to accommodate the increased total water consumption of heavier pigs. Nevertheless, excessive supply of water should be avoided to minimize water wastage and manure production. In addition, the height of pen partitions should be considered to accommodate the greater height of heavy pigs.

As BW increases, pigs generate more body heat but have decreased ability to dissipate this heat; thus, heavy pigs need lower critical ambient temperature and are

more vulnerable to heat stress than light pigs (Renaudeau et al., 2011). According to a prediction equation from Brown-Brandt et al. (2004), heat production of pigs increases by 2% for every 5 kg increase in BW, indicating that barn ventilation rates need to be adjusted accordingly (Table 4). A production manual published by PIC (2014) recommends that barn temperature should be maintained at 16°C for pigs from 96 to 138 kg and the minimal air exchange rates for pigs with 127 and 138 kg BW are 13.0 and 14.3 CFM/pig, respectively. In addition, ammonia emission is augmented as feed intake and manure production increase in heavy pigs (Ni et al., 2000), which can create a further challenge for proper barn ventilation.

*Animal Health.* The duration of immunity following vaccinations for common swine pathogens when pigs are kept in barns to heavier weights is a complex subject. In theory, the need for vaccine protection is decreased in heavier pigs because of their more developed immune system compared with young and naïve pigs. The necessity of providing heavy pigs an additional vaccination should be evaluated based on the immune status of the herd, because pigs with originally low antibody titers have greater response to vaccination, while pigs with originally high antibody titers have marginal benefits from the additional vaccination. It is also important to realize that the duration of immunity given by vaccination varies among vaccine products, types of vaccine (live vs. killed virus), and pathogens that vaccines are developed to against. Typically, vaccines designed to be given as 2 separate doses have longer protection than those given as single dose (Dick Hesse, personal communication). However, given the high economic cost of mortality in heavy pigs and the fact that risks of late-finishing disease, such as porcine reproductive and respiratory syndrome, influenza, and mycoplasma pneumonia, are still high, an additional dose of vaccine for heavy pigs has been occasionally used by producers (Dick Hesse, personal communication). However, for many vaccines, the effectiveness of an additional booster has not been critically evaluated and caution needs to be taken in regard to the legal withdraw period required following the vaccination.

*Transportation.* Transportation can induce a high amount of stress in heavy weight market pigs. dalla Costa et al. (2009) observed elevated salivary cortisol concentrations and heart rate during loading and transport and Fitzgerald et al. (2009) reported higher mortality rate when pigs were transported at heavier weights compared with those marketed at lighter weights. As pigs grow heavier, they need more space provided in the trailer and better ventilation as they can become exhausted faster during transportation than light weight pigs. Meanwhile, the number of animals that can be transported per truck decreases with greater marketing weight (Table 4). Based on recommendations by Grandin (2012), truck space re-

quired by pigs transported during cool weather increases from 0.43 to 0.50 m$^2$/pig as marketing weight increases from 125 to 150 kg. Requirements for truck space may further increase when distance of transport and ambient temperature increase because pigs tend to spend more time laying (Guise et al., 1998; Torrey et al., 2013). The efficiency of loading and transporting heavy pigs also depends on the trailer design. Heavier pigs are reluctant to walk up a steep ramp and should be provided no more than a 15° ramp slope (Grandin, 2012).

*Packing Plant.* With an increase in marketing weight, there are several practical packing plant considerations needed, including: processing equipment, transportation, and worker safety concerns. Through personal communication with meat scientists associated with large packing plants, increased body size, carcass length, and limb length of heavy pigs have been a main area of consideration. First, with an increase in final BW, line speed may decrease due to fewer numbers of pigs that can be stunned through carbon dioxide chambers used at nearly all major pork packing plants. Line speed can also be limited by USDA inspection, because a greater amount of time is needed to inspect a larger carcass. Second, as carcass length increases, pigs may not be able to be properly exsanguinated due to large variations in hind limb length and rail height. Rail height in older packing plants may also be a risk factor for de-hairing and scalding equipment as carcasses may drag on their backs at the bottom of scalding tanks. Furthermore, as pigs exit the de-hairing process, workers splitting carcasses will have to spin or roll a greater than 130 kg carcass into position. As the carcass continues through the harvesting process, longer limbs may also contribute to issues at the gambrel table, on conveyor belts, and on the main break table. Increased carcass weight may result in ergonomic concerns as workers need to handle and manipulate heavier hams, shoulders, and loins. Automated loin pullers and belly cutters may help mediate some of these issues. In addition, wind speeds and cooling times required to properly chill heavy carcasses will need to be evaluated. Increased carcass size creates challenges on cooling capacity of packing plants, as greater airflow around and under the carcasses is needed. Coolers in older packing plants may already be running at the maximum wind speeds and cooling capacity and these packing plants may not have the capability to build additional cooling system. Finally, more storage space is also needed in coolers for the increased carcass weight and length.

Another consideration for increased carcass weights are consumer preferences. As carcass weight increases, there is a large weight increase in all of the primal cuts. Longer loins would be more desirable from a processing standpoint compared with increased loin diameter. This is because larger LM area would result

**Table 5.** Recommendations for future research needs in production of heavy weight market pigs

| Item | Future research needed |
|---|---|
| **Nutrition** | |
| Protein and AA | Lysine and other AA requirements for pigs greater than 140 kg |
| Protein and AA | Minimum CP (CP:Lys ratio) requirement for pigs greater than 140 kg |
| Energy | Effect of decreasing and increasing dietary energy on growth performance |
| Energy | Effects of restricted feeding (feed intake and energy intake restrictions) on energy and nutrient utilization |
| Fiber | Assess the ability of heavy pig to maintain feed intake and utilize dietary energy when fed high-fiber diets |
| Gender effect | Applicability and necessity of split-sex feeding and housing |
| **Meat quality** | |
| Color | Effects of increasing carcass weight on meat color and customer preference |
| Sensory property | Effects of increasing carcass weight on sensory property |
| Food safety | Antibiotic treatment timing and duration on resistance in heavy pigs |
| Food safety | Pathogen (e.g. Salmonella) shedding during transportation of heavy pigs |
| **Animal health** | |
| Immunity | Validation of duration of protection by major swine disease vaccines |
| Immunity | Effects of an additional vaccine booster on disease control of late finishing pigs |
| Bone structure | Macro and micro mineral requirements for pigs greater than 140 kg |
| **Facilities** | |
| Floor space | Effects of serial marketing on the space requirement as marketing weight increases |
| Ventilation | Effects of increasing BW on barn ventilation requirement |
| Transportation | Effects of increasing marketing weight on transportation efficiency and loss |
| Packing plant | Industry survey for the maximum carcass weight that packers and cull plants can currently process |
| Economics | Effects of increasing marketing weight on profitability of finishing pig production |
| Meta-analysis | Effects of marketing weight on cumulative growth performance and carcass characteristics |

in changes in portion controlled cutting. Chops cut to a standardized thickness would be heavier and resultantly more expensive during retail marketing, impacting the number of chops sold per package. Conversely, chops cut to a standardized weight would be thinner, requiring modifications to cooking methods currently used by both foodservice and consumers. It is unclear what impact these changes in chop thickness and weight would have on consumer preference. Furthermore, increasing marketing weight also affects the processing capacity of cull plants that specialize in handling lightweight cull pigs. When marketing weight range increases, cull pig weights would also have to increase. Some of these plants would have to drastically alter their plant design and space to process larger carcasses.

### *Conclusion*

Many production variables are affected with increasing marketing weight. Generally, heavy weight market pigs eat more, but gain more slowly and less efficiently than pigs marketed at lighter weights. Heavier carcasses are associated with greater carcass yield, length, and LM area, but they also have greater backfat thickness and decreased percentage fat-free lean. Genetic selection of lean-type pigs and research on nutritional requirements for pigs greater than 140 kg are needed to mitigate the reduction in feed efficiency and carcass leanness (summary for future research needs are provided in Table 5). Increasing marketing weight may result in minimal impacts on pork quality, but future studies are in need to evaluate consumer preferences on pork from heavy pigs with a focus on color, portion sizes, and sensory characteristics. In conclusion, as marketing weight increases approximately 0.5 kg per yr (NASS, 2014), adjustments for nutritional and management guidelines, facility design, and packing plant equipment are necessary to accommodate increased biological and physical requirements of heavy weight market pigs.

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