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Improving

PIC® TOTAL CARCASS VALUE HANDBOOK

PIC®

Introduction/Preface

PIC's Pork Quality Blueprint was first developed in 1996 to assist the global pork supply chain in producing high-quality, desirable pork. Considering the complexity of the subject, it has been critical to define and address all the genetic and environmental interactions (GxE) throughout live production, transport, and slaughter plant factors that influence pork quality. Over the past 25+ years, this science-based and industry-focused, practical guide has been regularly updated to ensure that PIC continuously delivers value to the global pork industry.

This updated and comprehensive PIC Carcass Value Handbook represents our efforts to provide the industry with current, detailed information regarding total carcass value and practical recommendations to manage it. This value is defined as a combination of carcass quantity, meat quality, and fat quality. Key attributes include muscle pH and pH decline, meat and fat color and firmness, eating experience, and processing characteristics. This Handbook does not address the food-safety and shelf-life aspects of carcass value. An extensive bibliography and list of reference material is included at the end of this document.

PIC is committed to global pork industry success through balanced live-animal performance, carcass and pork quality genetic improvement programs, and related technical services. In addition, PIC's genetic programs focus on improving overall carcass merit, including primal and sub-primal weights, distribution, and quality. These programs have been in place for more than 50 years.

Genetic tools, computation technology, elite farms housing pure lines, commercial lines, and cross-bred pedigreed populations continue to progress, providing the best possible rates of genetic improvement. For the latest information about PIC's breeding programs for primal value and meat quality, please contact the Applied Meats Science team.

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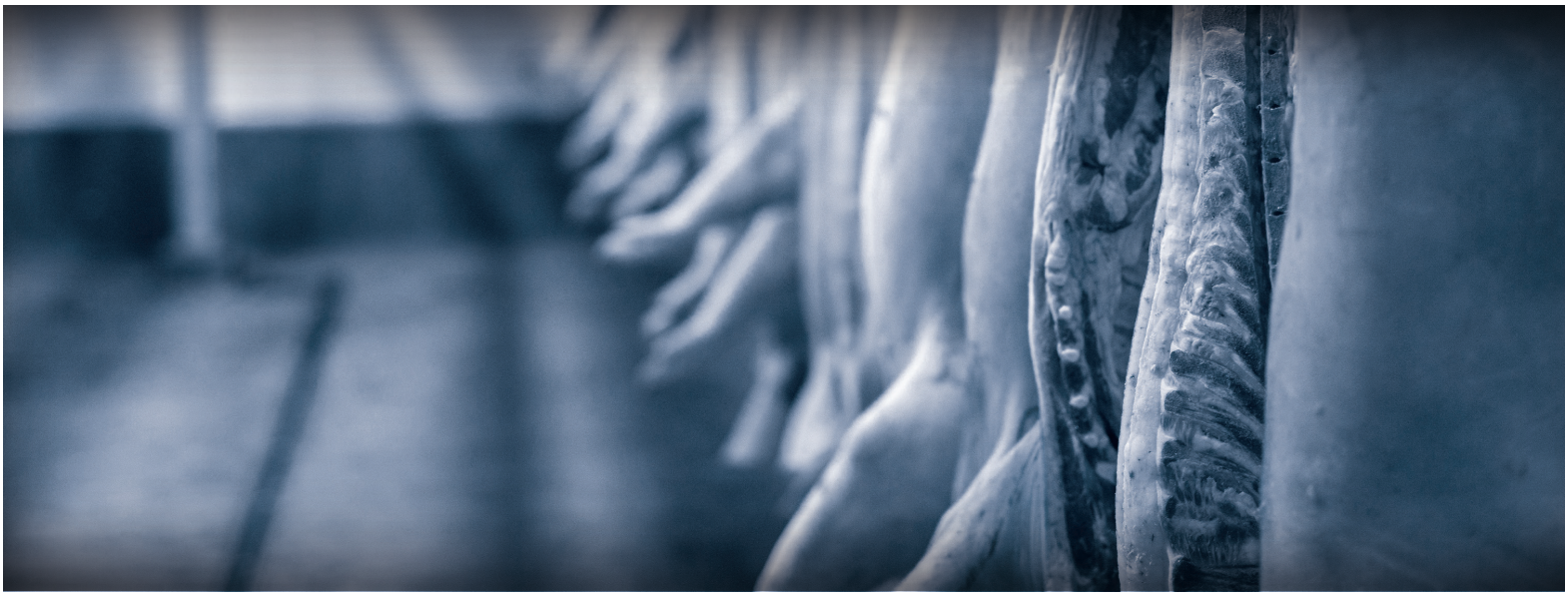
Section 1

Carcass Composition



Carcass composition is an important component in determining the carcass value. The measurement of carcass composition can range from simple weighing of the carcass, to the use of measurements assessing the lean composition of the entire carcass. Some aspects of carcass composition are typically used to pay for pigs around the world.

These criteria are based on what brings the most value to the processing plant that is buying the pigs or to the integrated system. Many countries mandate methods and equations that must be used for assessing carcass composition. In other countries, individual companies develop and use their own proprietary methods and equations.

Once an evaluation method is in place, a payment system is developed that assigns a value to the carcass. These payment systems are unique to each company, even when national evaluation standards are in place. Because payment systems are often based on the primal cuts that bring the most value, these systems can vary significantly in different regions. Also, depending on the region, the carcass may be cut in different ways to bring more value to primals of importance in that area.

The rest of this section will cover carcass composition measurements in more detail, including measurement methods, equations, carcass primals, and carcass yield.

1.1 Measurement of Carcass Composition

Methods for measuring carcass composition can vary from country to country and even between processing plants in a country. This sub-section will address the different types of measurements and equipment used to measure carcass composition.

Some of the most important factors that affect carcass value are:

1. Carcass and/or primal weights
2. Carcass and/or primal lean composition
3. Carcass yield/trim loss

Some of these are direct measures (e.g., carcass weight), while others, like lean percentage are more commonly estimated from simpler measurements.

The following sub-section outlines the five methods to determine carcass lean content.

1.1.1 Methods for Measurement of Carcass Lean Content

Direct Measurements

Direct measurements can assess a variety of carcass traits. Some of these traits may be used to directly assess carcass value whereas others may be used only to predict the value.

1. Primal weights
   a. Best overall assessment of carcass value.
   b. Measured by weighing each of the primals.
   c. Can be time consuming and labor intensive.
   d. More complex assessments of the primals can be obtained through proximate analysis or dissected lean.
2. Carcass length
   a. Measured in a straight line from the first rib to the aitch bone (Figure 1.1).
   b. Not usually considered to be a good measure of carcass value. However, longer carcasses can offer additional commercial benefits for primals, such as the loin or the belly.
   c. Virtually no relationship with the lean content of the carcass.
3. Backfat and loin eye area/loin depth
   a. Backfat can be measured at various locations on the midline with a ruler (Figure 1.1)
      i. 1st rib backfat
      ii. 7th rib backfat
      iii. 10th rib backfat
      iv. Last rib backfat
      v. Last lumbar vertebrae backfat
   b. Backfat and loin measurements can be measured on ribbed carcasses (Figure 1.2).
      i. P2 backfat thickness - measured 6.5 cm (2.5 in) from the midline typically at the last or 10th rib.
      ii. Loin depth - measured from the dorsal to ventral surface of the loin starting at the point where the P2 backfat thickness is measured and perpendicular to the skin surface.
      iii. Loin-eye area – measurement of the total area within the loin eye. This can be done using a grading grid, or by tracing the loin eye on acetate paper and measuring the actual area using a planimeter.
   c. Backfat is also measured using an intra-scope (Figure 1.3).
      i. Only measures backfat and not loin depth.
      ii. Considered a low-cost option for determining P2 backfat in a commercial processing plant with slower line speeds.

Figure 1.1 Common carcass measurement locations

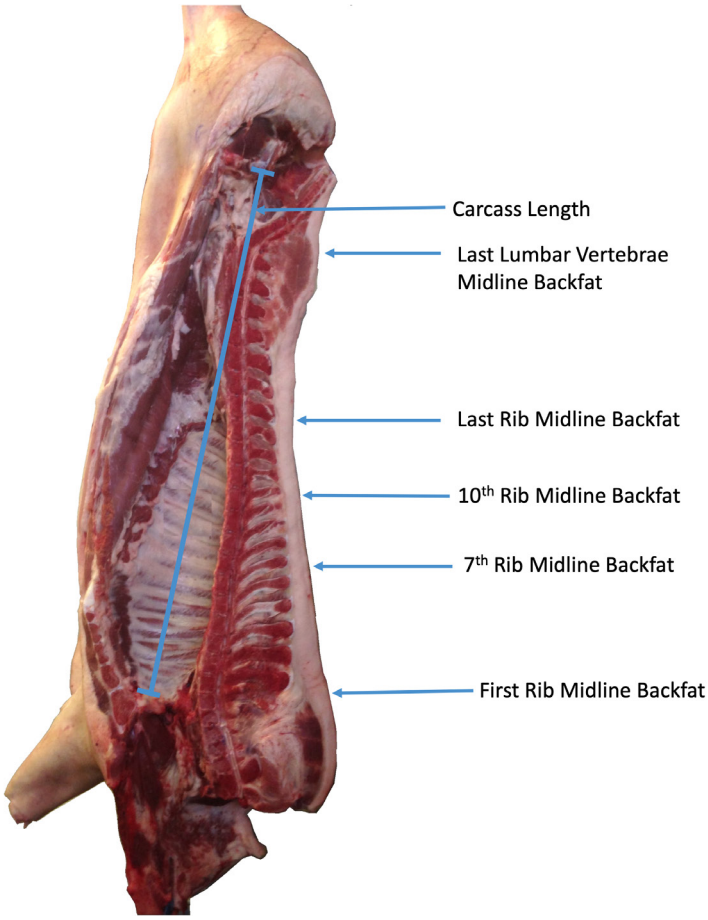


Figure 1.2 Grading ribbed carcasses

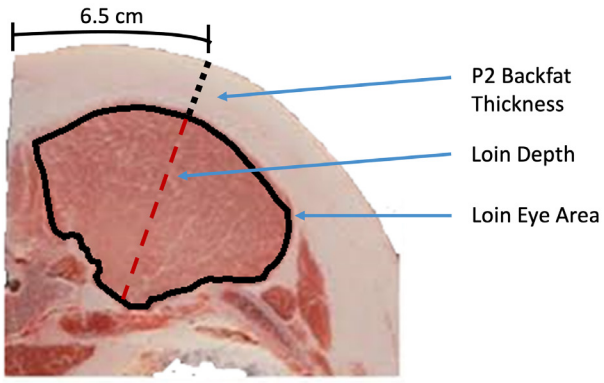


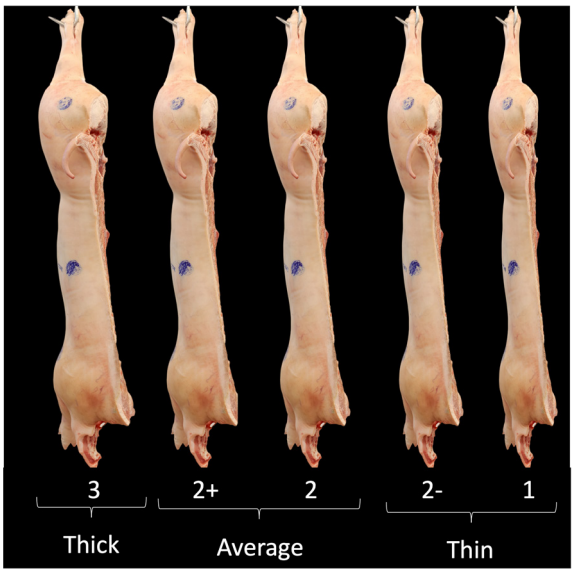
Photo courtesy of the University of Nebraska Porcine Myology

Figure 1.3 Intrascope used for measuring backfat thickness

Indirect Measurements

1. Visual Assessment of Conformation
   The conformation (or muscle score) of both live pigs and carcasses is used in some parts of the world to value the pig/carcass for payment or sorting purposes.
   a. Live Pig Visual Conformation
      i. In many parts of the world, buyers ("middlemen") will purchase pigs from farmers based on conformation of the live animal.
      ii. Buyers typically pay more for pigs with better conformation scores.
      iii. The conformation score is not usually standardized, and it is typically determined at the discretion of each buyer.
   b. Carcass Conformation
      i. In some markets around the world, visual assessment of carcass conformation is used to sort carcasses for product demands. It may be included in the payment, either directly or indirectly.
      ii. Systems for carcass conformation scoring do exist and most of these are similar in how they classify the carcasses (Figure 1.4).

Figure 1.4 Example of a system assessing pork carcass conformation



Adapted from original photo from Elisabeth Lonergan.

2. Fiber-Optic Probes
   Fiber-optic probes have been widely used for measuring carcass composition in processing plants for more than 30 years. Fiber-optic probes measure backfat thickness and loin depth. These numbers can help predict the amount of lean percentage or lean cuts in the carcass, using different equations.

   These probes work on the premise that the whiter fat and bone will reflect light differently than the reddish color of the lean tissue. Based on this light reflectance profile (Figure 1.5), as the probe is inserted (or removed depending on the model of grading probe) the fat depth and loin depth can be measured.

   Measurements of backfat and loin depth can be collected at any location along the length of the loin. However, most measurements are taken at the 10th rib or last rib at the P2 location because these locations have the highest correlation with carcass lean composition.

   Fiber-optic probes are ideal for use in commercial processing plants, as they can be used at line speeds up to 1,300 pigs per hour. Examples of fiber-optic probes (Figure 1.6) commonly used in processing plants around the world include:
   a. Fat-o-Meat'er™ grading probe
   b. Hennessey Grading Probe (HGP)
   c. PG-100 probe

Figure 1.5 Light reflectance profile of an optical grading probe to determine fat and loin depth

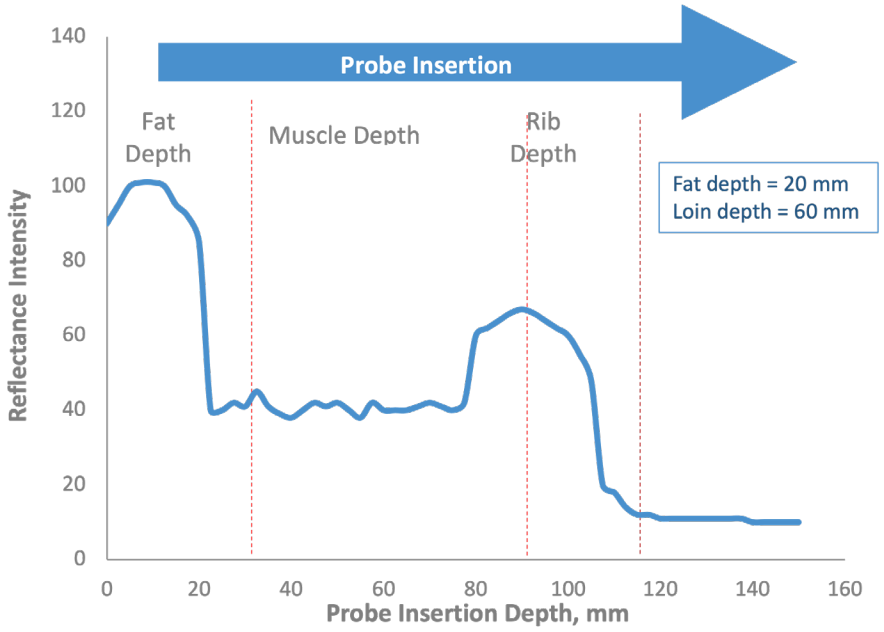


Figure 1.6 Optical grading probe example

Frontmatec Fat-O-Meat'er II™

Photo courtesy of Frontmatec (https://www.frontmatec.com/).

3. Ultrasound Measurements

   Ultrasound technology can be used to estimate carcass composition on both live pigs and carcasses. However, from a commercial pig pricing perspective, it is mostly used on the carcass.

   Depending on the technology, ultrasound measurements can be collected on a subsection of the loin, or on the entire carcass:

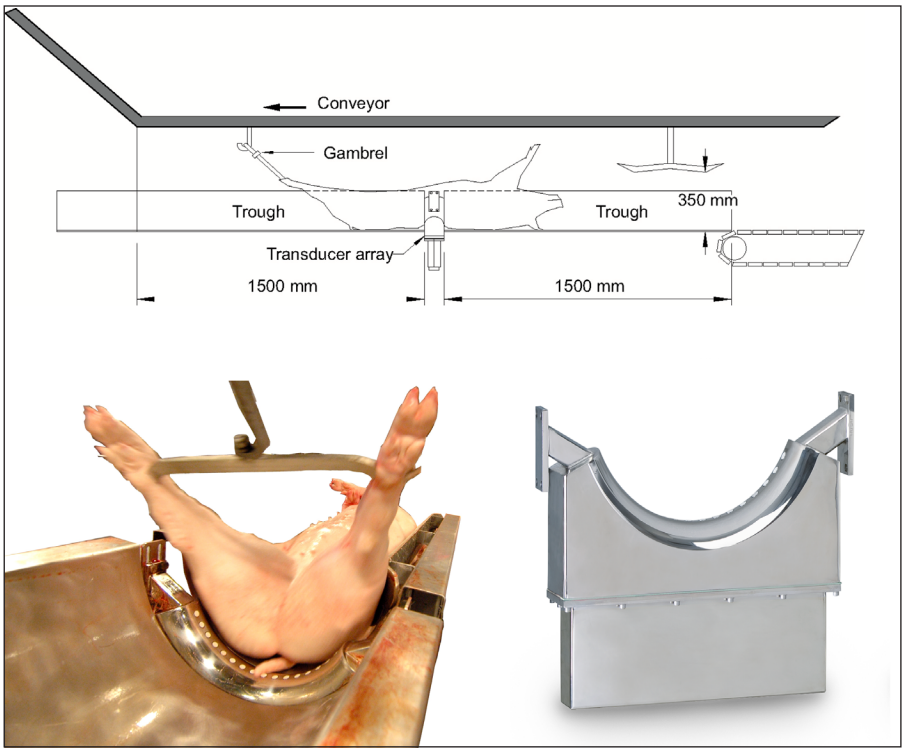
   a. The BioQScan and CVT systems (Figure 1.7) are two of the commonly used ultrasound systems that measure a subsection of the loin.
   b. TheAutoFOM (Figure 1.8) ultrasound system measures the entire carcass. AutoFOM is arguably the most detailed system used for commercial carcass grading since it takes up to 3,200 measurements per carcass. It can provide accurate information on individual primal/sub-primal weights, in addition to measuring backfat and loin depth.

Figure 1.7 Ultrasound carcass grading instrument

BioQscan®

Photos courtesy of Biotronics: http://www.biotronics-inc.com/.

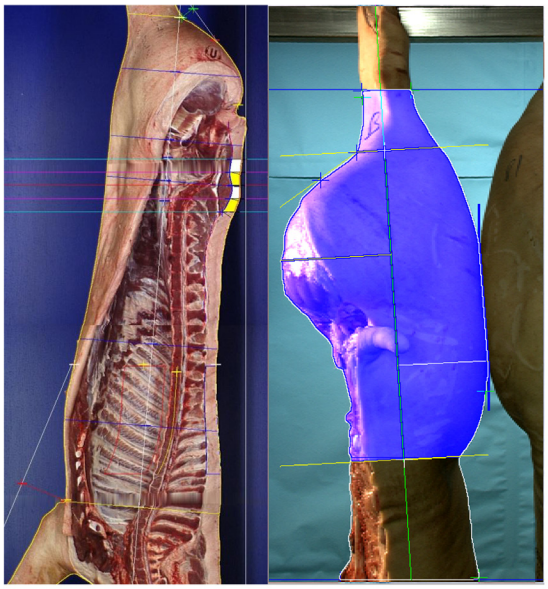
Figure 1.8 AutoFOM III system



Photos courtesy of Frontmatec (https://www.frontmatec.com/).

4. Video Image Analysis
   Video image analysis is infrequently used to evaluate carcass composition. Most systems focus on measurements of the mid-line of the loin, and some incorporate the conformation of hams (Figure 1.9). The two most common systems used to grade carcasses are the CS 2000 and CSB Image Meater.

Figure 1.9 Example of vision grading system



VCS 2000 Image System

Photos courtesy of e+V Technology GmbH & Co.

1.1.2 Carcass Lean Equations

Within each of the different methods of estimating carcass composition, equations must be developed to predict lean percentage and/or primal weights. Many countries develop mandatory "country equations" for each type of approved grading equipment to ensure standard practices. Other countries allow individual companies to develop and validate their own equations for their chosen grading methods.

Each of these equations may be developed based on unique methods; some equations may use total or partial carcass dissections, while others may use predictions for the percentage of primal cuts. Therefore, lean percentage may vary from equation to equation on the same carcass.

Table 1.1 shows 10 equations from different countries estimating lean percentage of a pig with 15 mm (0.59 in) of backfat and 65 mm (2.56 in) of loin depth. The lean percentage from these calculations range from 57.0% to 69.1% lean despite backfat and loin depth measurements being the same. This does not mean that one equation is better than the other but rather, shows that these equations were developed using differing methods to define lean percentage.

Table 1.1 Percentage lean of a pig with 15 mm of back fat and 65 mm of loin depth using equations from different countries

Country	Equipment	Intercept	Backfat Coefficient	Loin depth Coefficient	Lean Percentage
Czech Republic	Fat-O-Meater	59.8613	0.7293	0.1285	57.3
Croatia	Hennessey Grading Probe	59.6037	0.8640	0.1820	58.5
France	UltraFOM	66.4900	0.8910	0.1040	59.9
Germany	Fat-O-Meater	61.8000	0.8830	0.1550	58.6
Netherlands	CGM	66.8600	0.6549	0.0207	58.4
Poland	CGM	50.1193	0.6242	0.2698	58.3
Romania	Fat-O-Meater	60.2699	0.8151	0.2010	61.1
Spain	Fat-O-Meater	64.5300	0.8760	0.1810	63.2
South Africa	Hennessey Grading Probe	72.5114	0.4618	0.0547	69.1
USA 'SFK Standard'	Fat-O-Meater	58.9000	0.6100	0.1120	57.0

Development of these equations is a difficult process that requires extensive work. Variation in the population used for equation development is key to obtaining a statistically valid, and commercially applicable equation. It is important that the test carcasses are equally distributed over the entire weight, backfat, and loin depth ranges that are expected in the commercial grading application.

The tails of the distributions are especially important because they are typically found in the lowest frequency but are critical for developing a statistically sound equation. If the equation will be used on multiple genotypes, the equation should be developed with data from all the different genotypes. The same is true with the sex of the pigs/carcasses to be graded.

1.1.3 Payment Systems

Payment systems may vary from company to company and even from plant to plant within a company, although some standardization within countries does exist. Most payment systems are based on weight, using either live weight or dressed carcass weight, depending on the processing plant.

Most countries have standardized reporting of the base prices (Table 1.2). The base price is typically determined from the average weighted price within a country, or a region within the country. Base price may differ from plant to plant, depending on how much those entities will pay to purchase the pigs.

Table 1.2 Standard foundation for base prices in common hog producing countries

Country	Weight Type	Basis
USA	Carcass	$/100 lbs
Mexico	Live weight	$/kg
Canada	Carcass	$/100 kg
Colombia	Live weight	$/kg
Brazil	Live weight	R$/kg
Chile	Live weight	$/kg
Spain	Live weight	€/kg
Germany	Carcass	€/kg
Netherlands	Live weight	€/kg
Denmark	Carcass	kr/kg
Russia	Live weight	⍰/kg
Italy	Live weight	€/kg
Ukraine	Live weight	₴/kg
Poland	Carcass	zł/kg
Romania	Live weight	lei/kg
France	Carcass	€/kg
UK	Carcass	£/ 100 kg
Australia	Carcass	$/kg
South Africa	Carcass	R/kg
Phillipines	Live weight	₱/kg
China	Live weight	¥/kg
Vietnam	Live weight	VND/kg
South Korea	Carcass	₩/kg

In some instances, pigs may be sold on a base price-per-kg formula. In this case, the base price is established up front. Then the total price is adjusted through different incentive programs to direct the producer to deliver pigs with the attributes that the processing plant desires.

The most basic of these payment systems would be one where only weight is used. Figure 1.10 contains an example of a payment system based on carcass weight (in kg). The processing plant here signals that they want to have pigs within the 82 to 95 kg hot carcass weight range. The farther hot carcass weights are from the desired range, the greater the discount in carcass value is. This type of system helps ensure that producers deliver pigs of the preferred weight to the slaughter plant. Figure 1.11 shows the results of approximately 65,000 pigs slaughtered in a plant using the payment system shown in Figure 1.10. In this instance, almost 66% of the pigs were marketed in the ideal weight range. Only 1.5% of the pigs were discounted -$0.35 to -$0.75 per kg.

Figure 1.10 Example of a weight payment scheme

Weight range	Discount
< 58 kg	-$0.75/kg
59 to 68 kg	-$0.35/kg
69 to 74 kg	-$0.15/kg
75 to 78 kg	-$0.07/kg
79 to 81 kg	-$0.02/kg
82 to 95 kg	$0.00/kg
96 to 98 kg	-$0.04/kg
99 to 102 kg	-$0.10/kg
103 to 108 kg	-$0.20/kg
109 to 112 kg	-$0.45/kg
> 112 kg	-$0.65/kg

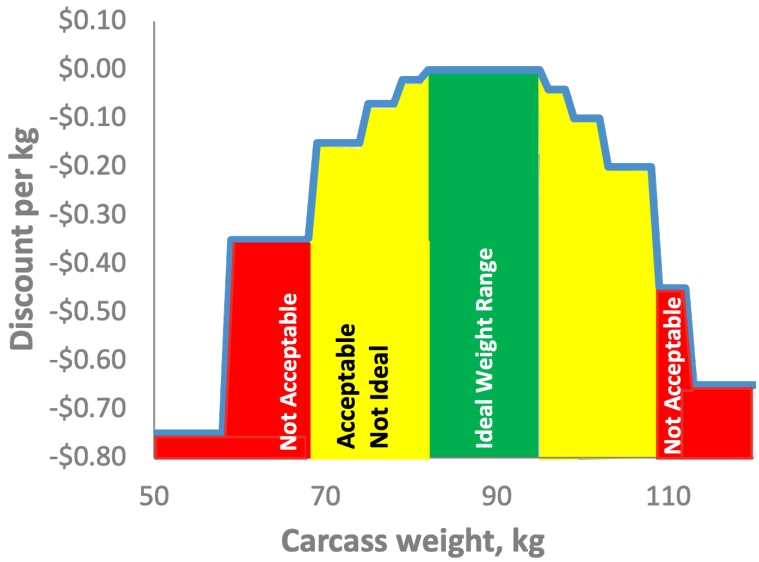
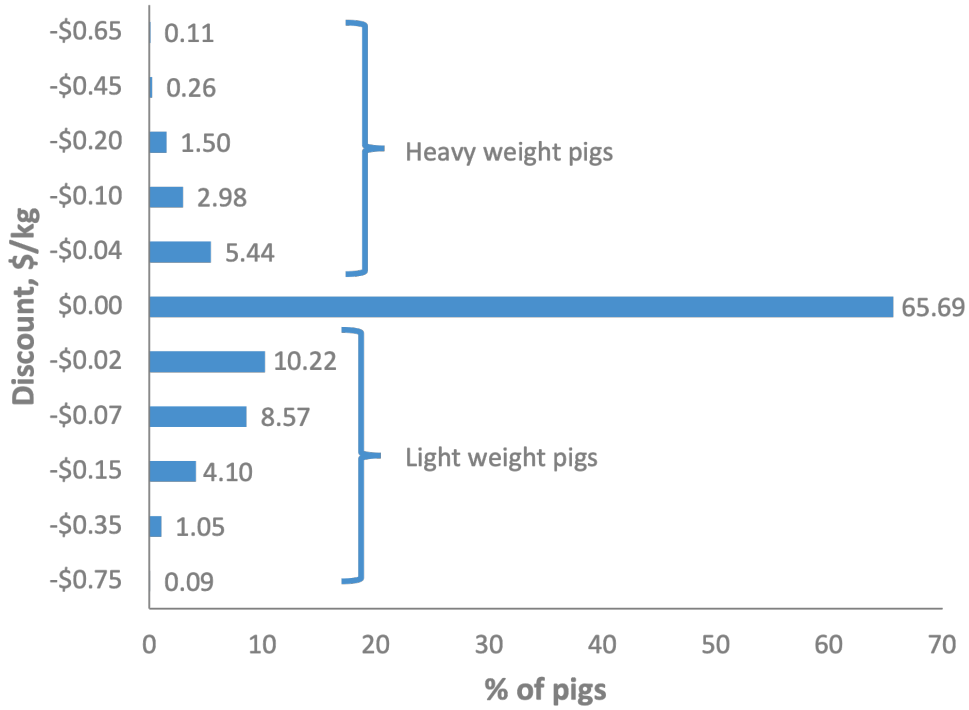


Figure 1.11 Demonstration of weight discounts driving market weights of pigs*



[a] Based on data from 5 producers marketing 64,669 pigs to a large processing plant in the USA.

This is only one example of many possible situations. These systems can vary in the number of weight discount categories, or even pay a premium on a weight category, depending on the slaughter plant's desired results.

Lean percentage is another common payment incentive. Figure 1.12 contains an example of a payment system based on carcass lean that was used in conjunction with the weight discount example in Figure 1.10. In this payment system, the processing plant wants carcasses with 51% to 60.9% lean. Any carcass with less than 51% lean will receive a discount. This lean premium system also incentivizes a desirable marketing behavior. Roughly 81% of the pigs were in the ideal range for lean percentage, while only 6.5% of the pigs were in the unacceptable range (Figure 1.13). These two examples of a weight and lean payment system demonstrate how incentives can influence pig marketing to ensure the right pigs are delivered to the processing plant.

Figure 1.12 Examples of a lean percentage payment scheme

Lean %	Discount
< 43%	-$0.25/kg
43 to 44.9%	-$0.20/kg
45 to 46.9%	-$0.15/kg
47 to 48.9 %	-$0.10/kg
49 to 50.9 %	-$0.05/kg
51 to 52.9 %	$0.00/kg
53 to 54.9 %	$0.05/kg
55 to 56.9 %	$0.07/kg
57 to 58.9 %	$0.09/kg
59 to 60.9 %	$0.06/kg
> 60.9%	$0.00/kg

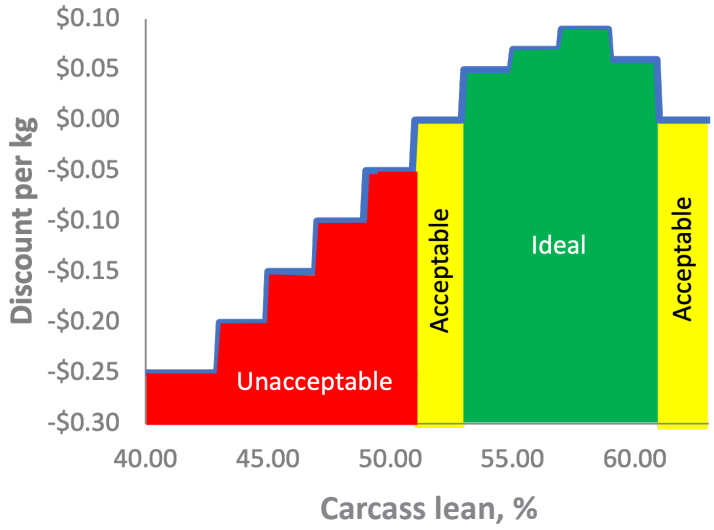
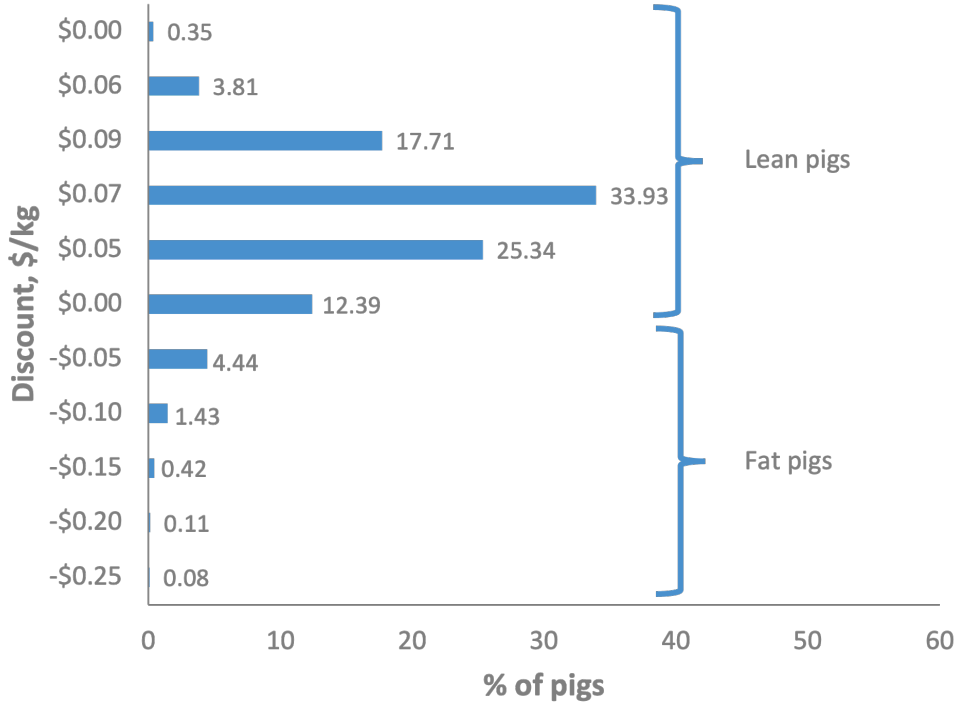


Figure 1.13 Demonstration of lean premiums/discounts driving carcass lean of pigs[a]



[a] Based on data from 5 producers marketing 64,669 pigs to a large processing plant in the USA.

Other variants of previously mentioned payment systems are used around the world. One example is SEUROP (Table 1.3), which is used in the EU. This system assigns a grade or class, based on the percentage of lean. This classification system is standard across the EU, although individual plants may pay differently for each SEUROP class. One company may pay 5 Euro cents more per kg for an "S" class carcass, while another company may pay only 2 Euro cents more per carcass but have a higher base price.

Table 1.3 European Union SEUROP lean meat classification system

SEUROP Code	% Lean Meat
S	> 60%
E	55 to 60%
U	50 to 54.9%
R	45 to 49.9%
O	40 to 44.9%
P	< 40%

Determining which plant will pay more or less is not as simple as determining which plant offers the higher premium within a class. While this classification system is used throughout Europe, it is not used for payment everywhere. Consider Germany, where many of the larger slaughter plants use AutoFOM to determine primal weights and lean percentage. The payment is based on primal weights, belly lean percentage, and carcass weight (Figure 1.14) as part of the system that uses index points to determine the final base price for the payment of the carcass.

Other national systems exist, such as the one used in Russia (Table 1.4). The main components of this system are measurements of carcass weight and backfat thickness between the 6th and 7th ribs. Although most large integrators in Russia do not use this grading/payment system, it is used by many slaughter plants to pay producers for carcasses and to sell carcasses to further processors.

Table 1.4 Russian national standard for carcass grading (GOST)

Grade[a]	Definition	Carcass weight, kg	Backfat thickness[b]	Price per kg
1	Barrows and gilts[c]	Skin on - 47 to 68 kg[d] Skin on - 52 to 75 kg[e]	20 mm and less	140.00 ₽
2	Barrows and gilts	Skin on - 47 to 102 kg[d] Skin on - 52 to 113 kg[e] Skinned - 45 to 91 kg	30 mm and less	138.00 ₽
3	Barrows and gilts	Skin on - up to 102 kg[c] Skin on - up to 113 kg[d] Skinned - up to 91 kg	Over 30 mm	135.00 ₽

[a]Other grades exist for non-market pigs (i.e. 4 = sows; 5 = 3 to 7 kg piglets; and 6 = boars).
[b]Measured on the midline between the 6th and 7th ribs.
[c]No scratches, injures, or bloodspots on skin
[d]Head, front feet, and tail removed.
[e]Head, front feet, and tail not removed.

Figure 1.14 Payment system used in german plants with AutoFOM

Boneless Loin Weight, kg	Index Factor
< 6 kg	2.5
6 to 6.5 kg	2.75
6.6 to 7.5 kg	3.6
7.1 to 8 kg	3.4
> 8 kg	3

Belly Lean %	Index Factor
< 45%	1
45 to 49.99%	1.05
50 to 54.99%	1.5
55 to 59.99%	1.8
≥ 60%	1.7

Boneless Ham Weight, kg	Index Factor
< 15kg	1.8
15.0 to 17.0 kg	2.3
17.1 to 18.5 kg	2.75
18.6 to 21 kg	2.5
> 21 kg	2

Carcass weight, kg	Index Factor
< 85 kg	-1
85 to 87.99 kg	-0.5
88 to 102 kg	0
102.1 to 105 kg	-0.5
> 105 kg	-1

* The weight of the loin (or ham) is used to determine the index factor and then the loin (or ham) weight is multiplied by the index factor to get the amount of index points.
* The lean percentage of the belly is used to determine the index factor for belly and then is multiplied by the belly weight to determine the amount of index points.
* If carcass weight is outside the ideal range then the Index Factor is multiplied by the difference of actual weight and the outer limits of the ideal weight range.

  For Example:
  - Carcass weight is 82 then: 88 - 82 = 6 and 6 x -1 = -6 index points.
  - Carcass weight is 105 then: 105 - 102= 3 and 3 x -0.5 = -1.5 index points.

* Minimum and maximum number of index points are 70 and 104, respectively.

Example 1

	Wt or %	Index Factor	Index Points
Boneless Loin	8.0 kg	3.40	27.2
Boneless Ham	18.5 kg	2.75	50.875
Belly Lean	59.00 %	1.80	-
Belly Weight	14.2 kg	-	25.56
Carcass weight	100 kg	0	0
	Total Index Points		103.64
	Base Price, $/kg		$1.30
	Adjusted Base Price, $/kg		$1.35

Example 2

	Wt or %	Index Factor	Index Points
Boneless Loin	7.3 kg	3.40	24.82
Boneless Ham	19.0 kg	2.50	47.5
Belly Lean	54.68 %	1.50	-
Belly Weight	16.0 kg	-	24
Carcass weight	105 kg	-0.5	-1.5
	Total Index Points		94.82
	Base Price, $/kg		$1.30
	Adjusted Base Price, $/kg		$1.23

Although weight and lean percentage are the main components in payment for pigs, other factors can also influence the payments. Some processing plants pay premiums for homogeneity within a load of pigs to minimize weight variation. Many processing plants around the world measure fat quality, which influences the price paid to pig producers. This typically occurs by setting a minimum average that producers are required to meet over a pre-determined period (i.e., monthly average). In some countries, boars are discounted in price, when compared to gilt and barrow prices.

In summary, each processing plant may pay differently. Minor differences in the payment systems can influence the weight, carcass composition, and other attributes that determine which type of pigs receive the highest net margins.

1.2 Primal and Sub-Primal Cuts

Because pork is a globally traded commodity, carcass cutting is mostly standardized around the world, especially in large processing facilities. In most cases, the carcass first goes through a process called the main break, where the carcass is cut into thirds, albeit in differing proportions. These thirds include the ham/leg, middle (loin and belly), and shoulder (Figure 1.15). As the carcass moves through the cutting process, the sections will be further cut into primals.

The six main primals include:

1. Bone-in ham
2. Bone-in loin
3. Belly
4. Spareribs
5. Butt
6. Picnic

These primals can be broken down further into sub-primals. The primals and sub-primals can differ slightly due to cut specifications between the companies and plants, but the largest differences exist between different regions of the world. These differences will be explained later in this section. The nomenclature also varies around the world and these differences will be explained as well. Figures 1.16, 1.17 and 1.18 provide examples of how carcasses can be broken down into primals and sub-primals in North America.

Figure 1.15 Carcass primals

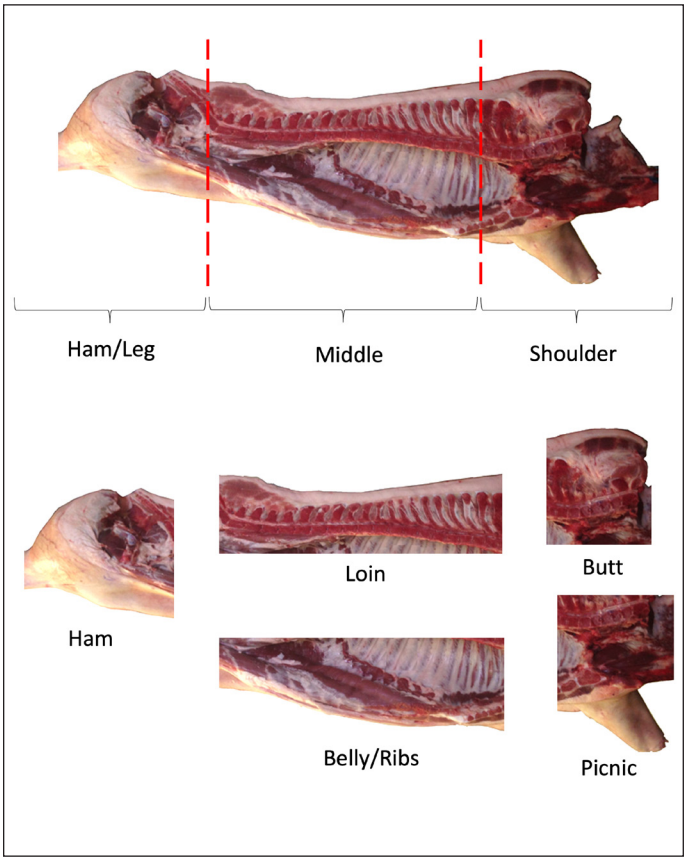


Figure 1.16 Ham primals and major sub-primals

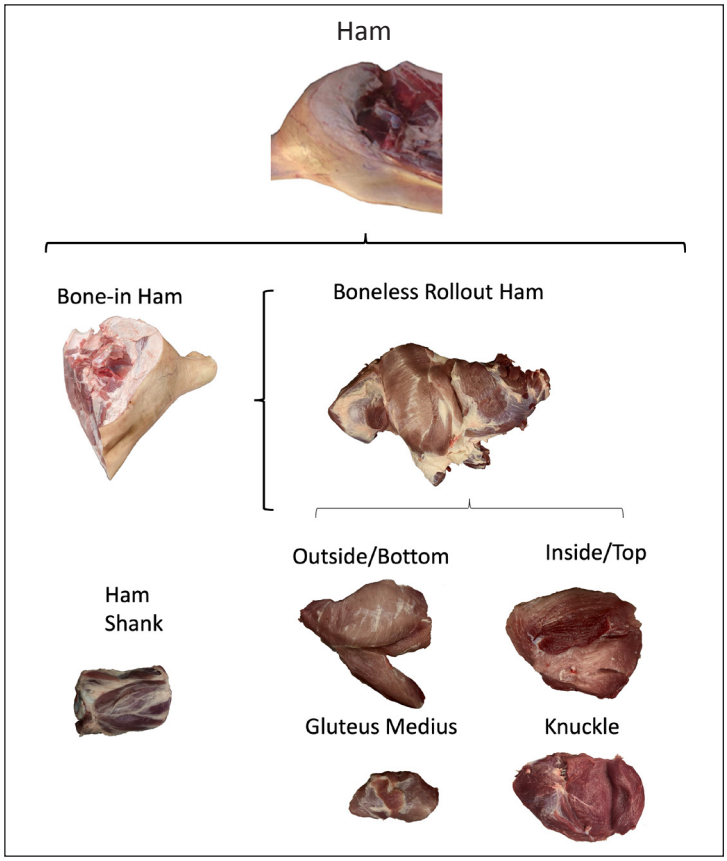


Figure 1.17 Middle primals and major sub-primals

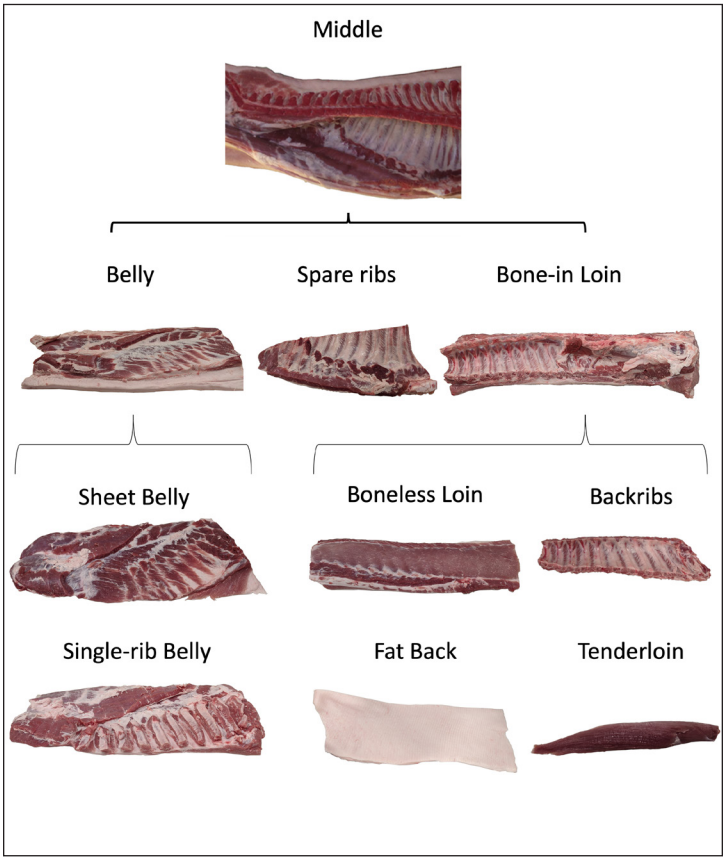
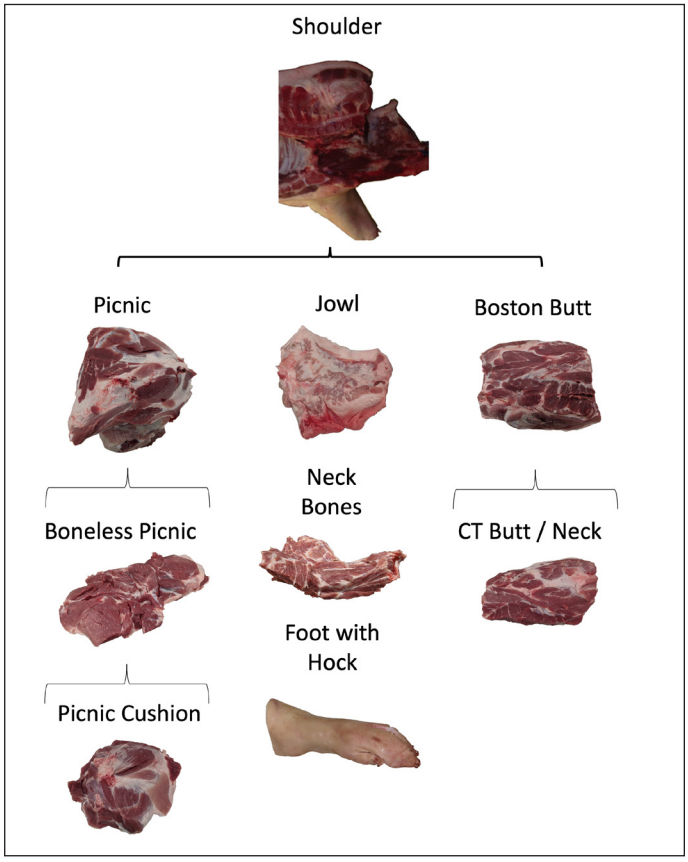


Figure 1.18 Shoulder primals and major sub-primals



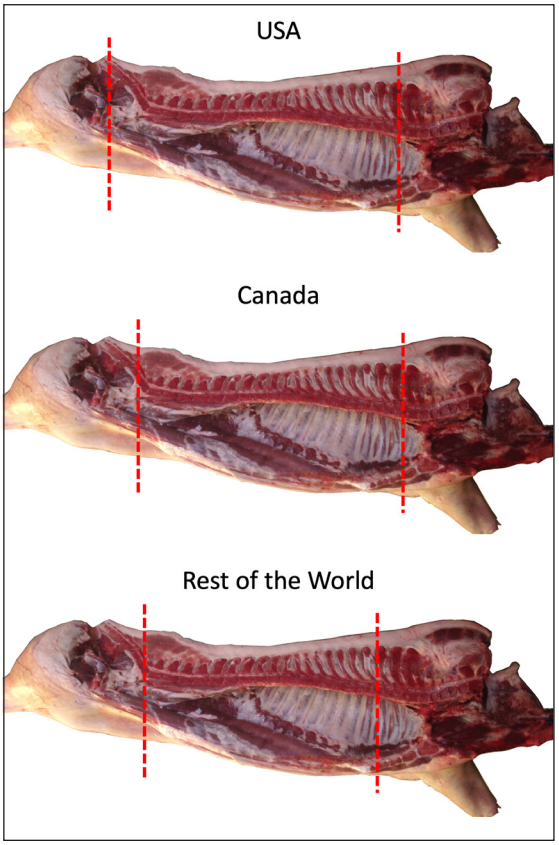
1.2.1 Regional Differences

Figure 1.19 outlines the major differences in how the ham, middle, and shoulder sections are separated, depending on the region of the world where the pork is processed.

In the USA and Canada, the ham section is normally removed at the same location, at about 3.8 cm to 8.8 cm (1.4 to 3.5 in) anterior to the aitch bone and cut perpendicular with the shank. In most other regions of the world, the ham is removed perpendicular with the ham shank, but it includes the sirloin from the loin region. Thus, bone-in hams would be much larger outside of the USA and Canada due to this difference in carcass breaking.

The shoulder section is also removed from the middle section differently around the world. In the USA, the separation is in the region of the 1st and 2nd ribs, while in Canada the separation is made in the region of the 2nd and 3rd ribs. In most other regions, the break is made between the 4th and 5th ribs (referred to as the 4-5 break). These differences result in much heavier loin and belly weights in the USA and Canada when compared to the other regions.

Figure 1.19 Difference in main carcass breaks



1.3 Carcass Yield

1.3.1 What Is Carcass Yield, and Is It Important?

Carcass yield (sometimes called “dressing percentage”) is often misunderstood, and the terminology is often misused. It is important to not use the terms primal yield and carcass yield interchangeably, since they are completely different.
Carcass yield is the amount of carcass yielded from a live pig. Primal yield is the amount of primals yielded from a carcass. Carcass yield is expressed as a percentage. To calculate this number, simply divide the carcass weight by the live weight and multiply by 100 (Figure 1.20).

Most processing plants have historically provided carcass yield information to producers, so producers often think that yield is important to their pig production business. In many cases, carcass yield is not important. The key is whether the producer is paid on a live-weight basis or on a carcass-weight basis.

Figure 1.20 Carcass yield calculation

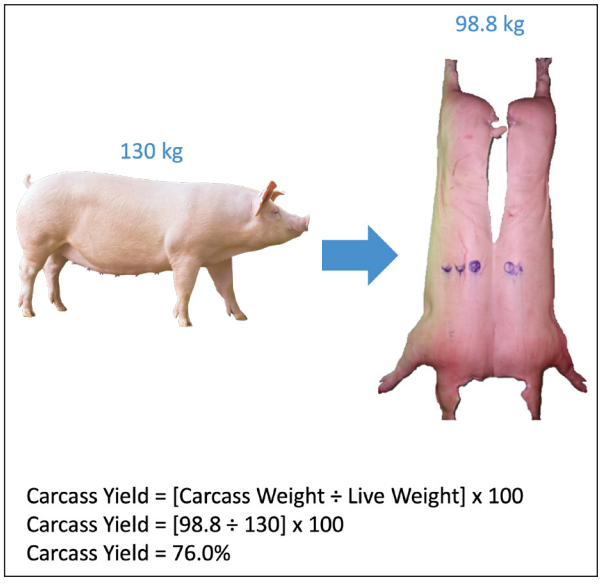


Figure 1.21 contains caluclations for pig payment on a live and carcass weight basis using two different scenarios. In scenario 1, live weight increases while the carcass weight stays the same, leading to decreased yield. In this scenario, the payment on a carcass basis results in the same amount for the same size carcass, but payment on a live weight basis increases as the live weight increases.

This means that on a live-weight basis payment, the processing plant could pay more for the same size carcasses. The processing plant will be at a disadvantage under this scenario, as their procurement cost per kg of carcass would increase with lower-yielding pigs. The producer with lower-yielding pigs would have an advantage and receive more money for less carcass.

In scenario 2, live weight remains the same and carcass weight is increased, leading to increased carcass yield. Under this scenario, the payment on a live-weight basis results in the same amount for the same weight pig. On a carcass weight basis, the payment increases as the carcass weight increases. Thus, the processing plant would pay less for a heavier carcass (higher yielding) when paying on a live-weight basis.

The processing plant will be at an advantage using live-weight basis under this scenario, since the plant's procurement cost per kg of carcass is increased. The producer with higher-yielding pigs is at a disadvantage and will receive less money when delivering more carcass per pig.

The key is that when the payment transaction is based on carcass weight, yield does not matter. In other words, neither the producer nor the processing plant has an advantage based on carcass yield. This common, commercial approach is the most desireable, since many factors can influencecarcass yield.

Figure 1.21 Effect of pig payment on a live weight or carcass weight basis

Live Price 1.19 €/kg	Carcass Price 1.50 €/kg

Scenario 1 – Live weight increases while carcass weight stays the same.
Scenario 2 – Live weight stays the same while carcass weight increases.

Live weight	Carcass weight	Carcass yield	Value (Live wt.)	Value (Carcass wt.)
110	88	80.0	€ 130.35	€ 132.00
111	88	79.3	€ 131.54	€ 132.00
112	88	78.6	€ 132.72	€ 132.00
113	88	77.9	€ 133.91	€ 132.00

Scenario 1

Live weight	Carcass weight	Carcass yield	Value (Live wt.)	Value (Carcass wt.)
110	86	78.2	€ 130.35	€ 129.00
110	87	79.1	€ 130.35	€ 130.50
110	88	80.0	€ 130.35	€ 132.00
110	89	80.9	€ 130.35	€ 133.50

Scenario 2

1.3.2 Factors Affecting Carcass Yield

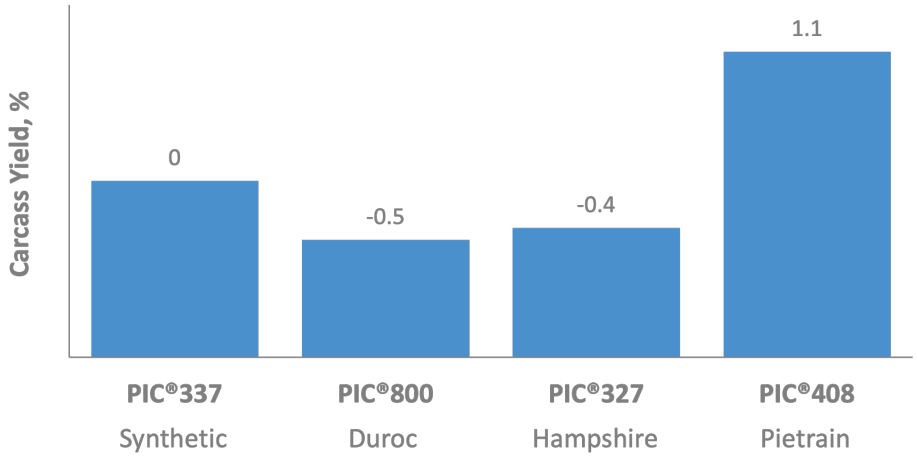
Six main factors influence carcass yield, including:

1. Genetics/sex/weight
2. Feed withdrawal/gut fill
3. Nutrition
4. Accuracy of weights
5. Location where weights are taken
6. Carcass dressing procedures

Genetics/Sex /Weight

The genotype, sex, and weight of pigs can all impact carcass yield. Figure 1.22 contains data from PIC's Performance Validation Program, which demonstrates the differences in carcass yield between different breeds/lines. The Pietrain line (PIC408) clearly has the highest carcass yield, followed by the synthetic line (PIC337) and the Hampshire (PIC327) and Duroc (PIC800) lines.

Figure 1.22 Effect of genotype on carcass yield*



* Data based on multiple PIC Product Validation trials.

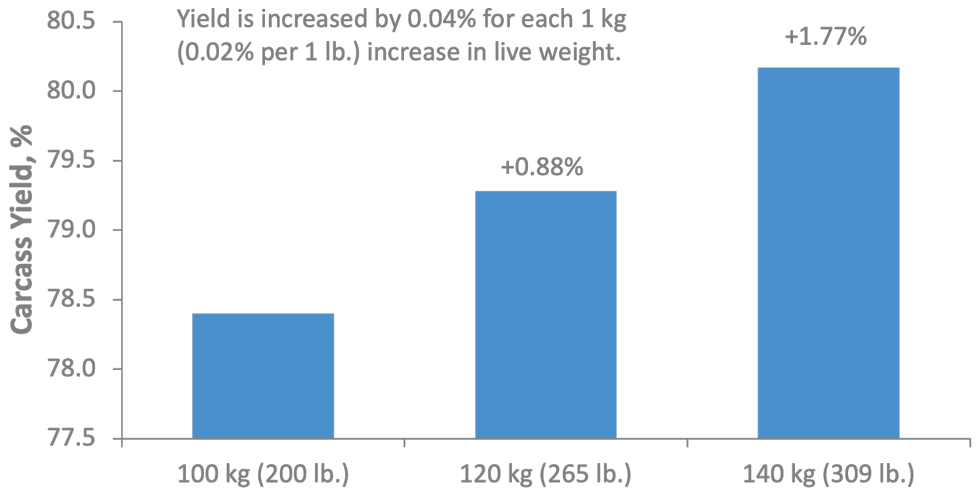
With regards to sex, Table 1.5 shows 7 different trials that determined the differences in carcass yield between barrows and gilts. The results were inconsistent, with barrows having higher yields in 4 trials, and gilts having higher yields in 3 trials. Overall, the barrows averaged 0.10% higher carcass yield than gilts. In a literature review by Xue et al. (1997), involving 15 literature sources, barrows averaged 0.92% higher carcass yield than boars (differences in genitalia weight influenced most of this variation).

Table 1.5 Effect of sex on carcass yield

Reference	Barrows	Gilts	Difference
Xu et al., 2010	77.35	77.38	-0.03
Friesen et al., 1994	72.67	71.92	0.75
Christian et al., 1980	71.61	71.38	0.23
Latorre et al., 2008	78.50	78.40	0.10
Boler et al., 2014	78.72	78.51	0.21
Bertol et al., 2015	79.44	79.55	-0.12
Wagner et al., 1999	74.63	75.10	-0.47
		Average	**0.10**

Figure 1.23 summarizes data from 7 different literature sources to determine the effect of live weight on carcass yield. Live weights in the trials ranged from 91 to 182 kg (201 to 401 lb.). Regression slopes were calculated for each trial. Then the average slope of all trials was used to generate the data in the figure. On average, carcass yield increased by 0.04% for every 1 kg increase in live weight (0.02% per 1 lb. increase in live weight).

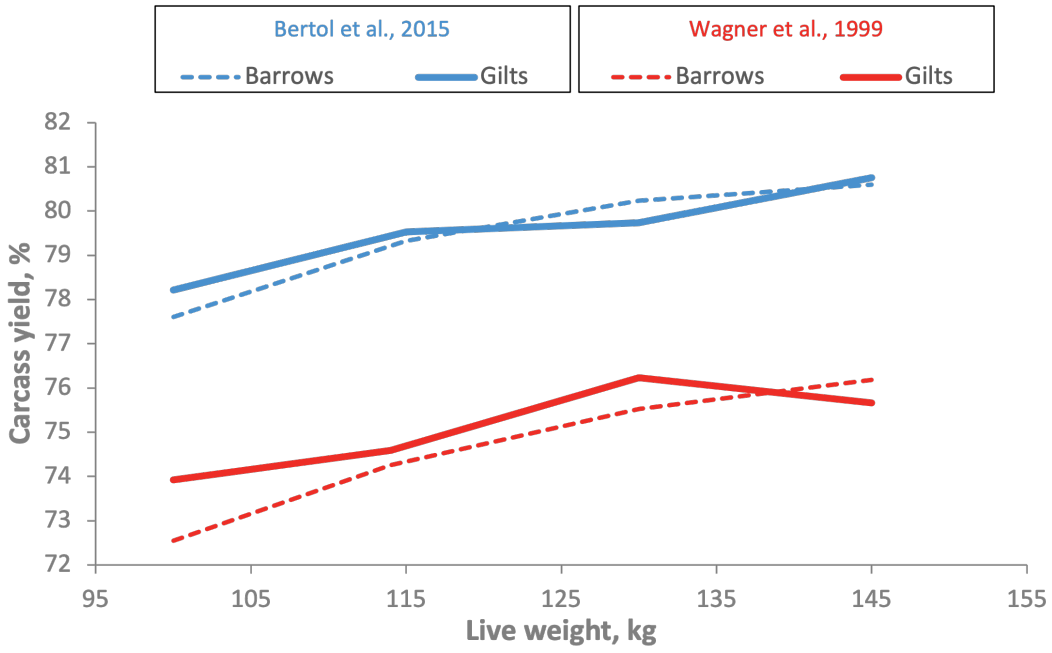
Figure 1.23 Effect of live weight on carcass yield*



*Data are derived from an analysis of data from 7 trials (Christian et al., 1980; Latorre et al., 2008; Apple et al., 2009; Virgili et al., 2003; Crome et al., 1996; Bertol et al., 2015; and Wagner et al., 1999) with slaughter weights between 91 and 182 kg (201 and 401 lb.).

Figure 1.24 demonstrates the interactive effect of sex and live weight on carcass yield. At lighter weights, the gilts had higher yields. As weights increased, the difference diminished, with the barrows having higher or similar yields at the heavier weights. This may explain the variability observed in the data in Table 1.5 between barrows and gilts, where the trials had different end-point weights.

Figure 1.24 Interaction of live weight and sex on carcass yield



Gut Fill/Feed Withdrawal

The main components of live weight not included in the carcass weight are the viscera, reproductive tract, blood, hair, toenails and head (if head-off carcass). The viscera are by far the largest component of live weight (≈14%) that's not included in the carcass weight.

The digestive tract makes up a large portion of the viscera. The weight of the digestive tract can be influenced by the amount of feed and water in the tract (gut fill). Using the calculations in Table 1.6 to determine the effect of gut fill on carcass yield, 1 kg of gut fill will decrease carcass yield by 0.60% (head-off yield) or 0.64% (head-on yield). Managing gut fill is an important factor in increasing carcass yield and reducing variation in that trait.

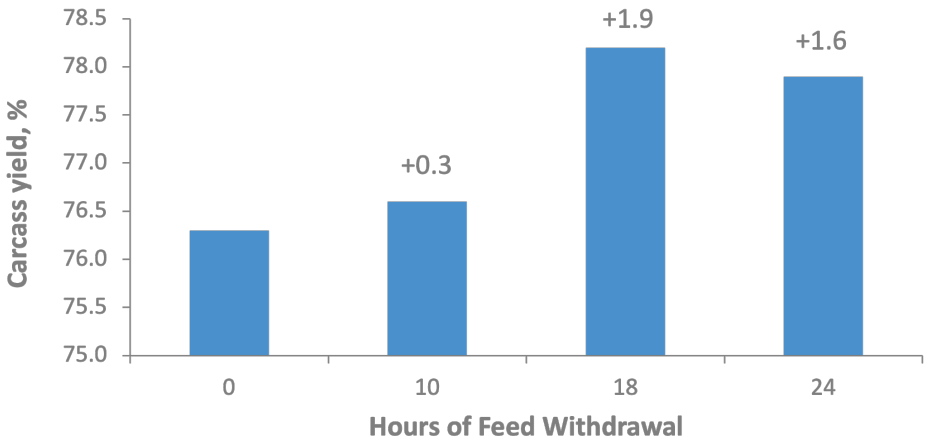
Table 1.6 Effect of gut fill on carcass yield

Item	Carcass without head		Carcass with head	
	0 kg fill	1 kg fill	0 kg fill	1 kg fill
Live weight, kg	125	126	125	126
Carcass weight, kg	95	95	101.25	101.25
Head (5%), kg	6.25	6.25	0	0
Hair/blood/nails (6%), kg	7.5	7.5	7.5	7.5
Visera (14%), kg	16.25	17.25	16.25	17.25
Carcass Yield, %	76.00	75.40	81.00	80.36
Effect of 1 kg of gut fill	**-0.60**		**-0.64**	

Feed withdrawal prior to slaughter is sometimes used to mitigate gut fill. Data from a large commercial trial suggests that carcass yield is increased as the number of hours off feed increases (Figure 1.25). The effect is minimal up to 10 hours off feed, but at 18 hours off feed carcass yield increased by almost 2%.

However, excessive feed withdrawal may decrease carcass yields. The data show that the difference between 18 and 24 hours of feed withdrawal is minimal, but it is more pronounced between 24 and 30 hours off feed. This is mainly due to potential loss of muscle mass in the carcass.

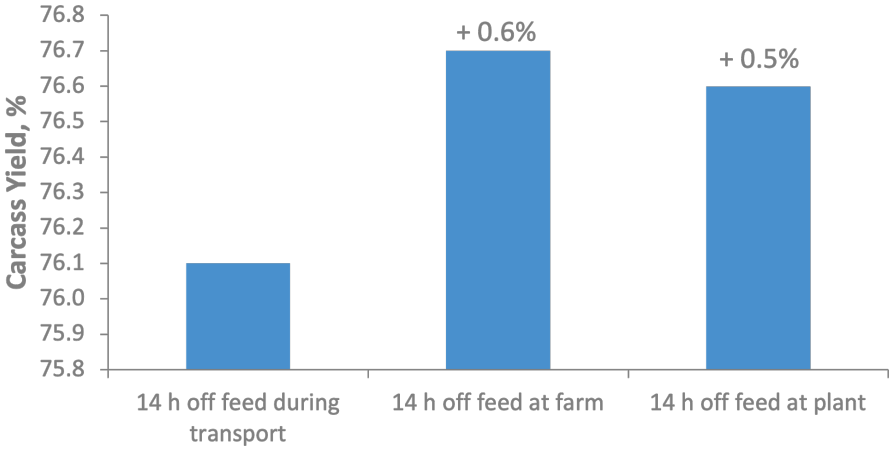
Figure 1.25 Effect of feed withdrawal time on carcass yield*



* Unpublished data from a large-scale commercial trial.

The timing of the feed withdrawal can also have an effect. A large commercial trial evaluated the effects of 14 hours of feed withdrawal and whether that occurred on-farm, during transport, or at the processing plant (Figure 1.26).

Figure 1.26 Effect of feed withdrawal type on carcass yield*



* Unpublished data from a large commercial trial. Total off-feed time was 16-17 hours.

Pigs that were off feed for 14 hours either on farm or at the plant had higher carcass yields (less gut fill) than the pigs that were off feed for 14 hours during transport. These differences are likely due to a shut-down of the gut metabolism during transportation due to stress, without enough rest at the plant for normal gut function to resume.

These data suggest that some level of feed withdrawal is necessary before loading and transportation to minimize gut fill and control carcass yields. PIC recommends a minimum of 6 to 8 hours of feed withdrawal prior to loading pigs, with at least 2 to 3 hours of rest time once pigs have been placed in pens after transport and before the pigs are moved to stunning. Ideally, the total feed withdrawal time (on-farm, transport, and plant) should be 12 to 20 hours, with no more than 24 hours of total feed withdrawal time.

It is also important to consider the negative effect feed withdrawal can have on pigs. Unless facilities or marketing strategies allow for sorting market pigs for feed withdrawal, the feed system is shut down for the entire finishing barn and/or pen within a barn. This will result in out-of-feed events for pigs that are not marketed on that day.

A large-scale commercial trial in the U.S. indicated that death loss can be increased by 0.25% when feed withdrawal is practiced 2 weeks prior to barn close-out, but other growth traits were not affected. However, large scale commercial observations in Europe have indicated that feed withdrawal 4 weeks prior to barn close-out had no effect on subsequent death loss.

This disparity may be explained by the death loss prior to marketing. In the U.S. trial, average death loss was more than 6%, while the average death loss was less than 2% in the European trial. This indicates that it's important to consider health status and/or out-of-feed events prior to the first marketing out of a barn, especially when considering feed withdrawal prior to barn close-outs.

It is important to note that the PIC-recommended feed withdrawal time also exerts a positive effect on pork quality. This will be discussed in sections 3.2.3.2 and 3.3.2.

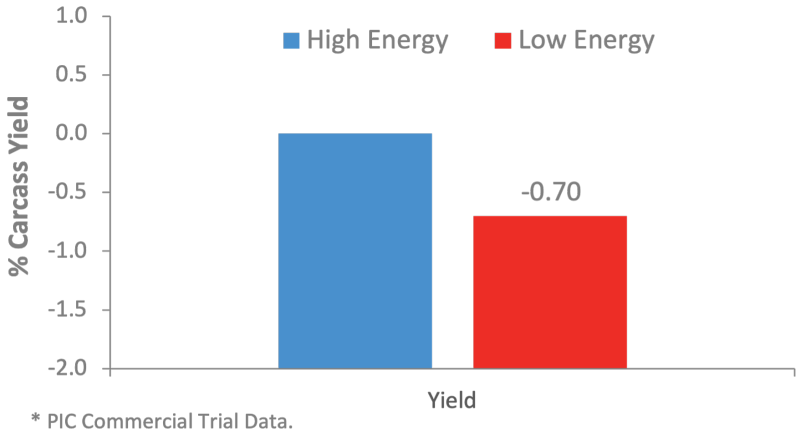
Nutrition

Many aspects of nutrition can affect carcass yield. One of the most common is feeding diets high in fiber, which will reduce carcass yield.

Numerous studies have evaluated high-fiber ingredients, such as corn distiller grains. Researchers havefound that carcass yield consistently decreases as the level of high-fiber ingredients increases in the diet. Much of this effect is attributed to slower gut passage rates associated with feeding high-fiber diets. This results in higher amounts of gut fill when the pigs are harvested.

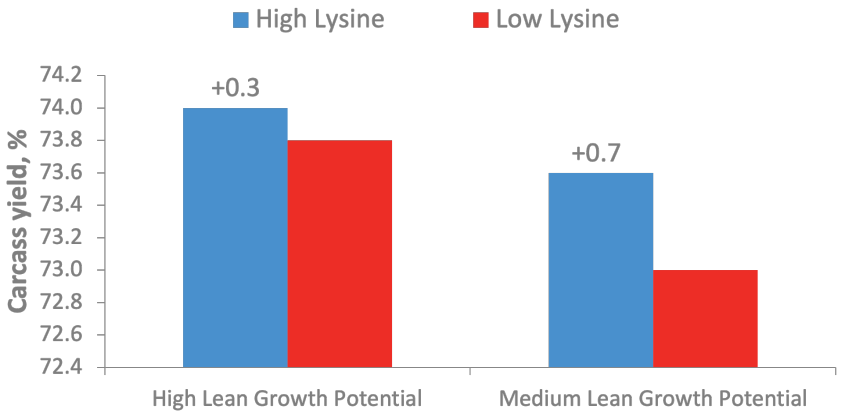
Similarly, PIC research shows that boosting the energy level of the diet (reducing fiber levels) will increase carcass yield (Figure 1.27). Other research involving amino acid levels suggests that increasing the level of amino acids with crystalline amino acids can decrease carcass yield (Figure 1.28). This effect of higher amino acid levels is connected to increased fiber content. Higher amino acids levels will result in higher-fiber diets due to the reduction in soybean meal added to the diet resulting in more gut fill.

Figure 1.27 Effect of dietary energy on carcass yield*



* PIC Commercial Trial Data.

Figure 1.28 Effect of lysine level on carcass yield*



* Adapted from Friesen et al., 1994; J. Anim. Sci. 72:946-954.

Accuracy of Weights

Accuracy of weights can make a big difference in carcass yield evaluations. If a scale is not maintained and/or calibrated frequently, the weights may be off and cause a lower- or higher-than-expected yield.

More importantly, live weights for yield calculations are normally taken by truckload (i.e., truck scale), while carcass weights are taken individually on a different scale. An accurate and consistent assessment of pig live weight and carcass weight is critical in measuring and understanding the commercial implications of carcass yield.

Location Weights are Taken

The location where pig live weights are measured can have a large effect on the carcass yield. When the live weight is taken on the premise of the plant, the yield is normally higher than when live weight is taken before or during transportation.

This is because pigs will lose weight during transport ("transport shrink"). The amount lost can vary but is normally in the 1% to 2% range. For example, assume a pig weighs 125 kg on farm and weighs 123 kg when it arrives at the plant (1.6% transportation shrink loss). If the (head-on) carcass weight were 100kg, the calculated carcass yields would be 80% for the on-farm live weight, and 81.3% for the live weight collected at the plant. This is a difference of 1.3% in carcass yield, due simply to place and time the live weight was collected.

Dressing Procedures

Dressing procedures can significantly influence carcass yield. Most countries leave the head on the carcass. In the USA, the head is removed from the carcass before carcass weights are measured. The head will account for 4-5% of the live pig weight and will affect yields by 4-5%. Typical head-on yields are 79% to 81%, while head-off yields are 74% to 76%. Other body parts that may or may not be removed that can affect yield are the leaf fat, kidneys, feet, and skin.

Excessive trim losses during the dressing procedures can also alter carcass weight, and may occur due to the following:

- Cryptorchids and rigs
- Ruptures, abdominal hernias ("belly busts"), etc.
- Black hair roots and/or "hard hair"
  - Requires skin removal
- Bug bites, disease / sub-optimal health
  - Skin lesions
  - Lung adhesions
  - Condemned offal
- Injuries, cuts, bruises, abscesses, etc.
  - Often caused by sharp objects in pens (bolts, gate latches, water nipples, etc.)
  - Broken bones
  - Tail bites
  - Fight marks
- Feed withdrawal
  - Reduced gut spill

While excessive trim losses can have a large impact on individual carcasses, the effect on the yield of an entire load may not be noticeable if the losses are confined to one pig. The greatest impact is seen when entire loads of pigs are sick or compromised in some way (i.e., bug bites).

Section 2

Defining Meat Quality and the PIC® Blueprint to Attain Desirable Outcomes

Meat quality is a term that is used broadly and frequently describes many different meat characteristics. The next two sections will define meat quality and discuss various industry-important aspects of meat quality.

A common definition for quality would be “the total of all characteristics that cause differences between samples of a product and which influence the appreciation of the product by the end consumer” (Hoffman, 1994). Thus, the end user defines the quality based on preferred or valued characteristics. For pork quality, the end user can mean the processor, wholesaler, retailer, or, most importantly, the consumer.

Meat quality can be allotted into 5 categories:

1. Hygiene and food safety
   - Aspects of the slaughter, handling, and cold-chain process that could affect whether the pork is safe to eat.
2. Nutritional composition
   - Aspects of the protein, fat, and carbohydrate composition, and how that nutritional profile is perceived as healthy for the end user.
3. Ethical/welfare
   - Aspects of how the pig was treated and raised on the farm until it is euthanized at the processing plant.
4. Sensory
   - Aspects of the actual pork eating experience.
5. Technological
   - Aspects that can predict the eating experience or processing suitability of pork.

Of these five categories, the hygiene/food safety, nutritional composition, and ethical/welfare components can be considered fixed aspects of quality. In other words, pork must be processed in an ethical manner and in a way that ensures safety and nutrition for consumers.

This manual focuses on the sensory and technological aspects of pork quality that define the actual or potential eating experience of the pork. It is important to note that the ethical/welfare component has some overlap with sensory and technological components, since poor welfare results in stressed pigs. This can have a negative effect on the eating quality of the pork.

The sensory component is comprised of the assessments made during consumption of the product (either knowingly or unknowingly) that define the eating experience. Scientific testing is conducted with either a sensory (trained) or consumer (untrained) panel. Panelists typically assess tenderness, juiciness, flavor, and off flavors. These two panel types will be discussed in more detail in Section 3 of the manual.

The technological component is composed of common measurements that are used to define or predict the quality of pork, including:

- pH
- Water-holding capacity
- Color
- Instrumental tenderness
- Marbling/intramuscular fat (IMF)
- Fat quality

The sensory and technological components of pork quality are divided into two categories for further discussion in the next two sections.

2.1 The PIC Blueprint

Thanks to our current understanding of the basic and applied science fundamentals regarding meat quality, a system can be developed to achieve desirable meat quality more consistently. The PIC Blueprint for Animal Welfare and Meat Quality, established by PIC in 1996, was one of the first industry standards for pork quality.

PIC designed the Blueprint to highlight practices that ensures animals are handled and slaughtered in a humane manner, which leads to improved meat quality. PIC actively monitors and contributes to new scientific knowledge to continuously update the Blueprint.

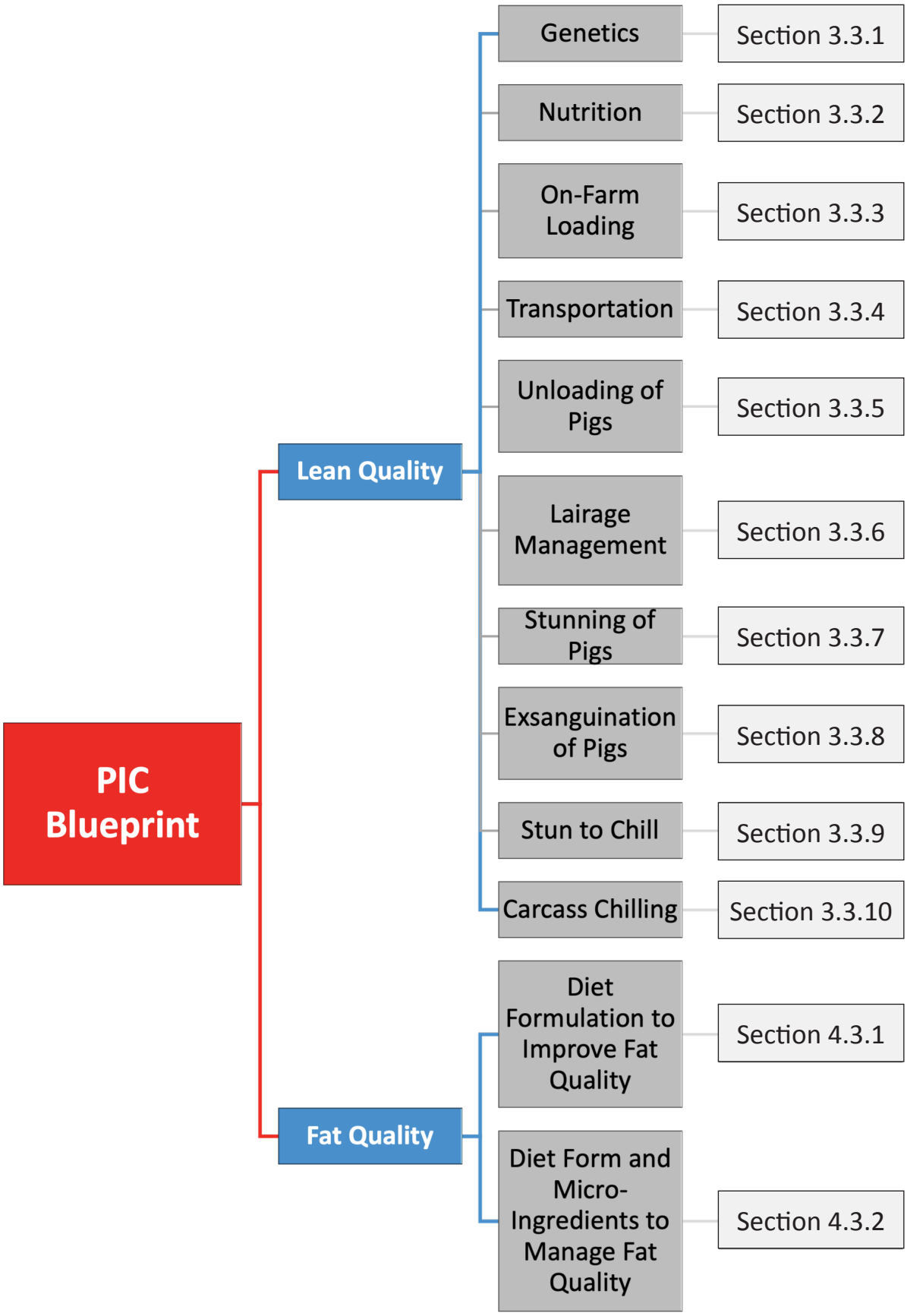
When it comes to managing lean meat quality (MQ), three main factors must be addressed: glycogen storage levels (or glycolytic potential; GP), stress levels (S), and rate of carcass temperature (T) decline. Think of managing meat quality as an equation:

$$MQ = GP + S + T$$

The PIC Blueprint addresses 10 critical areas for the development of good meat quality. These include genetics, nutrition, on-farm loading, transportation, plant unloading, lairage management, stunning management, exsanguination, stun-to-chill management, and carcass chilling. The original PIC Pork Quality Blueprint only addressed lean quality and animal welfare. As fat quality has become increasingly important since the early 2000's, it is included in the revised PIC Pork Quality Blueprint.

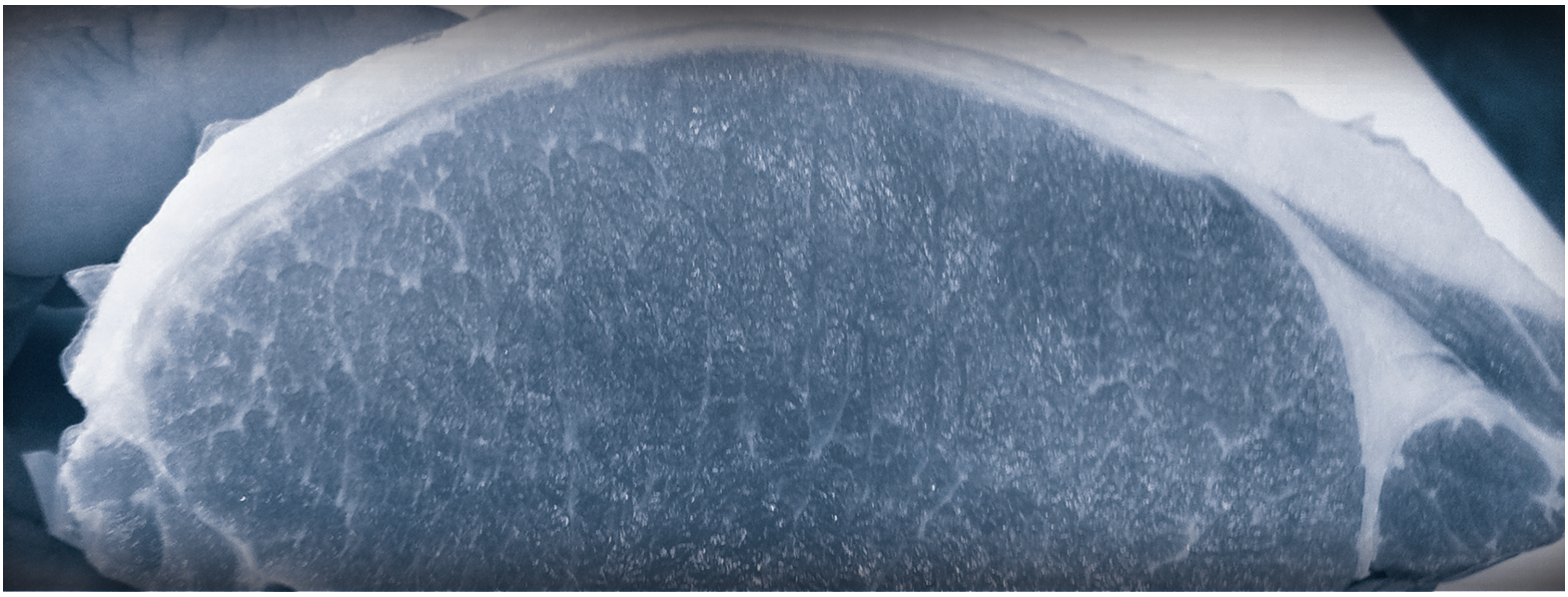
The PIC Pork Quality Blueprint for pork lean and fat quality is outlined in Figure 2.1. Although sections 3 and 4 will discuss the specific details of biology, as well as measuring and managing lean and fat quality, this outline will provide a quick reference to help locate specific management practices.

Figure 2.1 PIC Pork Quality Blueprint



Section 3

Pork Lean Quality



3.1 Measurement of Pork Lean Quality

Defining pork lean (muscle) quality can mean different things to different people. These features often include how the pork looks or feels. The ultimate gauge of pork lean quality, however, is its eating quality (tenderness, juiciness, and flavor).

The following metrics can be used to measure or predict lean quality and can be affected by several factors discussed below. This section focuses on these metrics and the equipment and methods for evaluation. Factors that influence these metrics during the conversion of skeletal muscle to meat, plus how to manage those biochemical processes will be discussed.

3.1.1 Key Metrics

The metrics can be divided into two categories: 1) indirect measurements that are used to predict the lean quality, and 2) direct measurements that assess lean eating quality.

Indirect Measurements

- pH
  - Measurement of acidity in the muscle/meat.
  - Post-mortem lactate formation in the muscle/meat causes pH to decrease.
  - pH is an objective measurement.
- Color
  - Color of the lean muscle/meat.
  - Color is affected by myoglobin levels and pH.
  - Color can be measured subjectively or objectively.
  - Color could also be a direct measurement, since consumers may select product based on color.
- Water-holding capacity
  - The ability of the muscle/meat to retain water.
  - Directly related to the pH of the muscle/meat.
  - Drip loss and purge loss are common ways of measuring.
  - Cook loss is also influenced by water-holding capacity
  - Mostly measured in an objective manner.
- Firmness
  - Measurement of the firmness of a muscle or group of muscles.
  - Firmness is affected by many factors including pH, fat composition, temperature, weight, etc. within a primal or sub-primal cut.
  - Mostly measured in a subjective manner.
- Marbling/IMF
  - Level of intramuscular fat (IMF) within a muscle.
  - Not related to pH level.
  - Can be influenced by genetics, diet, and sex.
  - Can be measured subjectively (marbling) or objectively (analyzed IMF/lipid level).
  - Marbling could also be a direct measurement, as consumers may select product based on the degree of marbling.
- Temperature
  - Declines as muscle is converted to meat during the initial ~24 hours post-mortem.
  - Rate of temperature decline is important in regulating post-mortem metabolism and pH decline.
  - Temperature is measured objectively.

Direct Measurements

- Shear force
  - A direct measure of pork tenderness.
  - Also correlated with pH, juiciness, and flavor.
  - Shear force is measured objectively.
- Sensory analysis
  - A panel of people conduct taste testing under a controlled set of conditions with standardized scoring.
  - Panels can consist of a trained or consumer (untrained) panel.
  - Sensory analysis, for the most part, is a subjective measurement. A highly trained sensory panel reduces the subjectivity.

3.1.2 Pork Quality Measurement Procedures

3.1.2.1 pH Measurement

Many different meters are available for measuring the pH of meat. Some of the common ones being used around the world are found in Figure 3.1.

Figure 3.1 Commonly used pH meters

MPI pH Meter
http://www.meatprobes.com/

Frontmatec pH*K21
Photo courtesy of Frontmatec
(https://www.frontmatec.com/)

Hanna HI98163
https://www.hannainst.com/

Hanna Halo Bluetooth FC2022
https://www.hannainst.com/

Figure 3.2 Probe types used for measuring pH in meat

Glass Tip Probe

Non-Glass ISFET Probe

The key to obtaining good, reliable pH measurements depends less on the pH meter itself and more on the quality of the pH probe used with the meter. It is important to use a pH meter fitted with a pH probe that is designed for determining pH in food products.

The two most common probe types used for measuring meat pH are the glass tip or the non-glass ISFET probe (Figure 3.2). These tips are spear shaped to allow insertion into an intact muscle. The ISFET probe is desirable from a food safety standpoint because it reduces the risk of broken glass tips contaminating the meat. However, the glass tip probes are more accurate and reliable.

The main challenge with an ISFET probe is that it is difficult for the sensor to make proper contact with the meat since it is slightly inset in the probe. An ISFET probe also has a slower reaction time compared to glass. Despite the drawbacks, it may be necessary to use ISFET probes in processing plants that forbid the use of glass-tipped probes.

Note: Some pH probes (Smart Probes) have the capability of measuring pH and temperature simultaneously.

Most pH meters are designed for use in a laboratory environment, and therefore, are not practical for use in processing plants. Some models are developed to be portable and water resistant, however, making them ideal for use in a processing plant environment. Three basic hand-held pH meter styles are available:

- Pistol style:
  - Designed specifically for measuring pH in meat; allows for one-hand use.
  - Usually more expensive, with a price range of $2,500 to $5,000 USD (2021 prices)
- Handheld corded:
  - Requires using both hands, as the pH probe is on a cord.
  - Lower-end models start at about $200 USD without a pH probe. Depending on the probe type, probe costs range from $150 to $300 USD.
- Bluetooth: can be used with either one or two hands (requires a smartphone or tablet).
  - The probe is the pH meter, but it is equipped with an app to record pH. These probes cost around $200 USD.

Another consideration when selecting a pH meter is the ability to log and store results as pH measurements are collected and download the data at a later time. This allows for easier, more accurate data collection and flexibility for obtaining more measurements in less time. The capability of logging at least 500 samples is ideal for most applications in a processing plant.

Also consider calibration capabilities when selecting a pH meter. At minimum, the pH meter should be capable of 2-point calibration with pH 4.0 and 7.0 buffers.

Assuming no limitations regarding glass-tip pH probes, we suggest the following specifications when selecting a pH meter:

- pH meter that uses glass-tipped probes.
- pH meter with the ability to adjust temperature manually.
- pH meter with the capability to log and download results.
- Minimum capability to calibrate at pH 4.0 and 7.0.
- Measurement speed of < 5 seconds.

All the pH meters presented in Figure 3.1 meet these specifications. Other pH meters may be available that are equally effective.

The calibration and storage procedures of a pH meter are key to obtaining consistent, reliable pH results. Calibration of the pH meter should be conducted with fresh pH 4.0 and 7.0 buffer at the start of each day. Recheck calibration throughout the day with the pH buffers. Recalibrate if the calibration is off by more than 0.05 pH units.

If a pH probe has not been used for more than two days, soak the probe in old calibration buffer for 30 minutes prior to calibration to prevent drift in the measurement.

Store the pH probe tip in pH calibration buffer after calibration and between measurements. When storing pH probes overnight, the probe tip should be placed in either storage solution (4M KCl or similar) or buffer solution (4.0 or 7.0 pH). For longer storage periods, using storage solution is preferable to buffers.

Buffers should be stored in airtight containers. Excessive air exposure will deteriorate the buffers. For daily calibration, it is best to have small containers of each calibration buffer that are refilled weekly from the original buffer containers.

Typically, pH is measured in either the ham or the loin. Ham pH is most commonly measured in the semimembranosus muscle, while loin pH is measured in the longissimus muscle. These two locations are often considered the worst-case scenarios for pH, thus accounting for more variation for detecting differences due to genetics and/or environmental factors. The loin and ham pH can be collected on the intact carcass or on the individual primals, depending on which method works best in the processing facility (Figure 3.3 and 3.4). When measuring pH in the loin of an intact carcass, measure between the 10th and last ribs to avoid measuring muscles other than the longissimus.

Figure 3.3 Loin pH measurement

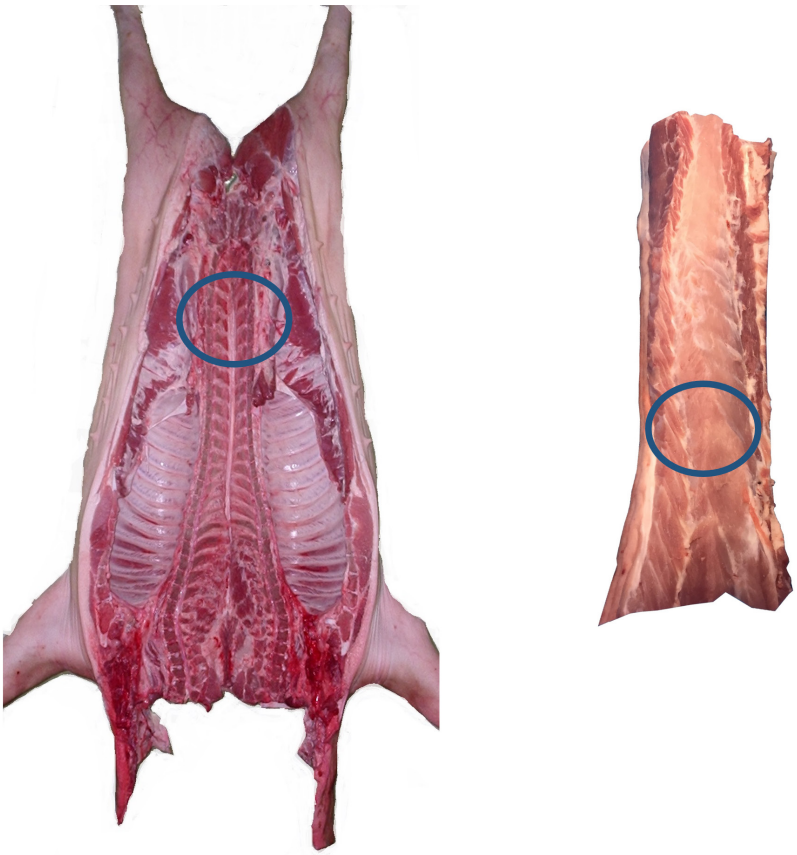
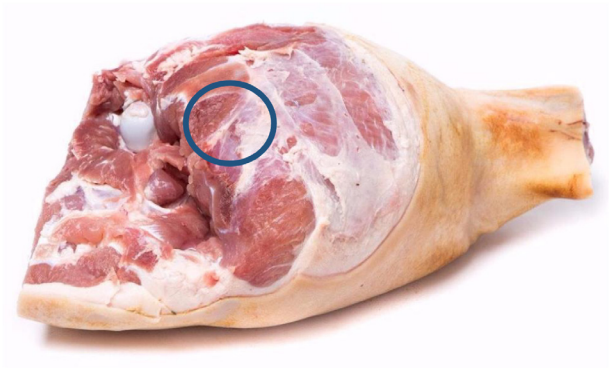


Figure 3.4 Ham pH measurement



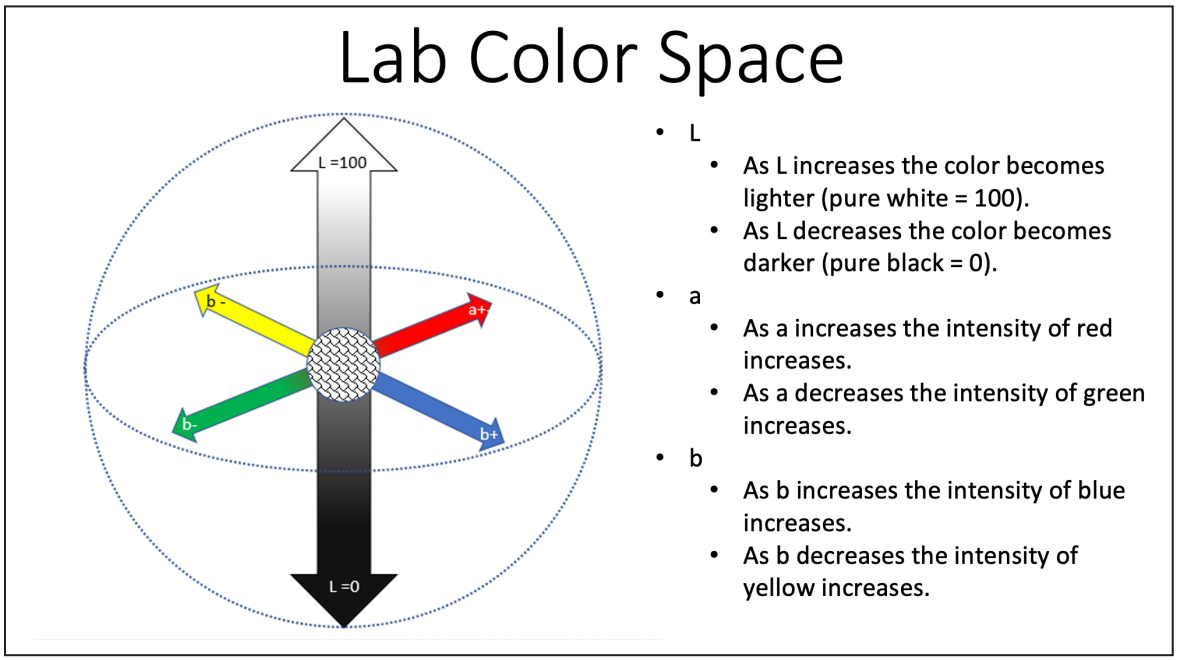
3.1.2.2 Color Measurement

Pork color can be measured objectively or subjectively. Objective measurements of pork color are commonly measured with colorimeters, while subjective measurements are determined using a set of defined standards.

Objective measurements

There are four key components of instrumental color measurement, including color space, illuminants, observer angle, and measurement aperture size. Typically, only two-color spaces are used in the meat industry: 1) CIE L*a*b*, or the Hunter L a b. These three-dimensional color spaces provide the "L", "a", and "b" values that we use to assess the color of meat (Figure 3.5).

Figure 3.5 Lab color space



The L* value represents the lightness/darkness (white to black), with a lower number (darker color) preferred in pork. The a* value represents the redness (red to green,) with a higher number (redder) preferred in pork. The b* value represents the yellowness (yellow to blue), with a lower number (less yellow) preferred in pork. The L*a*b* values are dependent on the illuminant and observer angle used.

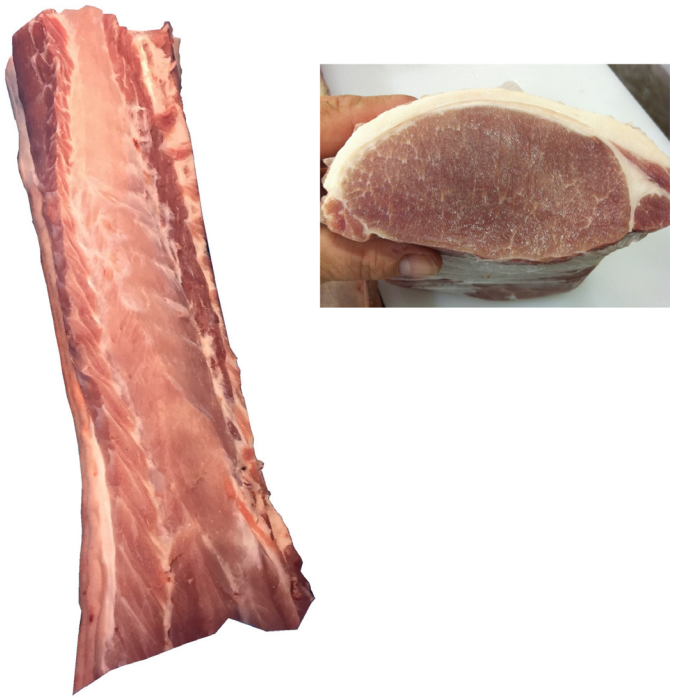
Typically, pork is measured using either the C or D65 illuminants, although in some instances the A illuminant can be used. The C illuminant represents average daylight, excluding the ultraviolet wavelength region. The D65 illuminant represents average daylight but includes the ultraviolet wavelength region. Illuminant A represents incandescent light.

Observer angle is a component of instrumental color measurement that basically standardizes the human field of view. The 2° or 10° observer angles are used with the 10° observer angle, providing a larger field of view.

Measurement aperture size is the final component of color measurement to consider. The aperture size is the diameter of the circular area measured. The 8 mm and 40 mm apertures are most frequently used.

Although instrumental color can be measured anywhere on the carcass, most measurements are taken on the loin and/or ham. On the loin, the measurement can be taken on either the cross-sectional area of the loin muscle, or on the rib surface of the loin (Figure 3.6).

Figure 3.6 Color measurement locations for loins



For the ham, measurements are typically taken on the inside semimembranosus muscle, or “inside”, (Figure 3.7) but may be taken on the gluteus medius on the cut ham face. The inside muscle of the boneless ham where the lean is separated from the bone is often measured, as this location can have a paler color due to poor chilling (Figure 3.7).

Figure 3.7 Locations for color measurement of hams (SM and inside)

When measurements are taken it is important to ensure that the color reading is on lean tissue and not fat tissue. High levels of marbling can result in readings that are less desirable, because it is difficult to avoid measurements without fat tissue influencing the color.

For objective color measurement, the most commonly used tools include the Minolta CR-400 (or CR-410) colorimeter and the Hunter Lab Miniscan. These instruments generally cost between $5,000-$10,000 USD (as of 2021). Many new, less expensive options are being tested that would allow for more wide-spread use of objective measurement of pork color. Color Muse and Nix devices that measure color can be purchased for a few hundred dollars US, but they have some limitations on color spaces, illuminants, and/or observer angles. They also typically require a smartphone or tablet computer for use. Although these devices are less expensive, further evaluation is needed to determine if they have the accuracy required for commercial applications.

Subjective measurements

Subjective color measurement is based on a set of standards and requires graders to compare the sample to the standards for determination of color. The two most commonly used standards are the Japanese standards and the National Pork Board standards (USA).

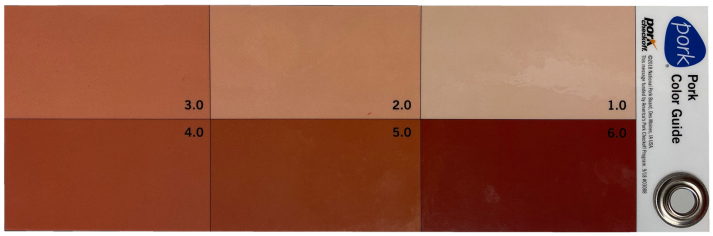
The Japanese color score system is used primarily within a commercial setting in plants exporting pork to Japan (Figure 3.8). The scores are 1 (pale colored) to 6 (dark colored) in 1-unit increments. Half scores are given when color is in between standards. The Japanese color standards can be purchased online at (http://hamukumi.lin.gr.jp/color_standard.html). (Note: It may be difficult to buy without having a party in Japan to facilitate the purchase).

The U.S. National Pork Board (NPB) has developed Pork Quality Standards (Figure 3.8) that include a color standard. These are available for purchase online at (http://egashops.directedje.com/PorkStoreProducer/product-details.asp?ID=92&CID=39&P=1). The NPB standards are similar to the Japanese color standards, since they score meat from 1 (pale color) to 6 (dark color). However, the scores are not interchangeable, and the NPB color standards are used mostly by academia.

Figure 3.8 Methods for subjective color scoring

Japanese Color Block

National Pork Board Color Standards



The subjective color scoring standards are typically used for scoring loin color but could be used in other primals when assessing lean color. As with objective color measurement, loin color measurement can be taken on either the cross-sectional area of the loin muscle, or on the rib surface of the loin. When conducting subjective color scoring, it is critical to score in a well-lit area, as this will affect how the color is perceived. Also, having a panel of two people can increase consistency of the subjective color scoring process. Trained individuals should score within ½ unit of one another on individual scores.

Once a product is cut, it will undergo a bloom period where oxygen interacts with the exposed muscle tissue and causes a change in color. It is important to either have a consistent amount of bloom time before taking measurements or wait until the bloom period is complete.

Most research indicates that L* values are not affected by bloom, but a* and b* values can be affected by bloom up to 10 to 18 minutes after cutting. Remember, account for intramuscular fat when color scoring either objectively or subjectively. The goal is to color score the lean tissue only.

3.1.2.3 Water-Holding Capacity Measurement

Water-holding capacity reflects meat's ability to retain fluid. From a commercial perspective, water-holding capacity is normally measured in the form of drip loss or purge loss in the absence of any external forces other than gravity. Drip loss is usually measured to represent the amount of fluid lost in a retail cut (i.e., chop), while purge loss is the amount of fluid lost in a vacuum packaged primal (i.e., whole boneless loin).

In the basic protocol for measuring drip/purge loss, the sample is weighed, stored under commercial conditions for a pre-defined period, then reweighed to determine the amount of weight loss. The weight loss is then expressed as a percentage of the initial weight: % Drip Loss = [(Initial Weight-Final Weight) / Initial Weight] x 100.

Drip loss can be measured in many ways, but it is important to follow some basic guidelines to ensure accuracy. First, samples should have consistent dimensions, as the amount of surface area will affect the amount of fluid lost. This can be accomplished by either cutting samples into 25 mm (1 inch) cubes from a chop, or by cutting a 25 mm-thick (1 inch) chop and then removing a 25 mm (1 inch) diameter core from the chop with a coring device.

When removing chops, it is important not to use an end chop, as fluid loss begins once the surface is exposed. To overcome that, cut a 25 mm (1 inch) chop from the end. Then use the next 25 mm (1 inch) chop for obtaining the drip-loss sample.

All samples for drip loss must be thoroughly trimmed of external fat and connective tissues. Enclose the sample so it is not exposed to external elements. Suspend the sample so the fluid loss can separate from the sample. This can be accomplished in different ways. Two of the most common methods include the "fish-hook" or EZ drip tube methods (Figure 3.9).

Figure 3.9 EZ drip loss tubes and coring device

With the fishhook method, attach the sample to a suspended fishhook or similar device. Then enclose the sample with a plastic bag. Take care to ensure the plastic bag does not touch the sample.

The Danish Meat Research Institute (EZ) drip tube method (https://www.dti.dk/specialists/ez-driploss-equipment/35497) uses a tube that suspends the sample above a drainage channel, allowing the fluid loss to separate from the sample.

The sample should be stored under the refrigerated conditions (1 to 5°C or 34 to 41°F) for a pre-determined amount of time (usually 24 or 48 hours). Having a consistent storage period and temperatures are essential since drip loss increases in a non-linear fashion with both increased time and temperatures.

Finally, use a scale that can accurately determine drip loss. For the sample size dimensions described above, the sample weight is normally between 10 and 20 g. Therefore, a scale that measures to the nearest milligram would be most suitable.

Purge loss can be measured on any vacuum packaged primal or sub-primal, although it is commonly measured on boneless loins. Purge loss represents the amount of fluid loss from the time the loin is packaged at the processing plant until it is opened for cutting into chops or opened by the consumer. Since this process covers a longer time period, purge loss is typically measured over a period of at least 7 days. It could be measured up to 28 days to simulate fresh products that are exported to Asia. As with drip loss, samples should be stored in refrigerated conditions that represent the normal processes the product would incur in commercial conditions.

To measure purge loss, weigh the loin prior to packaging (or subtract the bag weight, if known). After the prescribed storage period, remove the loin from the bag. Lightly blot the meat with a paper towel to remove excess surface fluids, and then reweigh the meat. For typical loin weights, a scale with a total weight capacity of 10 kg (measuring to the nearest gram) is required to obtain accurate measurements.

3.1.2.4 Firmness Measurement

The NPB has defined standards for evaluating pork firmness. This scoring system is generally used on a chop surface and uses this 3-point scoring system:

1 = Soft; The cut surface appears soft, the surface appears distorted, and it does not hold its shape.
2 = Firm; The cut surface has very little distortion and holds its shape.
3 = Very firm; The cut surface is very smooth, with no distortion.

This system works well when evaluating the firmness of chops for research or quality assurance purposes. However, in a commercial setting, it is often difficult to evaluate chops using this scoring system, because this will reduce the value of a loin.

That is why the NPB method has been adapted to a 5-point scoring system for commercial evaluations of whole boneless loins. This scoring method is very similar to that of the NPB, but some of these whole-loin methods involve a 5-point scoring system as opposed to a 3-point system.

Figure 3.10 Firmness measurement

The sirloin end of the loin is evaluated based on the NPB system, but more emphasis is placed on how well the entire loin holds its shape, and the ease at which the loin is folded (Figure 3.10), to determine an overall firmness score.

This 5-point scoring system includes:

1 = Very soft; The loin folds with virtually no effort, and the loin does not hold its shape.

2 = Soft; The loin folds with ease and loosely holds its shape.

3 = Firm; The loin folds with some slight resistance and holds its shape.

4 = Moderately firm; The loin folds with moderate resistance and will not completely fold back on itself. It has a tight feeling and holds its shape well.

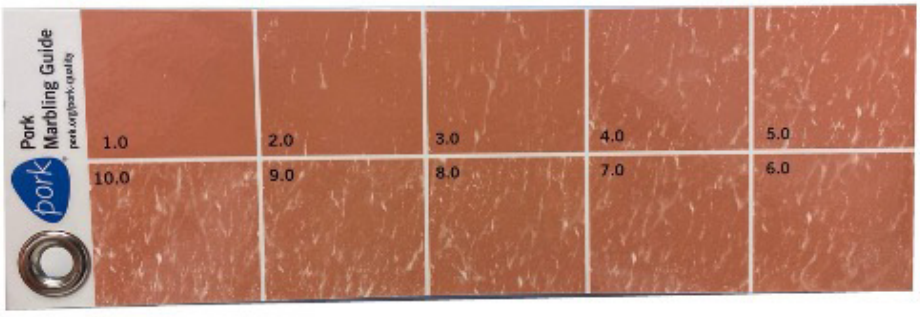
5 = Very firm; The loin is resistant to folding and will not completely fold back onto itself. It has a very "tight" feeling and holds its shape extremely well.

3.1.2.5 Marbling/IMF Measurement

The terms marbling and intramuscular fat (IMF) are often used interchangeably. For the purposes of this document, marbling is measured subjectively using a set of standards, and IMF is measured objectively using chemical or mechanical means. Measuring IMF is more expensive, because it is destructive to the final product, and the chemical analysis carries additional cost. IMF measurement is also more time consuming, since the sample must be collected, correctly prepared and analyzed.

The US National Pork Board (NPB) has developed marbling standards (Figure 3.11) (https://egashops.directedje.com/PorkStoreProducer/product-details.asp?ID=92&CID=39&P=1). These standards range from 1 (practically devoid of marbling) to 10 (heavily abundant marbling). Each of these scores within the standards is approximately equivalent to the percentage of IMF (i.e., marbling score of 3 is equal to 3% IMF).

Figure 3.11 National Pork Board marbling standards



Typically, marbling is measured on the loin, but in some regions of the world marbling is also measured on the ham. When measuring loin marbling under ideal conditions, the marbling score is taken on the surface of a loin chop. However, in most commercial situations the marbling score is taken on the rib (ventral) surface of the loin, because the chop surface is not exposed unless the loins are center cut. While subjective color scoring needs good lighting for scoring, it is sometimes necessary to shade the area being scored for marbling to better contrast between the fat and the lean color.

Intramuscular fat has traditionally been measured using wet chemistry methods in commercial and university labs. In recent years, near infrared (NIR) technology has become more common for measuring IMF. NIR methods using ground pork, as opposed to intact meat products, normally have a better accuracy but are more time consuming.

Note that these methods determine the percentage of lipid found in the meat product, not the actual IMF content. IMF includes lipid, protein, and water. Therefore, chemical and NIR results for IMF are typically lower than subjective marbling scores, unless the protein and water are accounted for after determining the lipid percentage.

Sample sizes depend on the chemical or NIR methods being used. These are normally dictated by the lab conducting the analysis. When collecting the samples, it is important to remove any intermuscular or subcutaneous fat from the sample, since this fat this will artificially inflate the IMF concentration.

3.1.2.6 Temperature Measurement

Temperature is one of the simplest carcass measurements that can be taken anywhere on the carcass. Since the rate of temperature decline can have a direct impact on pork quality, it is important to measure temperature in the carcass parts that can be influenced by poor temperature decline. These areas include the deep portion of the shoulder, ham and loin.

Take temperature measurements at standard time-points post-mortem using a common meat thermometer. Temperature measurements can also be taken in defined intervals throughout the chilling process by using temperature data loggers.

When taking specific time point measurements, a standard meat thermometer with a probe at least 100 mm (4 inches) long and capable of measuring to the nearest 0.1°C (0.2°F) is suitable. When measuring temperature decline curves, data loggers must be waterproof to hold up to the conditions during the chilling process, measure temperatures in 5-minute intervals. Both meat thermometer and data loggers must use a probe that is at least 100 mm (4 inches) long and capable of measuring the nearest 0.1°C (0.2°F).

Ideally, the data logger would have multiple data ports, so temperature decline curves can be measured in multiple primal locations, plus the ambient temperature can be measured during the chilling period. The ONSET company makes the Hobo 4-Channel Analog Data Logger MX1105 (https://www.onsetcomp.com/products/data-loggers/mx1105) that can be fitted with up to 4 sensors. Sensors include an ambient sensor (SD-TEMP-01) and a temperature probe sensor (SD-TEMP-SS-06), which work well for measuring temperature decline curves. The data logger unit can be placed in a dry bag to protect it from water during the process of getting the temperature decline curves.

3.1.2.7 Tenderness and Sensory Measurement

The gold standard for objectively evaluating pork eating quality is to directly assess it through instrumental tenderness measurement and sensory analysis. Objective tenderness is determined using Warner-Bratzler or slice shear force, while sensory analysis uses either a trained or untrained group of panelists to assess eating quality of pork.

The American Meat Science Association (AMSA) has assembled detailed methodologies for conducting both sensory and objective tenderness measurement (https://meatscience.org/docs/default-source/publications-resources/amsa-sensory-and-tenderness-evaluation-guidelines/research-guide/2015-amsa-sensory-guidelines-1-0.pdf?sfvrsn=6). While this AMSA document discusses these methods in detail, some basic guidelines hold true, regardless of the type of sensory panel or tenderness analysis.

Sample selection is key. The loin (longissimus dorsi muscle) is used in most pork sensory and tenderness analyses, but the semimembranosus muscle of the ham is often used, as well. Regardless of the muscle used, it is important to be consistent. Take samples from the same portion of the muscle.

Once you collect the sample, store it under normal, refrigerated conditions for 5 to 14 days (pork aging period) prior to analysis. Ideally, the product should be fresh and not frozen before cooking, since freezing pork results in lower shear-force values (the meat is more tender). Shear-force values for pork that has been frozen will not be comparable with shear-force values from fresh pork.

Cut chops to a standard thickness. In general, use 2.54 cm (1 inch) chops that are chilled at 2 to 5°C (36 to 41°F) prior to cooking. Since the degree of final cooked temperature can impact tenderness and sensory perception, closely monitor meat to avoid over or under cooking. Typically, this is accomplished with thermocouples inserted into the geometric center of the chop and monitored with some type of data logger.

Cooking methods can vary, but clamshell grills are often used, since they provide even cooking on both sides of the chop, and they are inexpensive. Other methods include open-hearth grills, belt cookers (i.e., pizza ovens), and sous vide. Upon completion of cooking, tenderness and sensory analysis have different processes, so they will be discussed separately.

Warner-Bratzler shear force is the most common type of objective tenderness analysis used worldwide. A Warner-Bratzler blade attachment (Figure 3.12) can be purchased and used with an Instron or similar type of testing apparatus. The shearing machine (Figure 3.12) and blade attachment, along with slice shear, coring and other sensory testing equipment, can be purchased from Tall Grass Solutions, Inc. (https://www.tallgrassproducts.com/home).

The premise behind shear-force testing is the amount of force (kg or N) required for the Warner-Bratzler blade to cut through a 1.25 cm (1/2 inch) core, perpendicular to the muscle fiber orientation. After cooking, refrigerate samples overnight after cooking to allow for consistent coring of samples from the chop. At a minimum, allow chops to equilibrate to room temperature before coring.

Prior to coring, the chop's edges are cut off to help determine the muscle fiber orientation, since the core must be taken parallel with the muscle fibers. Core the chop with a 1.25 cm (1/2 inch) coring device. At minimum, remove 4 cores from the chop for shear-force testing.

Once core samples are collected, they can be sheared with a Warner-Bratzler blade with a crosshead speed of 225 ± 25 mm/min. Take care to shear the cores perpendicularly in the center of the core. Average each of the core readings from the chop for the final shear-force value.

Figure 3.12 Warner-Bratzler machine and blade

As previously mentioned, sensory analysis can be evaluated using trained or untrained (consumer) panels. A trained sensory panel should consistently detect differences in a variety of traits. Although trained panels can detect differences, average consumers may not notice these differences. Consumer panels help determine if trained panel differences matter to the average consumer.

Sensory traits normally involve juiciness, tenderness, flavor, and off flavor. Scoring usually involves some type of line scale, where a lower number is less desirable, and a higher number is more desirable. In some consumer panels, the samples may be scored on a hedonic scale for likeability or preference.

After cooking, cut samples from the chop for the panelists. The chops should be cut into 1.25 cm x 1.25 cm x 2.5 cm (thickness of the chop) pieces for sampling. Keep samples warm until the meat is presented to the panelists.

Each panelist typically scores the samples under red-light conditions to avoid any biases due to color or degree of doneness of the sample. Between each sample, panelists should cleanse their palate with water and unsalted crackers. The panelists' scores are averaged to calculate an overall score for each chop.

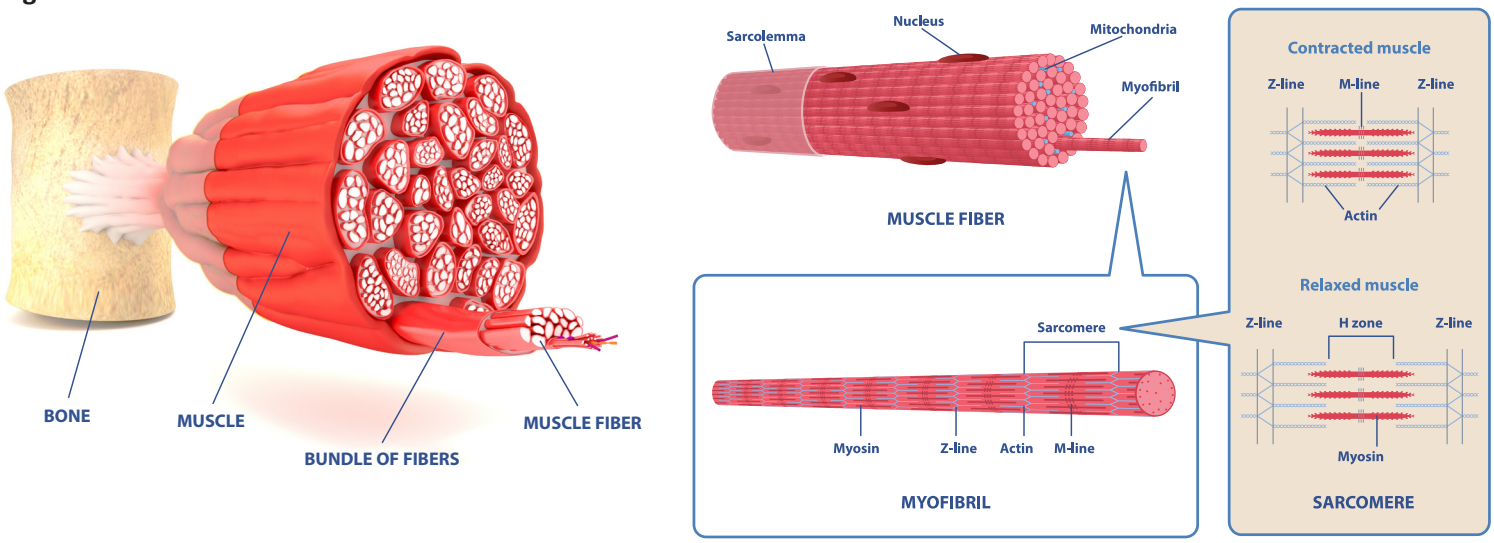
As with any testing, it is important to conduct sensory testing under standardized conditions to make direct comparisons between lots/groups of samples or in a benchmarking situation.

3.2 Factors Influencing Lean Quality

3.2.1 Conversion of Muscle to Meat

An individual skeletal muscle (Figure 3.13) is made up of hundreds, or even thousands, of muscle cells or fibers bundled together and wrapped in a connective tissue covering. Each muscle is surrounded by a connective tissue sheath called the epimysium. Fascia (connective tissue outside the epimysium) surrounds and separates the muscles.

Figure 3.13 Muscle structure breakdown



Each muscle cell has distinct regions when viewed under a microscope. These are known as *sarcomeres* that are formed from *actin* and *myosin*, as well as several associated "helper" proteins. Myosin is a protein composed of many interlaced tails of individual myosin units. The heads of the units stick above their rods and are attracted to the actin filament, forming cross bridges that enable muscle contraction and relaxation cycles.

Skeletal muscle is a complex tissue characterized by sophisticated physiological conditions. The nervous, circulatory, respiratory, and endocrine systems are all critical for providing oxygen and energy, and regulating the pH and temperature, maintaining muscle's homeostasis.

When a pig is slaughtered, these systems lose the ability to maintain homeostasis, and living muscle is gradually converted to meat. After death, metabolism continues for a limited time until either energy substrates and metabolites are depleted, or temperature-dependent reactions cease to operate.

3.2.1.1 Energy Metabolism

Muscles use an energy source called Adenosine Triphosphate (ATP) for work (contractile activities) and calcium (Ca^{2+}) homeostasis.

ATP is formed from glucose (or glucose precursors) under either aerobic (with oxygen) or anaerobic (without oxygen) conditions through glycolysis. ATP production is more efficient on aerobic conditions (38 ATP per glucose molecule) than under anaerobic conditions (2 ATP per glucose molecule).

Anaerobic metabolism occurs when stress hormones are secreted (mainly adrenaline and cortisol). Any stressor that causes the "fight or flight" response can initiate the release of these hormones, which in turn provides the animal with a boost of energy to survive by maintaining homeostasis.

The result of anaerobic metabolism is 2 ATP's and 2 pyruvates. When the animal is alive, pyruvate is converted into lactic acid, which is transferred from the muscle to the liver to be converted back into glucose. This glucose may go back to the muscle for energy production (Cori or lactic acid cycle), as the fight-or-flight response subsides.

At the time of death/exsanguination (bleeding), blood supply to the muscle cells is lost resulting in the loss of oxygen, nutrient supply, and the ability to regulate temperature. The loss of oxygen results in a shift to anaerobic metabolism.

Increased pyruvate from anaerobic metabolism results in increased muscle lactate, which lowers the pH of the muscle. The rate and extent of pH decline depends on the amount of peri-mortem muscle lactic acid build-up due to stress, amount of energy stored in muscle cells for post-mortem glycolysis (glycogen), and post-mortem temperature.

3.2.1.2 Rigor Mortis and Associated Conditions

Rigor mortis is a key physical characteristic of the conversion of muscle to meat that occurs when energy metabolism stops. Rigor mortis is the condition where muscles lose extensibility when the two key structural components of the skeletal muscle contractile apparatus (actin and myosin) become bound together (actomyosin cross-bridges).

The three phases of rigor development include delayed, onset, and completion. During the delayed phase, ATP levels are relatively constant, and the muscle is soft, elastic, and extendable. Creatine phosphate (CP) is an important part of this process since it is necessary for the conversion of Adenosine Diphosphate (ADP) to ATP for muscle contraction when no oxygen is present. Muscle will remain in the delayed phase if CP is available to maintain the ATP levels, even without oxygen.

Shortly after CP levels are depleted, the ATP levels will begin to decrease, moving rigor development into the onset phase. During the onset phase, muscle becomes inelastic and unextendible. ATP levels are decreasing, allowing Ca^{2+} release, which in turn allows actin and myosin to form the actomyosin cross-bridges. This continues until depletion of muscle ATP below 1 um/g, when the actomyosin cross-bridges become permanent, as ATP is required to break these bridges.

At this point, the muscle is in the final phase of rigor mortis completion. The actomyosin bridges formed during rigor mortis are the same as during normal muscle contraction and relaxation cycle. However, in normal muscle contraction, only about 20% of the possible binding sites are used, while virtually all binding sites are used in the rigor mortis stage.

The onset of rigor mortis in pork normally occurs between 15 minutes and 3 hours post-mortem, with rigor setting into most muscles by 10 hours post-mortem. Because rigor development involves some muscle contraction (rigor shortening), it directly effects meat tenderness.

The following conditions associated with rigor mortis may occur:
Cold shortening:
Cold shortening may occur when the muscle is chilled to < 7°C (< 45°F) before rigor is complete, and the muscle pH is above 6.30. Since rigor is not complete, ATP is available, which normally regulates Ca^{2+} availability to the myofibrils for contraction and relaxation. Under these cold conditions, however, Ca^{2+} becomes unregulated due to excess Ca^{2+}, along with residual ATP, result in a severe contraction that shortens the muscle. In this process, the actomyosin cross-bridges form permanently, as the ATP is consumed and depleted to contract the muscle.

Cold shortening is normally not a problem in pork, because of the rapid post-mortem pH decline. Rigor mortis is typically set when pH is less than 6.00 and before a low muscle temperature can be attained. The exception may be pork that is hot boned, which allows for quicker chilling of the muscle.
In beef and lamb, electrical stimulation is used to quickly decrease muscle pH to improve the muscle tenderness. However, electrical stimulation should never be used in pork, because the increased lactic acid production will create a faster rate of pH decline and impair meat quality.

Thaw rigor:
Thaw rigor occurs when pre-rigor meat is cut and frozen. Once these unrestrained muscles are thawed, the residual ATP and Ca^{2+} cause contraction of the muscle and shortening of the muscle up to 60% (beef, lamb). This contraction results in high moisture loss and severe toughening of the muscle.

As with cold shortening, thaw rigor is rare in pork, since rigor is normally completed before the muscles are dissected from the carcass and frozen. If it does occur in pork, the degree of shortening is much less than 60%, as the skeletal structure typically restrains the muscles.

3.2.1.3 Muscle Fiber Type

Muscle consists of Type I (red/oxidative), Type II (mixed, oxidative-glycolytic IIa and IIx), and Type IIb (white/glycolytic) fibers. The key characteristics for these fiber types are found in Table 3.1.

Table 3.1 Characteristics of muscle fiber types

Characteristic	Type I	Type IIb	Type IIa
Color	Red	White	Intermediate
Metabolism	Aerobic	Anaerobic	Both
Fatty acid level	High	Low	Intermediate
Glycogen content	Low	High	Intermediate
Contraction speed	Slow	Fast	Fast
Myoglobin content	High	Low	Intermediate

* Table adapted from Lonergan et al., 2019

Muscles are typically composed of all three fiber types, but the ratio of these fibers depends on the species of animal, genetics, or individual muscle. In pigs, the muscles used for continuous work, such as locomotion or the diaphragm, tend to have a higher proportion of Type I fibers. These muscles have a darker red color. Examples include the spinalis dorsi muscle of the shoulder and quadriceps muscle of the ham. The loin muscle and some muscles in the ham would have a higher proportion of Type II fibers.

The muscles with a higher proportion of Type IIb fibers are at a higher risk of developing poor quality. This is due to potential for increased anaerobic metabolism, resulting in higher levels of lactic acid. This lowers muscle pH at internal temperatures greater than 30°C (90°F) and leads to paler color and reduced water-holding capacity.

3.2.2 Development of Meat Quality

3.2.2.1 Water-Holding Capacity

Water-holding capacity is the ability of meat to retain water. This is important for both fresh and processed pork quality. In general, fresh products with a low water-holding capacity have less desirable eating quality. Processed products with a low water-holding capacity have a lower value due to the inability to uptake water, which is the primary component of brine solutions in these products.

Three main effects that determine the water-holding capacity of meat are: 1) net charge effect, 2) the steric effect, and 3) the proteolysis effect. The net charge effect is directly related to the muscle pH. As pH approaches the iso-electric point (≈5.2) water-holding capacity diminishes, with the lowest water-holding capacity occurring at the iso-electric point. The net charge effect only accounts for about 5% of the water within the muscle cell.

The steric effect involves the capillary forces which hold the water within the myofibrils. This involves the spacing of thin and thick filaments (sarcomere length; Figure 3.13) within the myofibril. Greater spacing indicates greater water-holding capacity. Factors influencing filament spacing include pH, ionic strength, and rigor status of the muscle. As pH and ionic strength increase, the spacing between the filaments increases.

The proteolysis effect is related to protein denaturation that occurs during the conversion of muscle to meat. A greater level of protein denaturation leads to poor water-holding capacity. This protein denaturation is associated with pH level and the rate of its decline. Lower and faster rates of pH decline are associated with greater protein denaturation and lower water-holding capacity. Protein denaturation also depends on muscle temperature, with less denaturation occurring as the muscle temperature decreases.

3.2.2.2 Color

The color of fresh pork is primarily controlled by myoglobin content. Two other factors also influence color, including cytochromes (which are responsible for oxygen storage in the muscle) and rigor mortis development.

Higher concentrations of myoglobin occur where oxidative (aerobic) metabolism occurs. Type I muscle fibers are more oxidative in nature, so they have higher concentrations of myoglobin and are redder in color.

Meat color is variable, in part, because of different muscle fiber types. These differences are expressed between different muscles with different functions. Also, different species may have different utilization of muscles. Differences can also occur within a breed/line in a species.

Older animals have higher levels of myoglobin than younger animals. However, meat color is not completely indicative of the myoglobin concentration. As mentioned before about water-holding capacity, protein denaturation occurs in muscle with high temperature and low pH. This denaturation also affects myoglobin (metalloprotein), with the denaturing changing myoglobin solubility. Once myoglobin solubility is changed, its contribution to the red color of the meat is lost.

The denaturation of muscle proteins changes color by influencing how light is reflected. If pH remains high (slow pH decline), little denaturation occurs, resulting in darker color spectra being reflected. Under conditions of low pH (rapid pH decline), however, more denaturation occurs, and the color appears lighter, due to lighter color spectra reflection.

Furthermore, the oxidative state of the heme iron (Fe) associated with myoglobin can affect color. When the heme Fe is in the ferrous state (Fe^{2+}), myoglobin can be in either the oxymyoglobin (with oxygen) or deoxymyoglobin (without oxygen) forms. Oxymyoglobin is bright red in color, while deoxymyoglobin is dark reddish purple in color. These two forms are responsible for the blooming of color once a muscle is cut.

Prior to cutting, the myoglobin is primarily in the form of deoxymyoglobin. Once the muscle is cut, the deoxymyoglobin is converted to oxymyoglobin, and the color changes to a brighter red due to the presence of oxygen. Eventually, the Fe^{2+} oxidizes to the ferric state of iron (Fe^{3+}), resulting in the formation of metmyoglobin and a grayish to grayish-brown color.

Metmyoglobin formation has practical implications, because it influences how consumers view the product in the retail meat case. Once these grey/brown colors develop, consumers find the product less desirable, due to perceived association with an “old” or “out of date” product.

3.2.2.3 Tenderness

Tenderness is a key quality trait associated with the overall eating quality. Physical properties of the meat and cooking temperatures can affect tenderness.

Physical properties of the meat include sarcomere length, fragmentation of the myofibril, amount of connective tissue, and marbling. Chemical properties such as pH also play an important role by influencing sarcomere length and fragmentation of the myofibrils.

Sarcomere length is important because it is associated with the degree of rigor shortening. Cold shortening has an extremely negative effect on tenderness, due to very short sarcomere length. Ordinarily, some level of rigor shortening will occur under normal conditions (not cold shortening). This will affect sarcomere length and meat tenderness.

Fragmentation of the myofibrils is important in tenderness development, since it causes site-specific structural damage of the protein in the post-rigor muscle that improves tenderness. Small, continuous increases in myofibril fragmentation result in incrementally improved meat tenderness. The calpain proteases (enzymes that break down protein) are mainly responsible for myofibril fragmentation. Calpain activity depends on the presence of Ca^{2+}. Calpastatin inhibits this activity.

A variety of environmental factors can influence calpain activity, including pH, temperature, and oxidation. Optimum calpain activity is observed at pH 7.0 and decreases as pH decreases. Vast meat science research indicates that rapid pH decline may completely halt activation of calpains, resulting in failure to degrade myofibril proteins. As meat temperature decreases, calpain activity also decreases, although some calpain activity still occurs at the temperature of chilled meat (4°C or 39°F).

The time when myofibril protein degradation occurs is the aging period. The desired period of aging in pork is from 5 to 14 days, with most improvements in tenderness occurring between 7 to 10 days of aging.

As the level of connective tissue (primarily collagen) increases in muscle, tenderness decreases. Collagen levels can vary, due to the muscle type and physiological purpose. Muscles designed for locomotion have higher collagen levels and are less tender. As animals age, the number of collagen cross-linkages increases, resulting in decreased tenderness.

A thorough literature review related to marbling (intramuscular fat; IMF) and tenderness in pork is inconsistent, concluding that marbling has a modest effect, at best, on pork tenderness. Improved tenderness due to marbling appears to be considerably less pronounced than the impact of muscle pH level and the rate of post-mortem pH decline on tenderness.

Cooking methods have a large effect on pork tenderness. Degree of doneness, or internal cooking temperature, affect sensory panel tenderness scores, with higher internal temperature resulting in less tender pork. The U.S. Department of Agriculture (USDA) recommends cooking pork to an internal temperature of 63°C (145°F) with a 3-minute rest time to optimize tenderness and ensure microbiological safety. While internal temperature is important, the type of cut, speed of cooking, and/or cooking method (i.e., grill vs. broil vs. sous vide) can all contribute to the ultimate level of pork tenderness.

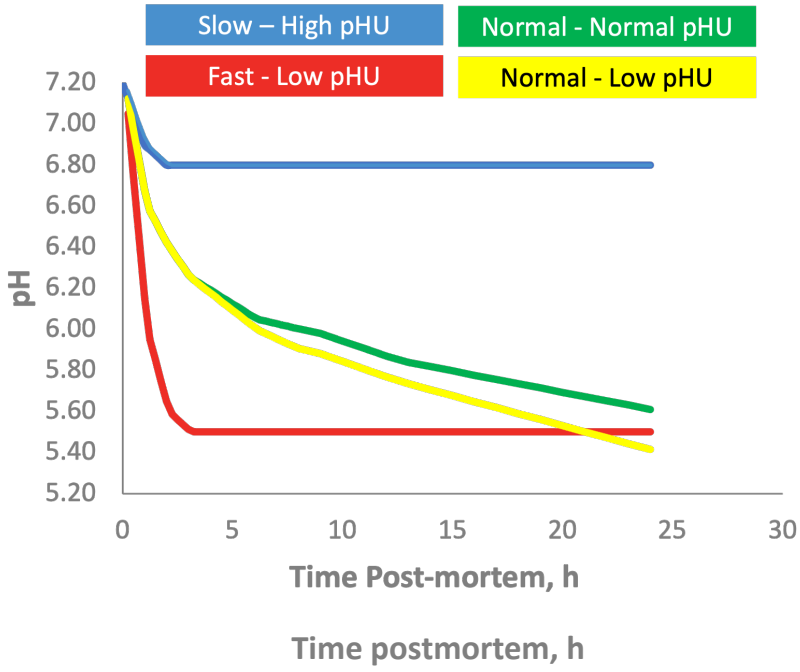
3.2.3 Factors Affecting pH Decline and Meat Quality

Both pH value at 24-48h post-mortem (pHu) and post-mortem rate of pH decline (ΔpH) play a vital role in the development of meat quality in terms of water-holding capacity, color, and pork tenderness. Four classical pH decline rates (Figure 3.14) are generally recognized and include:

1. Rapid pH decline with low pHu (pHu = 5.40 – 5.60), resulting in PSE (Pale, Soft, and Exudative) pork.
2. Normal pH decline with low pHu (pHu = 5.30 to 5.50), resulting in either RSE (Red, Soft and Exudative) or PSE pork.
3. Normal pH decline with normal pHu (pHu = 5.60 – 5.80), resulting in either RFN (Red, Firm, and Non-exudative) or RSE pork.
4. Slow pH decline and high pHu (pHu = 6.50 – 6.80), resulting in DFD (Dark, Firm, and Dry) pork.

Major factors that determine the rate and extent of pH decline include pig genetics, amount of stored muscle glycogen, pre-slaughter stress levels, and rate of carcass chilling. Other factors such as stunning and exsanguination can influence meat quality, as well.

Figure 3.14 Postmortem pH decline



Time postmortem, h

3.2.3.1 Genetic Effects on pH

Genetic selection programs can improve the genetic potential for higher pH. Muscle-fiber type differentiation and/or stress susceptibility are likely changed as a result of genetic selection for pHu. Historical breed effects have been observed for pH. With modern selection programs to improve other traits, however, these historical breed differences may not be as apparent in all lines within a swine breed. The post-mortem development of muscle pH, and particularly meat ultimate pH, are the most critical factors affecting meat quality. Therefore, a brief description of the genetics of muscle pH, with an emphasis on known major gene effects, is provided here.

Applying molecular genetics technology to pig improvement began in 1991 with discovery of the point mutation responsible for Porcine Stress Syndrome (PSS). This led to the discovery and subsequent commercial utilization of the DNA test (HAL-1843™; the trademark of The Innovations Foundation, Toronto, Canada; Fuji et al.,1991). The halothane or stress gene has been the most studied major gene affecting meat quality. Before the discovery of the causative mutation, the halothane test enabled breeders to only distinguish between pigs carrying no mutation (i.e., homozygous normal, or NN) and pigs with two mutated copies (i.e., homozygous reactor, or nn). The test could not identify those populations of pigs that were the stress-gene carriers (heterozygous, or Nn). A single-point mutation in the calcium release channel ryanodine receptor gene (RyR1) in recessive condition is responsible for PSS (also for Malignant Hyperthermia Syndrome, MHS). This gene also results in, or is closely linked to, a gene(s) involved in determining muscling and leanness.

When exposed to stressful environmental conditions immediately before slaughter, pigs that are homozygous for this mutation are likely to develop the Pale, Soft, Exudative (PSE) condition post-mortem. Stress imposed on the pig signals for increased muscle glycolysis, causing a rapid rate of glycogen breakdown and lactic acid production. Post-mortem, a rapid increase in lactic acid causes pH to decline very quickly while muscle temperatures are still high (38°C/100°F). This results in excessive denaturation of muscle proteins, which causes very pale color pork with poor water-holding capacity. Because these processes occur very rapidly, ATP is quickly depleted, allowing rigor mortis to form in 40 minutes or less, in some instances. The stress gene was removed from all PIC lines in early 2000's, but stress-gene positive Pietrain lines from other genetic organizations are still being used in some parts of the world.

Another major gene affecting meat quality that segregates predominantly in the Hampshire breed, is the RN- (Rendement Napole) gene. This dominant gene primarily increases the glycogen content of the IIB fiber and muscle types resulting in a high muscle glycolytic potential. The larger glycogen stores allow post-mortem glycolysis to proceed longer, increasing lactic acid production and lowering pH more than would be expected in normal pigs. RSE is typically forms when this phenomenon is associated with a normal rate of pH decline. PSE pork may result, however, if the rate of pH decline is increased due to stress.

The RN- gene has been associated with improved pork tenderness in. This is most likely caused by the low pH, resulting in excessive protein denaturing (acid tenderization). Excessive protein denaturation compromises water holding capacity, however, which reduces the value of pork for use in further processed products. The negative economic impacts of reduced water-holding capacity prompted PIC and most other genetic companies to remove this gene mutation from their respective Hampshire populations in the 2000s.

Aside from these two genetic mutations, genetic selection programs can be effective to improve the genetic potential for higher pH. Muscle fiber type differentiation and/or stress susceptibility are likely changed as a result of genetic selection for pHu. Historical breed effects have been observed for pH. With modern selection programs to improve other traits, however, these historical breed differences may not be as apparent in all lines within a swine breed.

3.2.3.2 Glycogen Storage Effects on pH

Since glycogen is the main fuel of glycolysis under aerobic conditions that develop lactic acid, the amount of glycogen stored in muscle cells can affect the extent of pH decline One of the best methods for reducing glycogen levels are through feed withdrawal and stress control prior to slaughter.

Withdrawing feed for 24 hours prior to slaughter can reduce glycogen levels by 20% to 50%. Muscles with a higher oxidative potential (more red muscle fibers) will lose a higher percentage of the glycogen stores, but they have less glycogen stores to begin with. Meat pH is higher when pigs are subjected to feed withdrawal due to the reduction in glycogen stores.

Antemortem stress can also reduce glycogen storage levels through anaerobic glycolysis. For glycogen reduction to reduce pH, however, pigs must be given ample time for excess lactic acid to be removed from the muscle prior to exsanguination. This should occur during the feed withdrawal period.

3.2.3.3 Pre-Slaughter Stress Effects on pH

Perimortem stress can have a profound effect on the rate and extent of pH decline. Unfortunately, the processes that occur from the time the pig leaves the farm until it is slaughtered are inherently prone to stress.

When a pig is stressed, a cascade of hormone release and physiological changes occur. This initiates anaerobic metabolism that leads to excess lactic acid production. If a pig recovers from stress, lactic acid is removed from the muscles through the blood. The typical slaughter process, however, may not allow enough time for lactic acid to be completely removed from the muscle cells, which may affect post-mortem pH decline rate.

Stress that occurs close to or immediately before the exsanguination process makes a huge impact on postmortem pH decline. Once exsanguination occurs, no further lactic acid is removed from the muscle.

In general, stress starts with the loading process, transportation, and unloading. Although these stressors can be severe in some instances, they often have smaller effects on postmortem pH decline if pigs are provided enough rest in the lairage prior to slaughter. Stressors that occur from the time the pig leaves the pen in lairage until the pig is rendered insensible through stunning have a much larger impact on post-mortem pH decline than the stress that occurs prior to arrival at the slaughter facility, since the pig has no chance of recovery.

Many factors that can create stress, including:

1. Environmental extremes
    a. Extremely hot or cold temperatures
    b. Humidity coupled with hot weather
    c. Poor air quality (ventilation)
2. Facility design flaws affecting pig movement
    a. Excessive or inadequate lighting, or light positioning issues
    b. Excessive or inadequate space affecting pigs' movement
    c. Walkways that require pigs to make > 90° turns, require a pig to climb or descend an incline, require pigs to walk long distances, have transitions in flooring, or have walls that are not solid.
    d. Improper drainage of water that causes reflections or distractions
    e. Defective or poorly designed equipment (i.e., loading and unloading chutes)
3. Inadequate lairage space to allow ample rest for pigs prior to slaughter

4. Improper transportation procedures
    a. Excessive stocking density
    b. Failure to provide bedding
    c. Use of trailers not conducive to the stress-free movement of pigs on and off the truck (i.e., pot-bellied trailers)
5. Improper animal handling procedures
    a. Moving too many pigs at once
    b. Moving pigs too fast
    c. Rough handling, using improper handling tools, or misusing proper tools
    d. Improper human-pig interaction to stimulate movement of the pig
6. Method of Stunning

Various factors may directly or indirectly stress the pigs. For instance, rough handling of a pig causes direct stress on that particular pig. However, if a worker is moving a large group of pigs, and the group stops unexpectedly, indirect stress occurs. Since the group size is too big to allow the handler to easily move the pig in front, excessive and/or rough handling of the pig(s) in the back may occur to in an effort to move the group. In this case, the stop did not directly stress the lead pig but indirectly stressed the pig(s) in the back of the group. It is important to mitigate these stressors as much as possible, not only from a pH and meat quality perspective, but to ensure pig welfare.

3.2.3.4 Carcass Chilling Effects on pH

Chilling of the carcass is critical to pH decline and ultimately meat quality. If pH values fall below 6.0 before the internal carcass temperature is reduced to 35°C (95°F) or lower, the risk of poor meat quality increases. Conversely, if the internal temperature of the carcass is chilled below 15°C (59°F) before the completion of rigor, cold shortening may occur, resulting in less tender pork.

Under normal industry conditions, the risk of cold shortening is minimal, even with more aggressive chilling systems. Poor chilling is a more common issue in the industry. This results in rapid or extended pH decline and a subsequent reduction in pork quality.

At the time of exsanguination, muscle temperature is ≈39°C (102°F). By 24 hours post-mortem, the carcass temperature should drop below 5°C (41°F). After exsanguination, muscles lose the ability to regulate temperature, since blood is critical in muscle temperature homeostasis.

Initially, temperature of the carcass slightly increases due to the metabolic post-mortem conversion of skeletal muscle to meat that occurs. In extreme circumstances, deep loin muscle temperature can reach 42°C (108°F), and deep ham temperature can reach 43°C (109°F), between 30 and 60minutes post-mortem.

The level of metabolism occurring, and the ambient temperature of the processing floor help determine the extent of temperature increase post-mortem. In most situations, the carcass will enter the chilling process around 30 to 45 minutes post-mortem. By that time, the heat increase has peaked or peaks shortly after. Once carcasses enter the chilling process, the type of chilling system used will dictate the rate of temperature decline.

3.2.4 Principles of Pork Carcass Chilling and Effects on Quality

Chilling of pork carcasses should be performed as quickly as possible. Understanding the mechanisms behind chilling is important to ensure fast chilling is implemented through the pork industry.

A thermal gradient must be present for heat to be successfully removed from the carcass. This thermal gradient is the difference in temperature between the carcass being chilled and the ambient temperature to which it is exposed. Cold temperatures in the carcass chilling environment result in a thermal gradient that reduce the temperature until thermal equilibrium is achieved.

Since the rate of temperature decline depends on the temperature difference between the carcass and ambient environment, larger temperature gradients result in faster temperature declines. The two mechanisms of heat removal in carcasses are convective and conductive cooling. Convective cooling occurs when heat is transferred by a medium passing over the surface of the carcass. The two mediums used to chill pork carcasses include air and water. The rate of convective cooling depends on the air flow rate around the carcasses. Forced convection utilizes fans to move air around the carcasses while natural convection does not. Forced convection speeds up heat transfer, since heat surrounding the carcass is actively removed and replaced with colder air. This maintains the temperature gradient and sustains the chilling rate. Many pork chilling systems use water spraying systems that work along this same principle.

In conductive cooling, heat transfer is accomplished in a solid through vibrating molecules. These move heat in the direction of the temperature gradient. As the outer part of the carcass is chilled, a temperature gradient is formed with the internal parts of the carcass, thereby removing heat from the internal parts of the carcass. It is important to note that both mechanisms occur simultaneously. The rate of chilling is influenced by the temperature gradient maintenance.

Three primary means for chilling carcasses include conventional chilling, spray chilling, and blast chilling. Conventional chilling systems commonly use temperature set-points between -1°C (30°F) and 2°C (36°F), with fan speeds ranging from 0 to 3 m/sec (0 to 10 ft/sec). Temperatures are often adjusted during the chilling cycle to either speed the chilling process or prevent the carcass from getting too cold.

Spray chilling involves spraying water on the carcass. Two main types of water sprays systems are used globally. The conventional spray-chill system applies water to the carcass in cycles during the first few hours of chilling, while undergoing the same ambient conditions of conventional chilling. The tunnel-spray chill system applies a fine mist of water on the carcasses as they move through a chilled tunnel (≈1°C or 34°F). The carcasses then undergo conventional chilling. The time in the spray tunnels can vary, but typically lasts from 3 to 6 hours.

Blast chilling involves very low temperatures combined with high air velocities. Blast-chilling systems for pork carcasses commonly have set-point temperature ranges of -10°C to -40°F (14°C to -40°F), fan speeds of 3 to 10 m/s (10 to 33 ft/sec), and last for 90 to 120 minutes.

Blast chillers normally have different sections with different set-points for temperature and air speed. Ideally, the lower temperature set-points and faster fan speed set-points occur early in the blast-chill process and moderate as the process proceeds. After carcasses exit the blast chiller, they enter chilling rooms (equilibration), where temperature and air speed set-points are like typical conventional chilling.

Factors such as carcass spacing can greatly influence the rate of chilling. It is important to space carcasses properly so heat can be removed between the carcasses and maintain a good temperature gradient. If carcasses are spaced improperly, this decreases the temperature gradient in all areas of the carcass that are touching the adjacent carcasses, resulting in poor chilling (Figure 3.15). Even with blast chilling, carcasses need to be properly spaced in equilibration to maintain the temperature gradient developed during the blast-chilling process.

These different chilling systems have a profound effect on carcass temperature decline, pH, and other aspects of meat quality, with the largest differences occurring between blast chilling and the other forms of chilling. PIC evaluated the temperature decline of 17 conventional chilling (with and without water sprays) and 9 blast-chill plants to determine the effects on temperature decline, pH, color, and firmness. Blast chilling has a more rapid temperature decline in the ham, loin and shoulder, and a lower ambient temperature overall (Figure 3.16). Blast chilling also improved loin quality. Specifically, pH improved by 0.10 pH units, the Japanese color score improved by 0.24 units, and firmness improved by 0.20 units (Figure 3.17).

If the chilling process is quick enough during the first 1 to 1.5 hours of chilling (internal loin temperatures below 32°C/90°F), pork color is generally good. However, if the chilling process is not quick enough (internal loin temperatures below 13°C/60°F) within the first 4 to 5 hours of chilling, the pH may be low, resulting in RSE pork. It is critical that the chilling process be quick enough to chill the carcasses for the first 4 to 5 hours to the targeted 13°C/60°F to ensure both the desirable color and pH.

Another benefit of blast chilling is the reduction in carcass shrink (difference between hot vs. cold carcass weights). Most conventional chilling plants have shrink losses around 2% to 4%, while blast-chill plants are typically below 1.25%, with many below 1% shrink. This is a huge economic consideration. Much of this moisture is retained due to higher pH/water-holding capacity throughout the fabrication procedures and maintains the weight of the final, saleable products.

Figure 3.15 Improper carcass spacing results

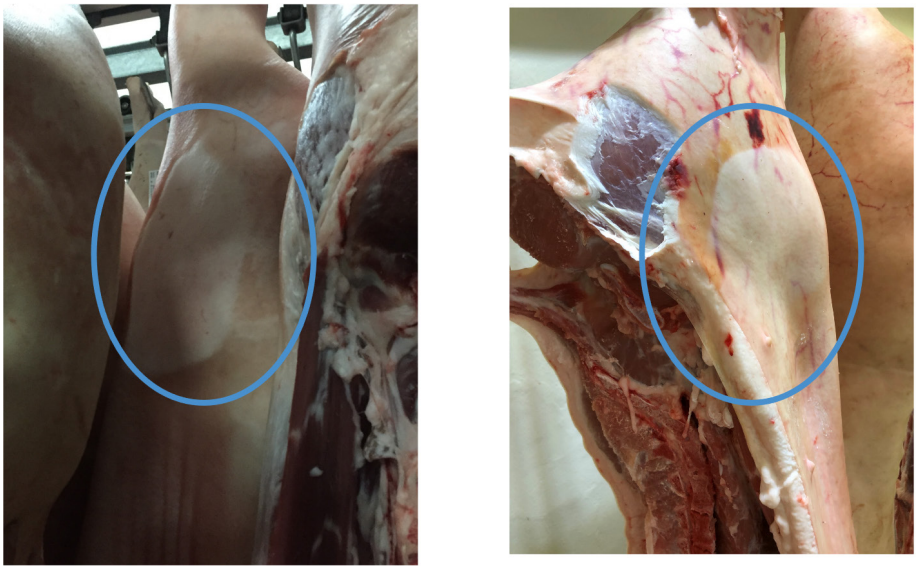


Figure 3.16 Chilling rate differences between conventional and blast chilling

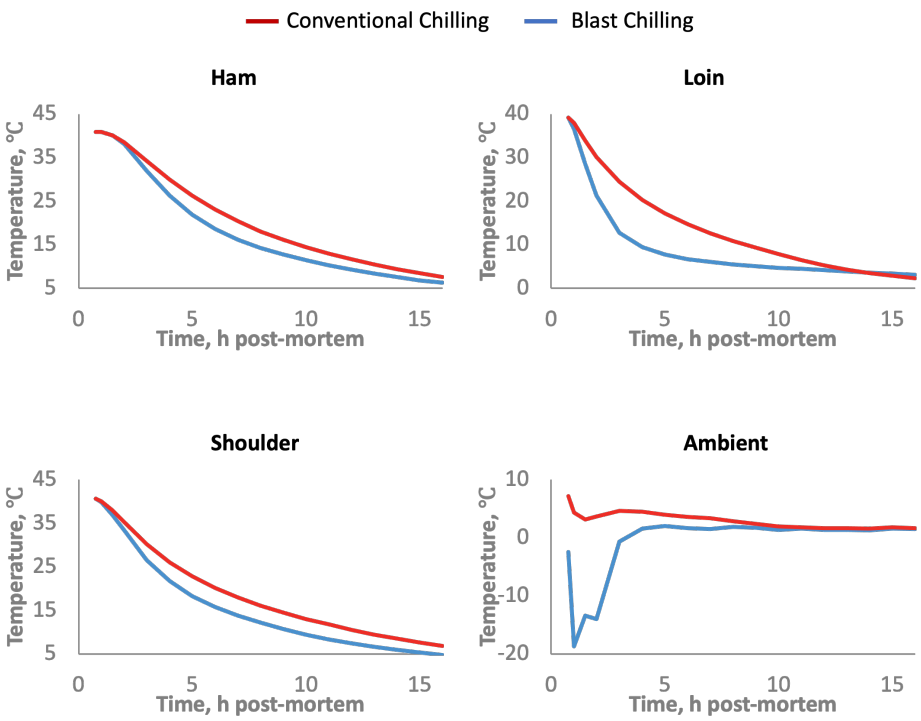
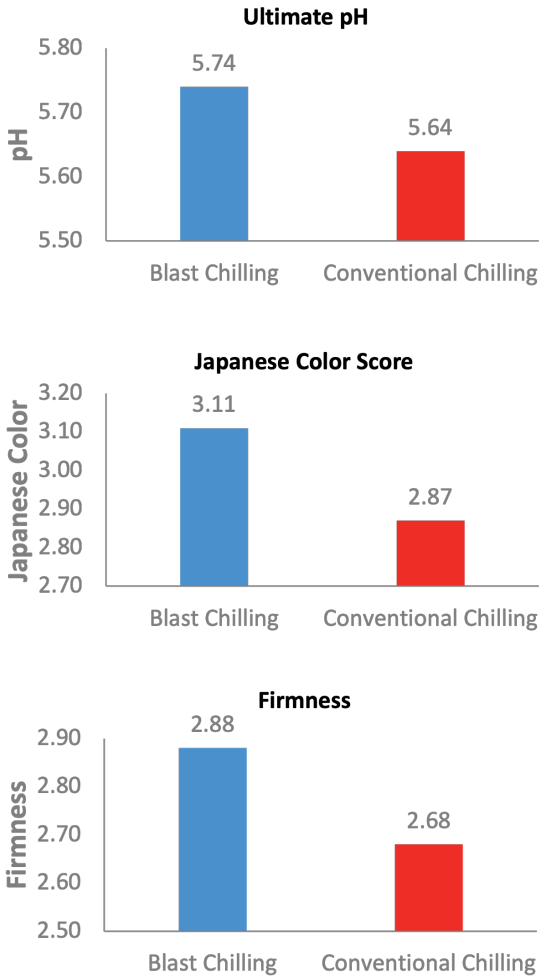


Figure 3.17 Pork loin quality differences between conventional and blast chilling



3.2.5 Principles of Pig Stunning and Effects on Meat Quality

Stunning of pigs renders a pig insensible prior to exsanguination. Three acceptable methods for stunning of pigs include captive bolt, electrical, and gas stunning. Most of the large-scale industry uses either electrical or gas (CO_2) stunning, so these will be discussed in more detail.

3.2.5.1 Electrical Stunning

Electrical stunning induces an epileptic seizure to render the pig unconscious. This is accomplished by applying a high voltage current through either head only or head-body electrical stunning.

For head only stunning, electrodes are placed on the neck behind the ears (Figure 3.18a) to run the current through the brain. Head-heart stunning uses the same probe for the head and an additional probe placed on the heart area (Figure 3.18b) to pass the current through the heart. Head only stunning is reversible, but head-heart stunning is not. It induces ventricular fibrillation (cardiac arrest) that typically causes death before exsanguination.

Figure 3.18 Correct electrode placement for electrical stunning

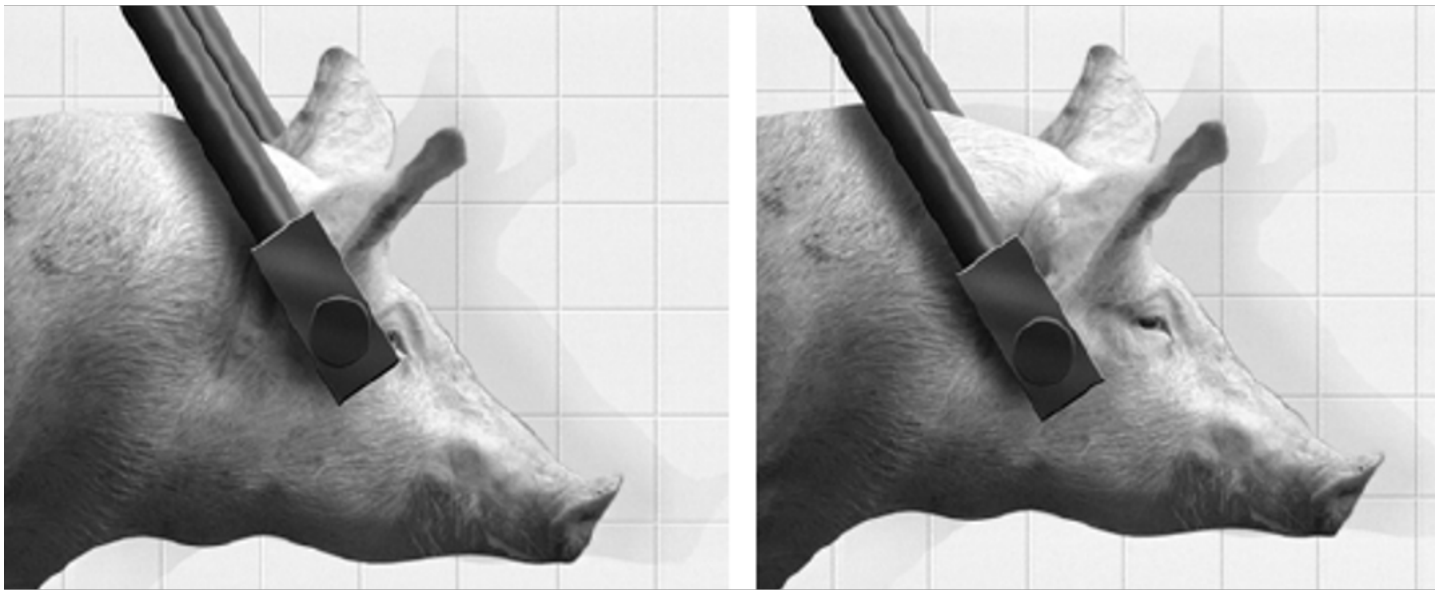


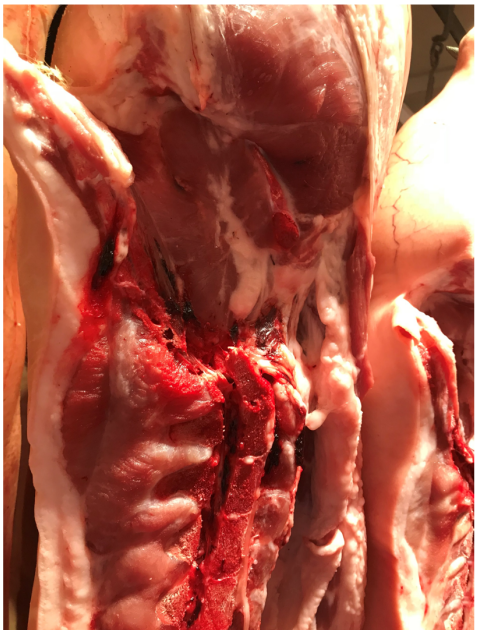
Photo Source: Humane Slaughter Association, 2016.

Using the correct current is very important to ensure an effective stun. According to Ohms law, current is equal to voltage divided by resistance. Current is measured in amperes (amps), and 1.25 amps is required in pigs for an effective stun. Resistance (ohms/Ω) is different in each pig. Many factors can influence resistance, such as the distance the current must flow and the conductivity of the materials the current must flow through. Pigs are often showered prior to stunning to reduce resistance, since water is an excellent conductor of electricity.

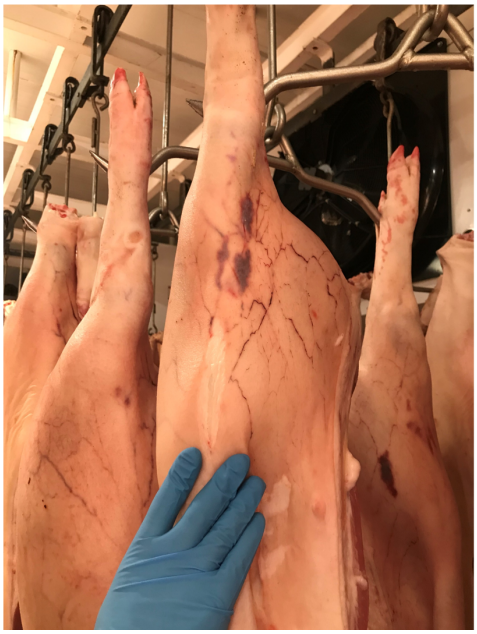
Resistance in a 100 kg (220 lb) pig is typically around 150Ω to 350Ω. Based on the minimum resistance of 150Ω, a minimum of 188 volts is needed to maintain the 1.25 amps. However, we cannot rely on the minimum resistance, because most pigs are not effectively stunned at 188 volts. With a resistance of 350Ω, a voltage of 440 would be needed to deliver a 1.25-amp current to effectively stun the pig, but this would deliver a much higher current (2.9 amps) than needed for those pigs with a resistance of 150Ω.

The higher current is not a problem from a welfare perspective. From a pork quality perspective, however, it can result in increased broken bones, blood splash (petechia, ecchymosis), or blood pooling/spider veining (Figure 3.19) that diminish the value of the product. Blood splash results from increased blood pressure during stunning, which can cause blood vessels to hemorrhage and leave visible blood in the meat.

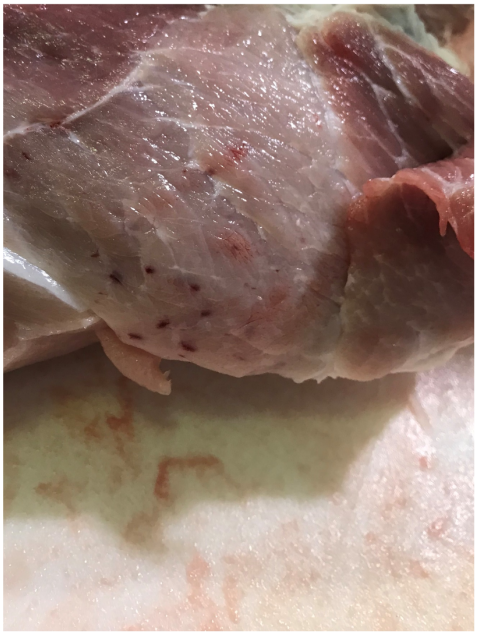
Figure 3.19 Damage caused by improper electrical stunning



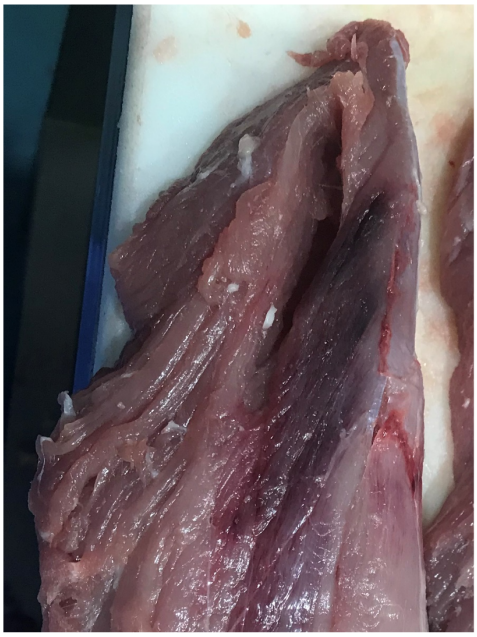
Broken bones



Retained blood and broken blood vessels



Blood spots in the ham



Blood spots in the tenderloin

High-frequency stunning is often used to ensure adequate stunning from a welfare perspective and to avoid meat quality defects. Frequency (measured in hertz/Hz) measures how many times the waveform of a current repeats per second. Typical electrical current has a frequency of 50 to 60Hz. High-frequency current (1000 to 3000Hz) minimizes broken bones and petechia. However, research has indicated that impedance is increased with high-frequency stunning. This results in the need to increase voltage by 100 volts over that used with standard frequency stunning.

Stunning systems can be either fixed or variable voltage. The variable voltage systems are more desirable, since they deliver a constant current, ensuring that pigs are not over- or under-stunned. The fixed-voltage system must be used at a voltage that will adequately stun all pigs. As a result, the current will be too high for some pigs, resulting in broken bones and blood splash.

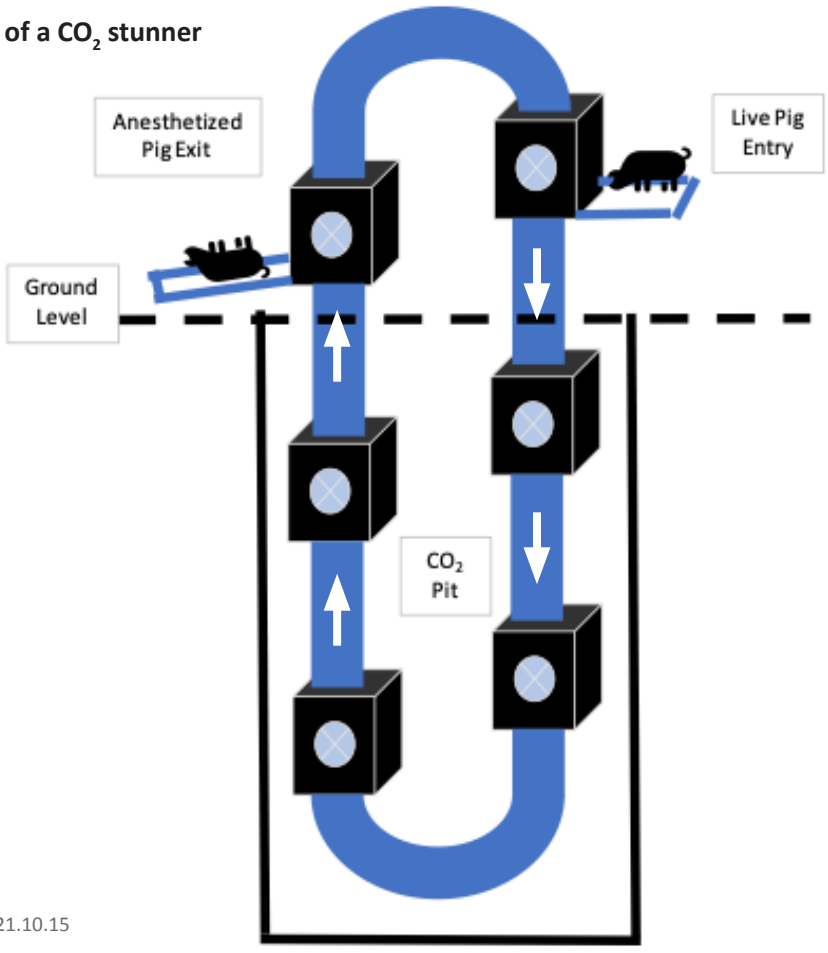
Proper stunning also depends on maintenance of the stunning equipment, proper electrode placement, and duration of the stun. Dirty or worn electrodes can increase resistance by 200Ω. Similarly, electrode placement can affect resistance and the effectiveness of the stun. The current should be applied for 3 to 5 seconds. Delivering the current for less than 3 seconds can result in an ineffective stun. Increasing the duration beyond 3 seconds will not provide further benefit in terms of inducing an irreversible stun. Stun times greater than 5 seconds may result in more broken bones, petechia, blood splash, and pooled blood remaining in the carcass.

3.2.5.2 Gas (Controlled Atmosphere) Stunning

The prevalence of CO_2 gas stunning in pigs has increased dramatically in the past 30 years. Pigs are immersed into a high concentration of CO_2 gas to render them unconscious. Most of the newer CO_2 systems are developed for stunning 4 to 8 pigs at a time, but some of the older systems for stunning 1 pig at a time are still being used.

The two basic designs are the multiple gondola and dip lift. The multiple-gondola system operates on the principle of a Ferris wheel. It has multiple gondolas (normally 4 to 7) that are lowered into a pit containing high levels of CO_2 gas (Figure 3.20). Pigs then return to the top where they are removed from the gondola, shackled, and bled.

Figure 3.20 General diagram of a CO_2 stunner



The dip-lift operates like an elevator. It also uses a pit filled with CO_2, but it only has one gondola. The gondola is filled with the appropriate number of pigs and then goes directly to the bottom of the pit, where the CO_2 concentration is greatest. Once the pigs are effectively stunned, the gondola is raised, and the pigs are removed and bled.

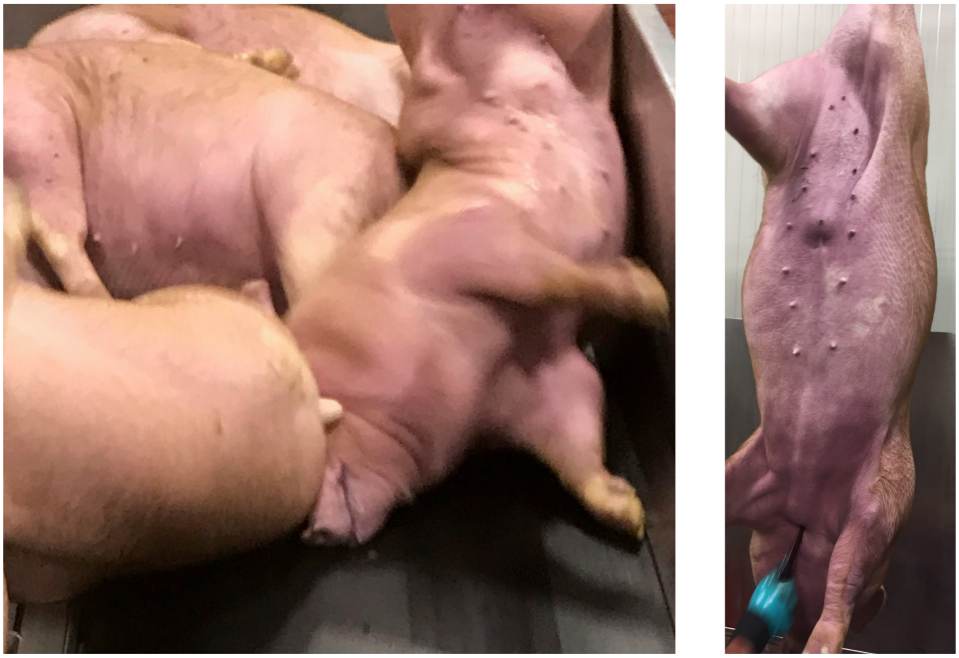
Most, if not all, new CO_2 systems are backloading, as opposed to older, side-loading systems. The side-loading stunners require single-file raceways (or "irons") to effectively load the stunner at line speeds. With the backloading systems, groups of pigs are loaded simultaneously, which allows the automated movement of pigs into the stunner. This greatly reduces stress levels imposed on the pigs which improves meat quality.

The main factors impacting the effectiveness of CO_2 stunning include CO_2 concentration, dwell time (length of gas exposure), and ambient temperature. It is important to use the appropriate level of CO_2. Since the induction phase of unconsciousness can be stressful to the pigs, it is best to minimize the amount of time from gas exposure to when the pigs are rendered unconscious.

Research indicates that CO_2 levels less than 90% require a longer time to induce unconsciousness. Raj and Gregory (1996) indicated that the time to induce unconsciousness was 15 seconds for 90% CO_2, and 22 seconds for 80% CO_2. Based on our general observations, posture and vocalizations will normally cease after about 15 to 20 seconds when using CO_2 concentrations greater than 95%. These often cease in the same time frame in concentrations above 90%. Since each plant and stunning system is unique, adjust the CO_2 concentration so all pigs lose posture and stop vocalizing by 20 seconds post-exposure to the CO_2 gas.

Dwell time is critical to ensure pigs remain unconscious until the exsanguination process. The amount of dwell time often depends on the CO_2 concentration, as well. Higher CO_2 concentrations require a shorter dwell time. Dwell time can be too long and cause issues with effective blood removal. When dwell time is longer than 180 seconds, blood will become trapped in the blood vessels, preventing its effective removal. These pigs will exit the CO_2 stunner with signs of lividity (Figure 3.21). This is a reddish to bluish-purple discoloration of the skin caused by the settling and pooling of blood following death.

Figure 3.21 Pigs exiting CO_2 stunning with lividity



When the ambient temperature in the CO_2 stunning area is below 7°C (45°F), pigs may show signs of returning to sensibility after exiting the stunner. If this happens, the CO_2 concentration should be raised by 1% to 2% to minimize this issue.

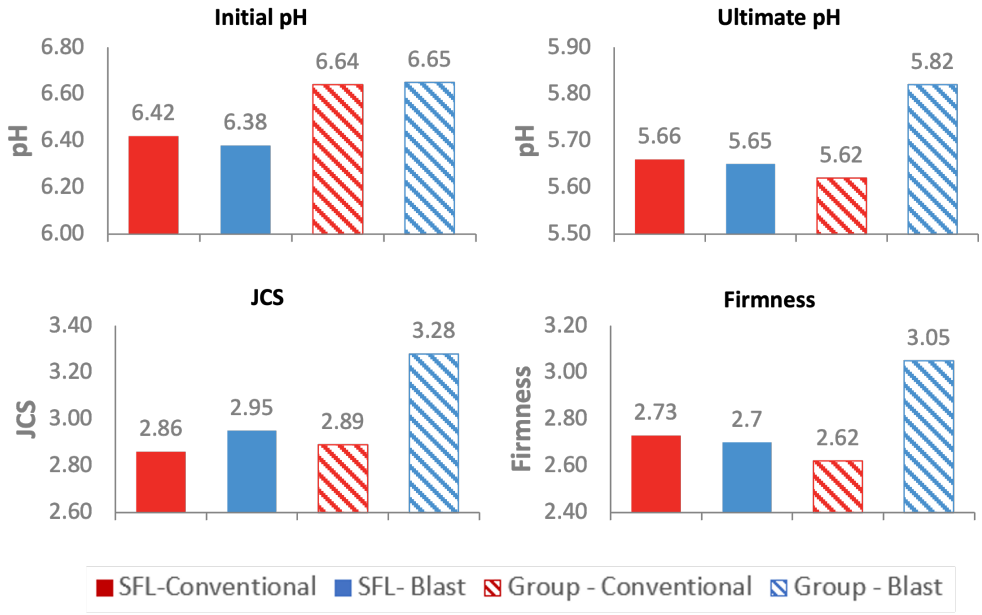
A literature review indicates that CO_2 stunning results in improved meat quality, compared to electrical stunning. The most consistent effect is the almost complete elimination of blood splash. Stunning with CO_2 does not increase the blood pressure like electrical stunning does, so it eliminates the broken blood vessels which cause blood splash. Most research concludes that stunning with CO_2 improves meat pH, color, and drip loss.

It is generally accepted that the improvements in meat pH, color, and drip loss are due to improved animal handling, not the actual stunning procedure. Replacing sideloading CO_2 stunners (single-file movement of pigs) with backloading CO_2 stunners (using group movement of pigs) leads to a substantial improvement (0.20 pH units) in initial pH. This clearly indicates that the group movement of pigs for stunning reduces pigs' stress levels and improves meat quality.

PIC evaluated temperature decline, pH, color, and firmness at 26 commercial slaughter plants to determine the effects of conventional chilling (with and without water sprays) versus blast chilling on meat quality. Plants were classified based on animal movement to stunning (group vs. single file) and chilling rate (blast vs. conventional). Group stunning consisted of CO_2 stunning with automated group movement of pigs into the stunner. Single-file stunning consisted of electrical and CO_2 stunning that required pigs to be moved to the stunner in a single-file.

The group-stunned pigs had an increase in initial loin pH (0.24 pH units), when compared to the single-file movement of pigs (Figure 3.22). Ultimate loin pH, color score, and firmness were only improved when combined with aggressive blast chilling. These results indicate that under commercial conditions, reducing pre-stunning stress levels alone is not always enough to improve pork quality when carcasses are subjected to poor chilling.

Figure 3.22 Effect of group stunning and chilling on loin quality



SFL = Single-file movement of pigs into stunning.
Group = Group movement of pigs into stunning.
Conventional = Conventional chilling.
Blast = Blast chilling.

3.2.6 Principles of Exsanguination and Effects on Meat Quality

Exsanguination can also impact meat quality. It is often referred to as “sticking” or “bleeding” the pig. The purpose of exsanguination is to kill the pig and remove blood.

Exsanguination severs major arteries and veins close to the heart. This requires severing the carotid arteries and jugular vein at a minimum, with other vessels being severed in the process, resulting in rapid blood loss. The knife is inserted at the mid-line in the depression superior to the breastbone and is directed toward the heart to sever major blood vessels close to the heart (Figure 3.23).

Removing as much blood as possible is critical for producing high-quality pork products. Generally, only 50% to 60% of the blood is removed from the carcass, with much of the blood remaining in the vital organs and viscera. Residual blood in the muscle and fat can lead to increased microbial growth, since blood provides an ideal bacterial-growth medium. Increased microbial growth can exacerbate issues with pork products’ shelf life. Residual blood in blood vessels (Figure 3.24) is also unsightly. It is considered a carcass and/or primal defect in commercial situations.

Figure 3.23 Knife angle for proper sticking

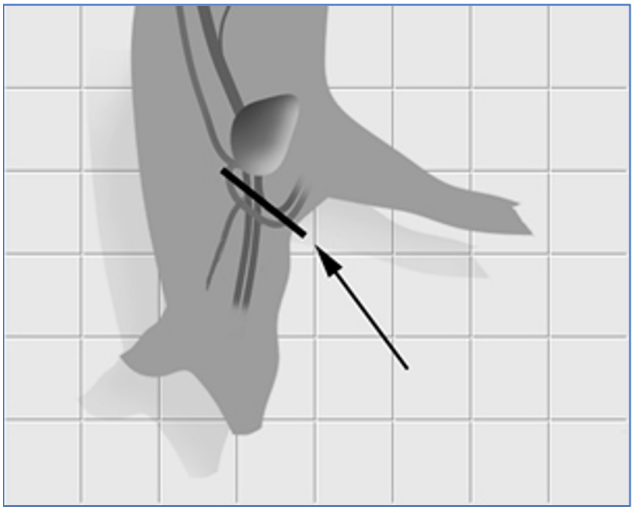
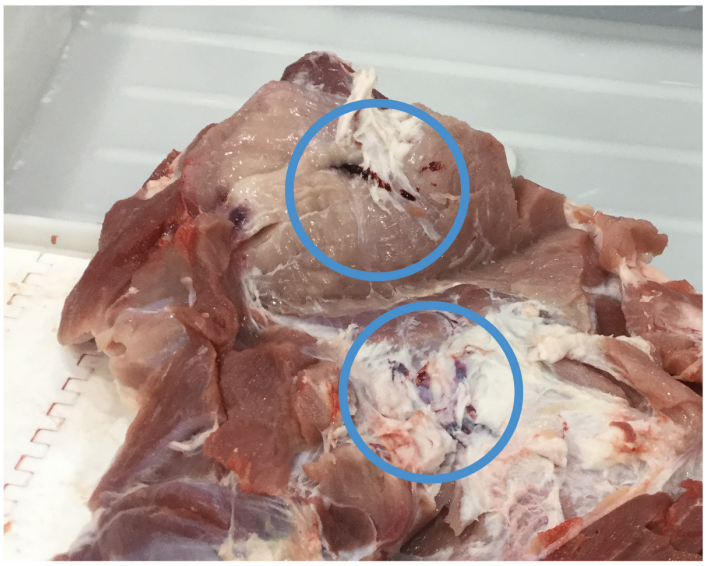


Photo Source: Humane Slaughter Association. 2016.

Figure 3.24 Residual blood in blood vessels



Optimal blood removal is connected to the pig stunning process. The amount of time that lapses from when pigs exit the stunning process to exsanguination is critical for ensuring the timely death of the pig before it may regain consciousness. Timing also facilitates optimum blood removal. This time should be less than 10 seconds with head-only electrical stunning. With CO_2 stunning, the greater issue is bleeding quickly enough to ensure optimum blood removal. Pigs will normally remain unconscious for more than 90 seconds, or they are already dead. Assuming a CO_2 dwell time of 180 seconds or less, all pigs exiting the gondola should be bled within 60 seconds, and no more than 90 seconds, to ensure proper blood removal.

Exsanguination can be done with the pig laying horizontal on a conveyer belt immediately after electrical stunning, or vertically after shackling and hanging with CO_2 stunning (and in some instances with electrical stunning). Vertical sticking is much easier to perform than horizontal. However horizontal sticking is often required with electrical stunning, since minimizing the stun-to-stick time is critical.

During exsanguination, it's important for blood to flow freely from the stick wound. When the pig is initially stuck, blood flow is profuse for up to 1 minute; then the flow diminishes. At this point, enough blood is lost to result in the pig's death, but additional blood needs to be removed to prevent blood pooling in the primals. Reduced blood flow can allow the stick wound to close enough to cause blood clots and prevent further blood removal. This is much more likely to occur with CO_2 stunning than electrical stunning, he stun-to-stick interval with CO_2 stunning is much longer.

One way to address this to install head knockers throughout the bleed chain (Figure 3.25). The pig's head is pulled over a bar, causing the head to swing and keep blood from clotting in the stick wound. One other technique with the sticking process is to insert the knife, twist the knife 90 degrees, and then remove the knife. This results in a stick would that's more of a 'T' shape, as opposed to a normal stick wound (Figure 3.26). This 'T' shaped wound reduces the likelihood of the stick wound completely closing. The twisting action of the knife severs more blood vessels, facilitating rapid blood loss.

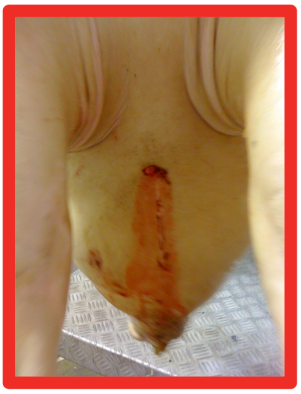
The stick wound also needs to be at least 2.5 cm (1 inch) wide, or it can easily close. Excessively large stick wounds (> 3.8 cm or 1.5 inch) are not necessary and may cause some losses in carcass value, due to extra trimming required in the stick-wound area.

Figure 3.25 Use of head knockers to prevent blood clotting

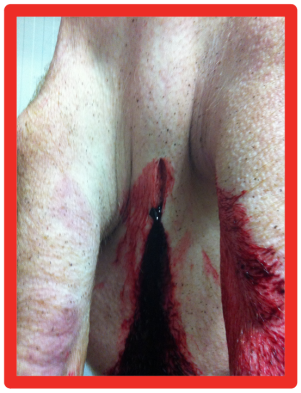
Figure 3.26 Proper and improper stick wounds

- Excessively large
- Flat cut (no twist of knife)

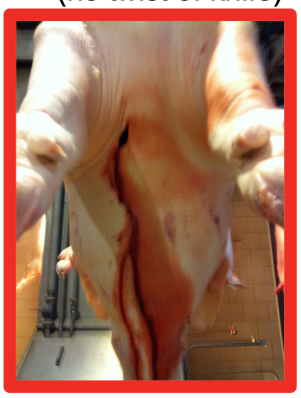
- Too large
- Flat cut (no twist of knife)



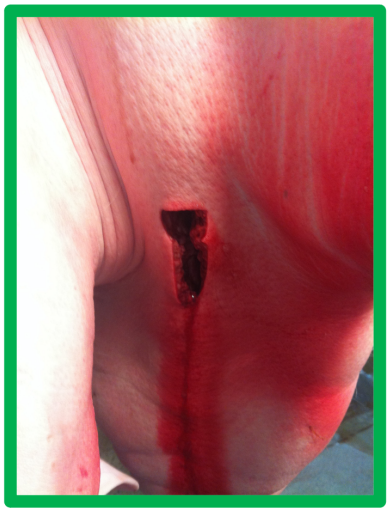
- Too small
- Flat cut (no twist of knife)

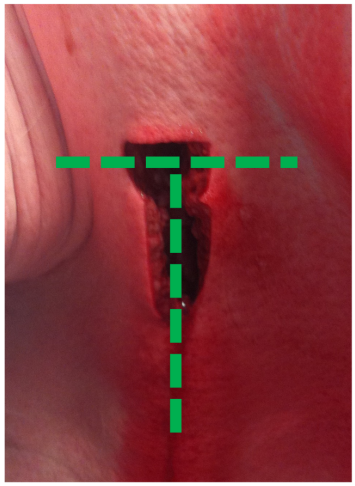


- Size ok
- Flat cut (no twist of knife)



- Size ok
- Flat cut (no twist of knife)
- Stick is offset too much





- Ideal
- Size ok
- Twist of knife resulting in 'T' shape

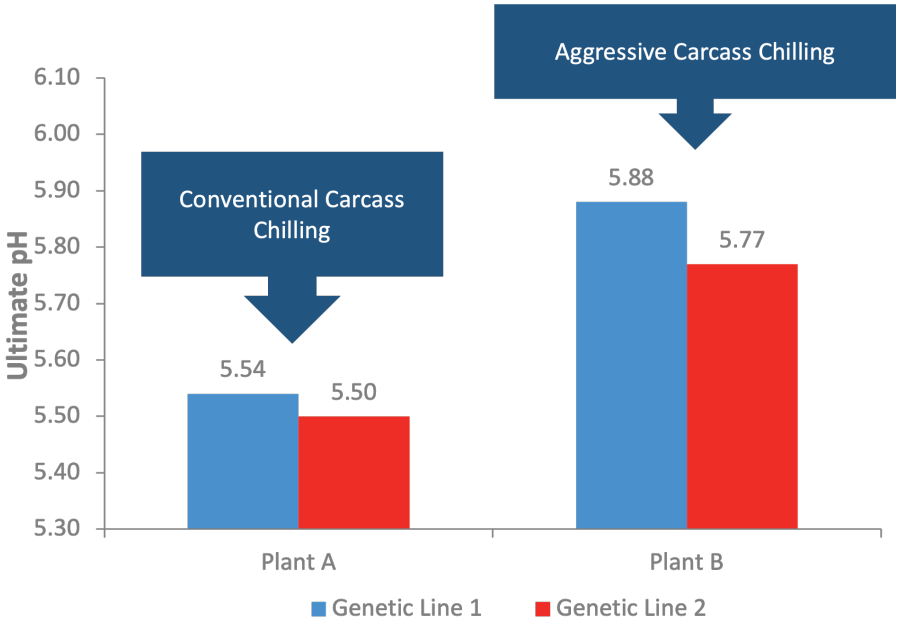
3.3 Managing Lean Quality

3.3.1 Genetics

Genetics are critical to high-quality meat. While they are often thought to contribute to a large amount of the variation in meat quality, systemic (manageable) and non-systemic (unmanageable) environmental factors can greatly affect realization of genetic potential.

Figure 3.27 provides an excellent example of how different management systems affect the expression of genetic potential. In this case, aggressive chilling allowed more expression of genetic potential by both genetic lines, but also allowed superior genetic potential to be more apparent in genetic line 1.

Figure 3.27 Environmental factors preventing genetic expression



It has been known for years that genetics contribute about 20% to 30% of the variation in pork quality. This assumes that the *HAL*-1843™ (stress gene) and *RN*- (Rendement Napole) genes are removed, as they would increase the percentage of variation due to genetics. Breeding for ultimate pH or reduced susceptibility to stress can improve the genetic potential for ultimate pH, color, water-holding capacity and eating quality. (See also section 3.2.3.1, Genetic Effects on pH.)

3.3.1.1 Genetics Recommendations

- Use genetics that have been selected for improvements in pork quality traits such as pH and tenderness.
- Use genetic lines that do not carry the stress gene and the RN gene mutations.

3.3.2 Nutrition

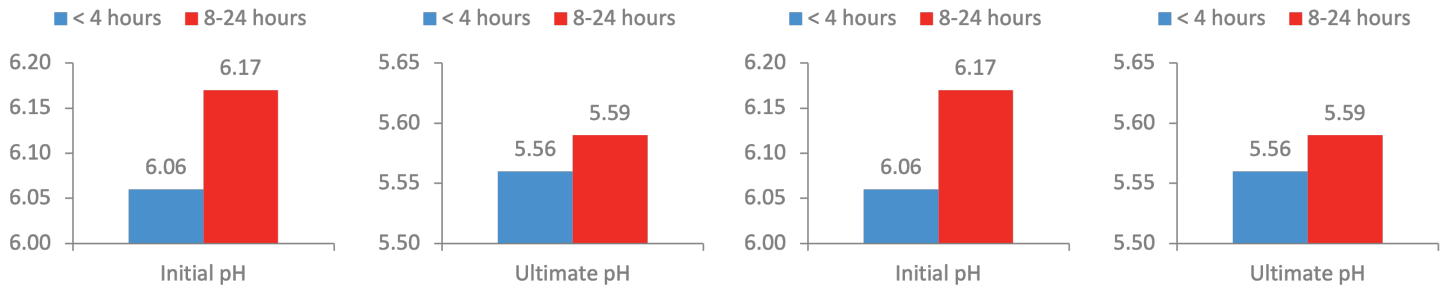
In the past 30 years, researchers have extensively studied the nutritional manipulation of meat quality. Feed ingredients evaluated include (but are not limited to) carnitine, chromium, betaine, creatine, magnesium, iron, manganese, niacin, vitamin E, vitamin D, and vitamin C.

Although these ingredients have demonstrated positive results on either pH, color, or drip loss, the response is often inconsistent, too small to be commercially meaningful, or not economically feasible for meat quality improvement. Mitigating pre-slaughter handling stress, and increasing the chilling rate of the carcass, affect meat quality much more than any nutritional intervention.

Nutrition can be used, however, to change carcass fat level or type, and marbling. Fatty acid profiles can easily be changed by feeding a fat with the desired profile. Different fatty acids can change the flavor profile of the pork when those differences are great enough. It is possible to increase intramuscular fat by feeding lysine deficient diets, but this is usually not economical, since it negatively impacts growth rate, feed conversion, and overall carcass leanness.

Feed withdrawal is the best nutritional intervention for improving meat quality, since it helps deplete some of the muscle glycogen stores. A meta-analysis of 11 trials comparing less than 4 hours of feed withdrawal to 8 to 24 hours of feed withdrawal indicates that initial and ultimate pH, color, and drip loss improved by extending feed withdrawal (Figure 3.28). Feed withdrawal also enhances food safety. It reduces gut fill, which prevents accidental leakage of intestinal contents on the carcass during the evisceration process.

Figure 3.28 Effect of feed withdrawal on pork quality*



*Summary of 11 trials from 9 papers. Trial was included if sample size was greater than 30 carcasses per treatment. The study had to have withdrawal times less than 24 hours and a control that consisted of 0 to 4 hours of feed withdrawal.

Although feed withdrawal is important for improving meat quality and food safety, excess feed withdrawal can diminish carcass value. Muscle-tissue shrink begins to occur between 24 and 30 hours of feed withdrawal. This reduces carcass weight and lowers the carcass value.

3.3.2.1 Feed Withdrawal Recommendations

- Feed withdrawal is important for pork quality and food safety.
- The goal is to have 12 to 24 hours off feed prior to slaughter.
- The total feed withdrawal time should:
  - Include transport time.
  - Include a minimum of 6 to 8 hours off feed on farm before loading.
  - Provide a minimum of 2 to 3 hours rest time after unloading at the plant before slaughtering the pigs.
- If multiple cuts are marketed out of a barn, feed withdrawal may not be as advantageous under certain conditions and for the first portion of the pigs.
  - If a barn has multiple out-of-feed events prior to marketing, feed withdrawal at marketing may increase the propensity for death loss in pigs remaining on the farm, due to ulcers or other gut health issues.

3.3.3 On-Farm Loading of Pigs

Loading pigs on the farm creates one of the first major stresses that can affect meat quality. Minimize this stress through proper pig handling skills, pig handling tools, and facilities conducive for pig movement.

Pigs should always be moved in small groups. The handler should never go forward of the point of balance, or into the pigs' blind spot (Figure 3.29). Any rough handling or loud noises can stress pigs. This is counterproductive in getting pigs to move. Eliminating distractions and ensuring adequate lighting without major light transitions are also critical (Figure 3.30).

Figure 3.29 Science of moving pigs

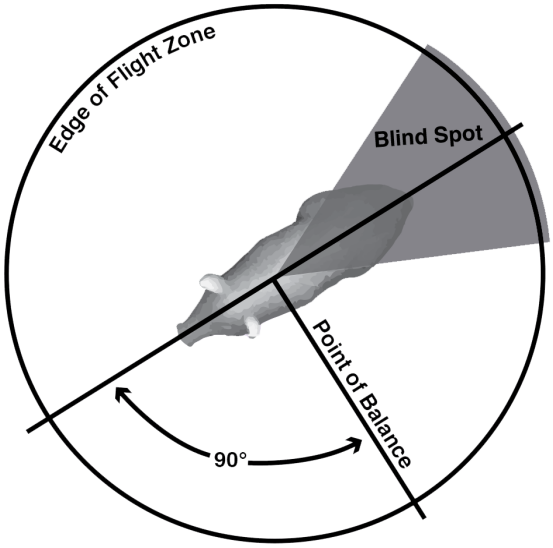
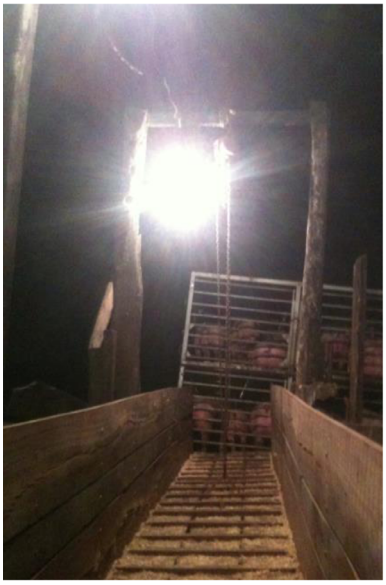


Photo Source: National Pork Board's TQA Handbook, 2018

Figure 3.30 Examples of poor lighting that can affect pig movement



Poor lighting and the only light is shining directly into the eyes of the pigs.

Good lighting, but low hanging lights are distracting to the pigs.

3.3.3.1 On-Farm Loading Recommendations

- Pigs should be moved in small groups (4-5 pigs) during the loading process through standard, 36-inch alleyways.
  - Wider alleys allow for moving larger groups of pigs.
  - Minimizes stress.
  - Allows for quicker loading.
- Use proper pig movement tools for loading pigs.
  - Don't use electric prods, if possible. If used, they should not be carried as the primary tool.
  - Use sort boards, paddles, and flags.
  - Avoid making loud noises, like shouting or banging on gates or chutes.
- Use a loading ramp that minimizes pigs' stress.
  - Ideally, avoid inclines, but if necessary, the ramp's incline should be 20 degrees or less.
  - The loading ramp's flooring should prevent pigs from slipping or falling.
    - The ramp could have cleats or an anti-slip flooring material.
    - Cleats should be evenly spaced for the size of the pigs, per industry guidelines.
- Ensure proper lighting in all areas where pigs will go during the loading process.
  - Pigs move easier in well-lit areas without major light transitions.
  - This is critical when pigs are moving from different areas (i.e., alley into the load chute, and load chute into the truck).
  - Lighting should be diffuse and mounted high enough that the light source does not distract pigs.
    - If mounting lights up high is not an option, use unidirectional lighting so the light does not distract pigs.
- Ensure a movement pathway (pen to truck) that facilitates pig movement.
  - Remove all objects (hoses, gate rods, etc.) and debris from the path, since these will distract pigs.
  - Avoid turns of 90 degrees or greater.
  - Avoid bottlenecks or other abrupt changes in the movement pathway.
  - Transitions in floor types, floor drainage, and reflections from pooled water on the floor will distract pigs and affect their movement.
  - Ideally, alley ways should be wide enough for two pigs to walk side-by-side. If alley ways are too wide, pigs may attempt to turn around.

3.3.4 Transportation of Pigs

After pigs are loaded on the truck, it's important to minimize transportation stress. If conditions on the trailer are not good, the stress of loading will not dissipate. Trips less than 2 hours generally do not allow pigs to adjust to the stress of loading and transportation before being unloaded.

Trailer design, pig comfort level (temperature and ventilation), and stocking density are three main factors that can impact pigs' stress levels during transportation.

3.3.4.1 Transportation Recommendations

- The type of trailer and management of the trailer can impact pigs' stress levels.
- Ideally, the best trailer type is one where pigs can be loaded without the use of an internal ramp or loading chute.
  - These trailers have either moveable, hydraulic decks, so pigs can all be loaded on the same level, or a hydraulic lift to raise the pigs to the level of the deck being loaded.
  - Straight-deck trucks are preferred to split-deck trucks (pots).
  - Ensure the truck's flooring has traction from either textured flooring, mats, or bedding.
- Proper temperature and air flow.
  - Insert trailer panels during cold temperatures, and remove panels during hot weather, according to industry standards. Consider the temperatures where you are going, as well as temperatures during loading.
  - During hot weather, provide water misting to cool the pigs on the truck. Only do this immediately prior to or at departure, so the movement of the truck will help control high humidity.

- Provide sufficient bedding in the truck. Adequate bedding:
  - Absorbs urine and prevents pigs from slipping and falling.
  - Provides warmth during cold weather.
    - Provides cooling in the summer when the bedding is wet. This assumes that the truck is moving to provide ample air flow and prevent an increase in humidity.
- Ensure proper stocking density.
  - Overstocking can result in increased DOA's and stressed pigs at the slaughter plant.
  - Understocking can result in more animals falling with the possibility of injury.
  - Large scale production research indicates that a stocking density of 225 to 250 kg/m^2 (46.1 to 51.2 lb/ft^2) can minimize DOA's and stressed pigs.
    - Even small increases in average pig weight can influence the stocking density and require fewer pigs to be placed on a trailer to minimize transport losses (Table 3.2).

Table 3.2 Trailer stocking density at different average live weights when using a stocking density of 250 kg/m^2 (51 lb/ft^2)

Average line weight kg/lb	Required floor space m^2/pig	Required floor space ft^2/pig	# Pigs stocked on trailer with 65 m^2 (699.65 ft^2) of space # pigs
99.8 / 220	0.399	4.297	162.8
102.1 / 225	0.408	4.394	159.2
104.3 / 230	0.417	4.492	155.8
108.9 / 240	0.436	4.687	149.2
111.1 / 245	0.444	4.785	146.3
113.4 / 250	0.454	4.882	143.3
115.7 / 255	0.463	4.980	140.4
117.9 / 260	0.472	5.078	137.8
120.2 / 265	0.481	5.175	135.2
122.5 / 270	0.490	5.273	132.7
124.7 / 275	0.499	5.371	130.3
127.0 / 280	0.508	5.468	128.0
129.3 / 285	0.517	5.566	125.7
131.5 / 290	0.526	5.664	123.6
133.8 / 295	0.535	5.761	121.4
136.1 / 300	0.544	5.859	119.4

- Once trucks are loaded with pigs, the truck should proceed directly to the slaughter plant and unload in a timely manner.
  - Avoid unneeded and prolonged stops.
  - Time the loading of pigs, so the truck can arrive at the slaughter plant at the scheduled time to allow for timely unloading of pigs.
- Typically, pigs with longer transport times/distances will have better meat quality.
  - Transport times of 2 hours or less do not allow pigs to overcome the stress of loading before they undergo the stress of unloading.
    - This compounds stresses that can impair pigs and/or meat quality.
    - Pigs with transport times less than 2 hours should be allowed to rest for a minimum of 3 hours after unloading at the slaughter plant.

3.3.5 Pig Unloading

Proper unloading procedures and a rest period before slaughter are crucial to help pigs quickly overcome stress. This is especially important when lairage size does not allow for adequate rest time prior to slaughter.

Minimize unloading stress with proper pig handling skills, pig handling equipment, and proper equipment use. Do not delay unloading after the truck arrives at the slaughter plant. Facilities should maintain a schedule for arriving trucks, and everyone should follow this schedule.

3.3.5.1 Unloading Recommendations

- Pigs should be moved in small groups (4-5 pigs) during the unloading process to:
  - Minimize stress.
  - Allow for quicker unloading.
- Proper pig movement tools should be used when unloading pigs.
  - No electric prods. If prods are used, they should not be the primary tool, and should be used on no more than 10% of the pigs.
  - Use sort boards, paddles, and flags.
- Use an unloading ramp that helps minimize pigs' stress.
  - Ideally, avoid declines or inclines, but if necessary, the loading ramp's decline/incline should be 20 degrees or less.
  - The loading ramp's flooring should prevent pigs from slipping or falling.
    - Use cleats or an anti-slip flooring material.
    - Cleats should be evenly spaced.
- Ensure proper lighting in the unloading area.
  - Pigs move easier in well-lit areas without major light transitions.
  - This is critical when pigs are transitioning from the trailer into the lairage areas.
    - This can be difficult to manage when the trailer is not under a shelter with a good light source.
  - Lighting should be diffuse and mounted high enough that the light source does not distract pigs.
    - If mounting lights up high is not possible, use unidirectional lighting so the light does not distract the pigs.
- Ensure a pathway (truck to pen) that facilitates pig movement.
  - Ensure that the proper gates are opened before starting the unloading process.
  - Remove all objects from the movement path, as these will distract pigs.
  - Avoid turns of 90 degrees or greater, if possible.
- Transitions in floor types, floor drainages, and reflections from pooled water on the floor will distract pigs and affect their movement.

3.3.6 Lairage Management

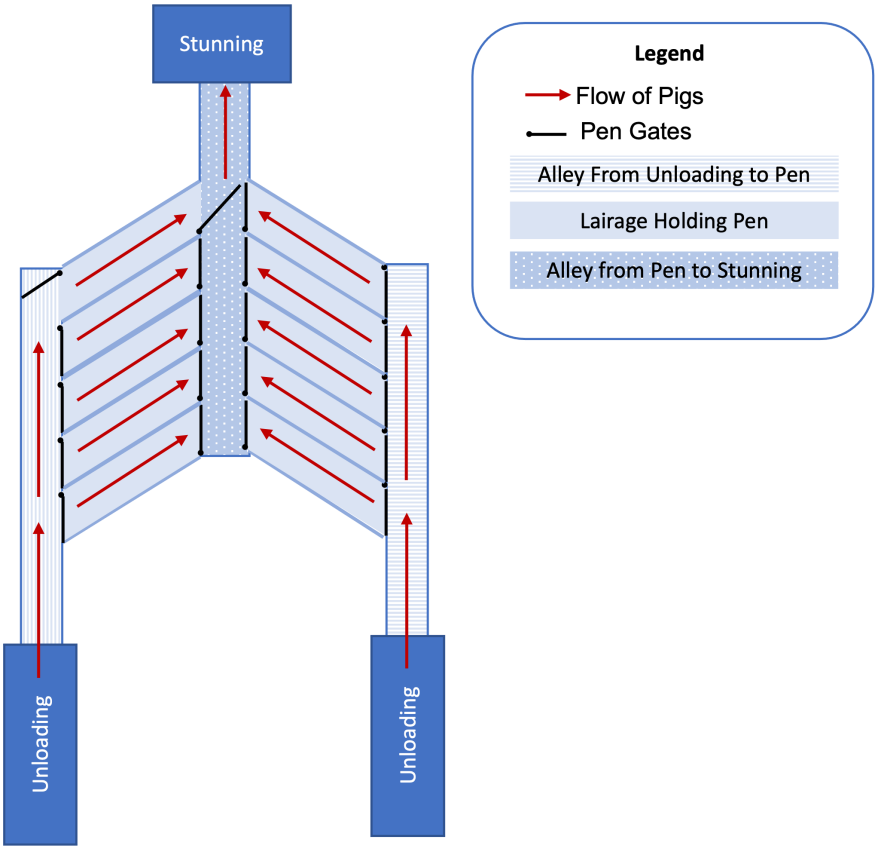
The time pigs spend in lairage (holding pens at the slaughter plant) helps alleviate stresses the pigs experience from the time they leave their home pen until they reach the lairage pen. Manage environmental conditions for the pigs' comfort, without creating any additional stress.

Once a pig leaves the lairage pen to undergo stunning, stress cannot be reduced. Thus, the lairage needs to be managed in a way that helps the pigs relax and overcome any stresses incurred to this point.

3.3.6.1 Lairage Management Recommendations

- Temperature and ventilation management are important for pigs' comfort when they are resting in the lairage.
  - Excessively high or low temperatures can stress pigs.
  - Maintain a temperature that's close to the temperature the pigs were accustomed to on the farm.
  - The lairage should be equipped with water misters to cool the pigs during hot weather (> 27°C / >80°F).
  - Do not spray pigs with water when temperatures are below 16°C / 60°F, since this can add stress.
  - Good ventilation is necessary to prevent excessive ammonia concentrations as well as humidity, which can stress pigs.
- Lairage design is critical for efficient, stress-free pig movement, along with ample time for rest prior to the slaughter process. This helps alleviate the stress of loading, transportation, and unloading.
  - An adequate number of pens is necessary to ensure that pigs receive the appropriate amount of rest time after unloading.
    - Ideally, all pigs should receive a 3- to 12-hour rest period after unloading.
    - At a minimum, pigs should receive 2 hours of rest prior to slaughter.
      - The number of loads receiving only 2 to 3 hours of rest prior to slaughter should be minimized (i.e., 1 to 2 loads at the end of the shift).
    - Rest times of 16 to 24 hours or more may result in carcass yield loss.
  - Pens within the lairage should be configured so it is easy to move pigs in and out of the pen.
    - Putting loading pens on one end and unloading on the opposite end is ideal.
    - Pigs should enter and exit pens at an angle less than 90 degrees.
    - A herringbone design is ideal (Figure 3.31).

Figure 3.31 Herringbone lairage design



- Minimize distances between the unloading area to the pen, and the pen to the stunning area.
- Pen sizes should be adequate for the number of pigs being delivered per load.
  - Avoid mixing multiple loads in one pen.
  - Minimum lairage pen stocking density should be 0.56 m^2/6.0 ft^2 per pig.
    - Load size or number of pigs placed in the lairage pen must be adjusted to meet the stocking density guidelines.
- Ensure proper lighting throughout the lairage.
  - Pigs move easier in well-lit areas without major light transitions.
  - The lighting should be diffuse and mounted high enough that the light source does not distract pigs.
    - If mounting lights up high is not an option, use unidirectional lighting so pigs are not distracted by the light when they are moving from the truck to the pen, or the pen to the stunner.
  - Proper lighting on the "final drive" from the pen to the stunner is essential, since distractions at this point causes stress that cannot be relieved prior to slaughter.
- Transitions in floor types, floor drainage, reflections from pooled water, or objects on the floor will all distract pigs. They can also affect pigs' movement and stress pigs.

3.3.7 Stunning of Pigs

The stress imposed upon a pig at stunning is probably the most influential stress on meat quality. Stunning is a point where there is no further, possible intervention. Any stress on the pig makes a lasting impact on meat quality development.

Stunning methods which use single-file movement of pigs in chutes or "irons" (Figure 3.32) impose more stress on pigs than group movement of pigs into stunning. Operating single-file systems makes it very difficult, if not impossible, to eliminate stress associated with stunning and handling. Newer CO_2 stunning systems allow group movement of pigs into the stunner and are much easier to manage (Figure 3.32). Improper stunner settings may also contribute to stress and/or defects in the meat.

Figure 3.32 Movement types into stunning

CO_2 stunning with single file movement of pigs

CO_2 stunning with group movement of pigs

3.3.7.1 Single-File Pig Movement Management Recommendations

- The key to reducing stress with single-file movement of pigs is keeping the flow of pigs as consistent as possible.
  - Avoid stressing the pigs before they enter the single-file movement (chutes/irons).
    - If pigs are stressed before entering the irons, they will be difficult to move.
  - Maintain a constant flow of pigs from the pens to the irons.
    - Pigs are more likely to continue moving if they are following another pig.
    - Pigs must be moved in groups large enough to maintain constant flow, but not so big that the pigs can't be moved without adding stress.
      - This may require more than one person to bring pigs from the pens.
  - Minimize the use of electric prods to move the pigs through the irons.
    - Electric prods should not be used on pigs that are already moving, as this may stop the movement.
- Ensure proper lighting from the pen to the stunner.
  - This is critical as the pigs enter the irons and stunner.
    - Lighting should be diffuse and mounted high enough that the light source is not distracting to the pig.
    - If mounting lights up high is not an option, use unidirectional lighting so the pigs are not distracted by the light.
- Avoid loud noises, since these can frighten (stress) pigs and impede the flow of pig movement.

3.3.7.2 Group Pig Movement Management Recommendations

- Group movement of pigs should be continuous. The pigs do not need to be pushed hard to maintain line speeds.
  - In most situations, the group size removed from the pen is dictated by the capacity of 2 to 3 gondolas in the CO_2 stunner.
    - If a gondola holds 7 pigs, then 14 or 21 pigs should be moved from the pen at a time.
    - The pigs will then be split into groups of 7 at the automated push gates of the stunner.
    - Based on most CO_2 cycle times and lairage configurations. this should allow line speed to be maintained.
  - Movement of pigs from the pen to the automated push gates should be timed so that when the pigs arrive at the automated push gates, they do not have to wait for entry into the automated push gate area.
    - Delays can result in pigs refusing to move after stopping and can potentially stress the pigs.
- Ensure proper lighting from the pen to the stunner.
  - This is critical as the pigs enter the stunner.
    - Lighting should be diffuse and mounted high enough that the light source doesn't distract the pigs.
    - If mounting lights up high is not an option, use unidirectional lighting so the light does not distract the pigs.
- Avoid loud noises, since they can frighten (stress) pigs and impede the flow of pig movement.

3.3.7.3 Electrical Stunning Management Recommendations

- Electrical stunning equipment settings and maintenance are critical for ensuring an effective stun on each pig.
  - Stunner settings deliver at least 1.25 amps to every pig for an effective stun from a welfare perspective.
    - In a constant amperage electrical stunning system, the amperage should be set at 1.25 amps.
    - With a constant voltage system, assuming an average resistance of 250Ω, the voltage would need to set at 313V to deliver the necessary 1.25 amps.
      - Depending on variation in resistance, it may be necessary to increase the voltage to ensure an effective stun.
  - The current should be applied to the pig for a minimum of 3 seconds and no more than 5 seconds.
  - These settings are a starting point. Adjust them as needed within each system to ensure an effective stun and minimize the amount of carcass defects (broken bones, blood splash, and residual blood).
  - Electrodes need to be routinely cleaned and replaced when necessary.
    - Many facilities develop their own electrodes for best use and replacement availability.
    - Dirty or worn electrodes can increase resistance by 200Ω.
  - Regular preventive maintenance should be performed on all components of the electrical stunning system to ensure it is working properly.

- Electrode placement is critical to ensuring an effective stun (Figure 3.18).
  - The head electrodes should be placed behind the pig's ear and at the eye level of the pig.
  - They must NOT be used on the neck.
  - If head-to-heart stunning is used, the heart probe should be placed behind the foreleg.
- Pigs should be sprayed with water prior to stunning to improve conductivity.
  - Water will reduce resistance, allowing effective stunning with a lower voltage.
- Electrical stunning systems with v-restrainer belts should be properly maintained. Only use them with the size of pig the restrainer was designed for.
  - Check restrainer belt speeds to ensure the belts are moving uniformly.

3.3.7.4 CO_2 Stunning Management Recommendations

- The CO_2 concentration and exposure time are the two most critical elements for ensuring an effective stun and minimizing stress.
  - The CO_2 concentration dictates how quickly the pigs lose consciousness. The exposure (or dwell) time is important for ensuring that pigs remain insensible.
  - CO_2 levels at the first gondola stop should be high enough that pigs lose posture and vocalizations stop after 20 seconds of gas exposure.
    - Normally, an 88% CO_2 concentration is required, but in some instances concentrations as high as 96% may be required.
    - Levels of CO_2 below 88% may render pigs insensible but rarely induce unconsciousness in less than 20 seconds.
    - Every CO_2 system installation may be different, so the correct CO_2 concentration for one slaughter plant may not be as effective in another slaughter plant.
    - During cooler weather (< 7°C / 45°F), the CO_2 concentration may need to be increased.
      - If the pigs are not losing consciousness quick enough or returning to sensibility, the CO_2 level likely needs to be increased.
    - Know the location of the CO_2 sensor(s).
  - The exposure time to CO_2 should be long enough that the pigs remain insensible until the they are dead, but not so long as to complicate blood removal from the carcass.
    - Exposure times of less than 90 seconds may result in pigs regaining consciousness before death, even with CO_2 levels as high as 95%.
    - Exposure times of more than 180 seconds may result in issues with blood removal, which shows up as lividity.
    - To maintain line speed, it may be necessary to increase or decrease the number of pigs per gondola, depending on how much the dwell time is changed.
      - Never put more than the recommended number of pigs in a gondola to decrease the dwell time.
      - When decreasing dwell time, not using one of the gondolas may be an effective option to maintain line speed and avoid changing the number of pigs per gondola.
  - Never load more than the recommended number of pigs per gondola.
  - Routinely have the CO_2 sensor checked to ensure it is working properly.

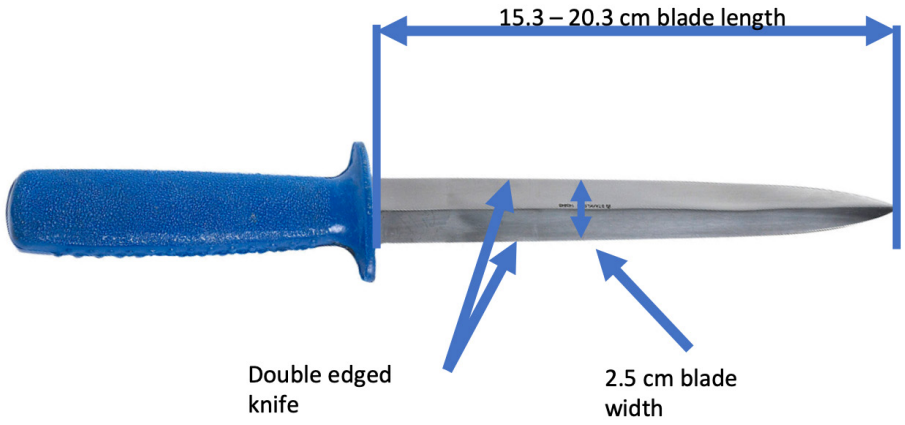
3.3.8 Exsanguination of Pigs

Timely exsanguination (sticking/bleeding) is important, so that the pig dies as a result of blood loss. If exsanguination is delayed, pigs could regain sensibility, which is unacceptable from a welfare perspective. Timely exsanguination is also important for ensuring maximum blood recovery from the carcass. Delaying exsanguination can result in blood clotting and prevent blood removal from the carcass.

3.3.8.1 Exsanguination Recommendations

- The timing of exsanguination depends on the type of stunning.
  - Pigs undergoing head-only reversible electrical stunning should be bled within 10 seconds after stunning.
  - Pigs undergoing irreversible head-body stunning that induces cardiac fibrillation should be bled within 30 seconds after stunning.
  - Pigs undergoing CO_2 stunning should be bled within 60 seconds. This should not exceed 90 seconds, if possible.
    - The time is calculated from the time the pigs exit the gondola until the last pig from that gondola is bled.
- Use proper equipment and procedures.
  - Use a knife with a blade that is 15 to 20 cm (6 to 8”) long and 2.5 cm (1”) wide, with both edges sharpened (Figure 3.33).

Figure 3.33 Knife used for exsanguination



- Insert the knife at the mid-line in the depression superior to the breastbone. Direct the knife toward the heart to sever major blood vessels close to the heart.
- Once the knife is inserted, twist the knife 90 degrees, and then remove the knife.
  - This results in a ‘T’ shaped stick wound that can help prevent blood clotting.
- The size of the stick wound should range between 2.5 to 3.7 cm (1 to 1.5”) wide.
- Use head knockers during the bleeding process.
  - Place the first head knocker so the carcass arrives at this head knocker less than 1 minute after sticking.
  - After the first head knocker, the carcass should arrive at another head knocker every 30 seconds. Install additional head knockers, as needed, to ensure this happens.
- Allowing more than five minutes of time on the bleed chain is not necessary since most of the blood is removed within 4 minutes post exsanguination.

3.3.9 Stun to Chill

The time from when the pig is stunned until it reaches the chilling process is critical from a carcass temperature perspective. Most modern slaughter plants have a stun-to-chill time between 25 and 45 minutes.

During this time, the hair removal procedures (scalding and singeing) may add additional heat to the carcass. Viscera removal is critical to allow heat dissipation from the carcass.

The use of buffer rails (rail-outs) to fill shackles without carcasses can affect the amount of stun-to-chill time if not managed properly. This can also impact the temperature decline rate during the early post-mortem period. It is important to put the carcass into the chilling process as quickly as possible, with limited exposure to heat sources that can increase carcass temperatures.

3.3.9.1 Stun to Chill Recommendations

- Manage the stun-to-chill time.
  - Stun-to-chill time should be less than 45 minutes.
  - Minimize line stoppages, which increase stun-to-chill time.
    - Proper preventative maintenance of equipment can prevent some line stoppages.
  - Consider avoiding or minimizing the use of buffer rails, since they will increase stun-to-chill time.
  - Avoid “dead” line space, where no processes are occurring.
- Manage the amount of heat introduced to the carcass.
  - Minimize the scald water temperature to a level that effectively removes hair.
    - Scalding duration can affect the temperature needed to effectively remove hair.
      - Short scald times may require a slightly higher temperature.
    - This is often a trial-and-error process, where the temperature is lowered or raised to determine the minimum temperature needed for effective hair removal.
    - For tub scalding, 60°C (140°F) is typically high enough temperature for effective hair removal under normal conditions, with a 6- to 8-minute scald time.
    - The temperature may be increased to 61°C (142°F) during hard hair season or when killing pigs with a high percentage of red or black hair color.
    - If possible, remove pigs from scald tubs during line stoppages.

3.3.10 Carcass Chilling

Carcass chilling is the critical, final component in the development of meat quality. Up until now, each process described in the Blueprint for managing meat quality builds upon the previous processes. In some instances, a later management event can partially alleviate previous failures in the control process (i.e., rest in lairage after transportation stress). This is not the case with carcass chilling.

Superior carcass chilling cannot correct issues occurring earlier (i.e., too much stress imposed on pigs immediately before slaughter). It will generally maintain the meat quality developed up until the start of the chilling process. Conversely, poor chilling can result in poor meat quality, even when other parts of the Blueprint are followed.

Not all plants have the luxury of using blast chilling but can still implement methods to improve quality and/or minimize quality variation with conventional chilling systems.

3.3.10.1 General Chilling Recommendations

- For optimum quality, the core temperature of the loin should be below 32°C (90°F) by 1.5 to 2 hours post-mortem, and below 13°C (55°F) by 4 to 5 hours post-mortem.
- For optimum quality, the core temperature of the ham should be below 32°C (90°F) by 3.5 to 4 hours post-mortem, and below 13°C (55°F) by 7 to 8 hours post-mortem.
- For optimum quality, the core temperature of the shoulder should be below 32°C (90°F) by 2 to 3 hours post-mortem, and below 13°C (55°F) by 7 to 8 hours post-mortem.

3.3.10.2 Carcass Blast Chilling Recommendations

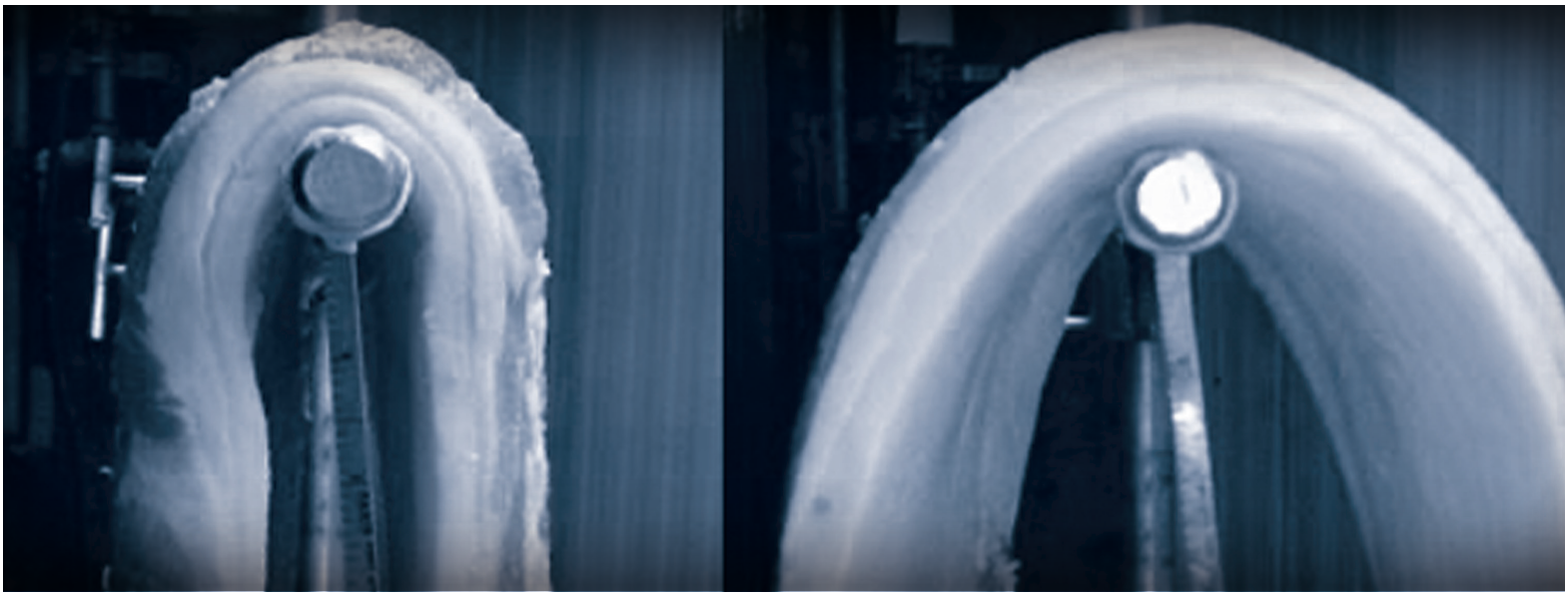
- Proper blast chilling involves low temperatures and rapid air movement.
  - Adjust the combination of these settings to increase carcass chilling rate.
    - For instance, a setting of -15°C (5°F) with 10 m/sec (33 ft/sec) fan speed could give the same carcass chill curve as a setting of -25°C (-13°F) with a 5 m/sec (16.5 ft/sec) fan speed.
- During the blast-chilling process, space the carcasses so air can flow between them to enhance convective cooling.
- Chilling rate is best when the first 30 to 60 minutes of the blast-chilling process include the coldest temperatures and the highest air movement velocities for convective cooling.
  - Directing air flow onto selected primals can enhance the chill rate.
  - A thin, frozen layer (crust) should form on the carcass during the blast-chilling process.
  - Ears and jowls will likely freeze solid, but primals (such as the belly) should not freeze internally.

3.3.10.3 Carcass Equilibration Chilling Recommendations

- Conventionally chilled carcasses enter the equilibration bay immediately. Blast-chilled carcasses enter after the blast-chill process.
- During the equilibration process, temperature, air velocity, and carcass spacing play a critical role in carcass chilling.
  - Typical equilibration temperatures should range from -1 to 2°C (30 to 36°F).
    - Temperature is often lower during the first half of equilibration and then increased during the latter half to ensure a quick temperature decline. This helps to avoid chilling the carcass to the point where it is difficult to fabricate into primals and sub-primals.
    - Temperatures lower than -1°C (30°F) may enhance carcass chill rates if these temperatures are attainable.
      - This is especially true with conventional chilling.
  - Air flow in equilibration is essential to move hot air away from the carcasses.
    - Normally, the air flow is less than 3 m/sec (10 ft/sec).
    - After the first 10-12 hours in equilibration, fan speeds should be slowed to 50% or less to prevent carcasses from drying out.
  - Space the carcasses properly for optimum chilling.
    - A minimum space between gambrels of 23 cm (9 in) is recommended.
    - The area between the rails should be minimally spaced 0.61 m (24 in) apart to ensure adequate air flow between the carcasses during the chilling process.
  - Water-spray use in equilibration can improve chill curves.
    - Water spraying should be considered under conventional chilling.
    - When carcass spacing is inadequate, consider spraying with water.

Section 4

Pork Fat Quality



While the quality of lean is key, as discussed earlier, fat quality (which is best defined by firmness) also plays a role in overall meat quality. Fat is included as an edible portion in many pork cuts, such as bellies, ribs, and as trim cover on primals and boneless cuts.

Soft fat often leads to fat layer separation and may be partially responsible for muscle separation in the ham and shoulder. Soft fat in bellies has been shown to reduce slicing yields in both regular and microwave bacon. In general, soft fat causes problems with product appearance when pork is packaged. Soft fat can lead to bacon that appears oily/wet or transparent, offers no slice definition when vacuum-packaged, and leads to faster oxidation rates (rancidity). Soft fat can also cause product appearance issues with sausage and can reduce yields in emulsion products like bologna. Generally, soft fat leads to reduced product “workability” and appearance, with an increased propensity for rancidity.

Fat is also a component of pork flavor. In some products, such as the Spanish Iberico ham, fat is manipulated via dietary formulations to have a higher C18:1 fatty acid level. This enhances the pork’s flavor profile. Conversely, if certain oils (such as fish, linseed, or flaxseed) are fed, the fatty acid composition has a higher proportion of long chain (> 20 carbon) polyunsaturated fatty acids that may cause the pork to smell or taste “fishy”.

As commercial pigs have become leaner over the past 30 years, fat quality has become one of the key traits that defines carcass value. A focus on fat quality has increased in the past few years as feed prices have risen. Least-cost formulated diets sometimes use ingredients that may compromise fat quality, as well as the value of pork bellies.

This section will address fat measurement, factors influencing fat quality, and methods for managing fat quality.

4.1 Measurement of Pork Fat Quality

4.1.1 Key Metrics

Fat firmness can be assessed using either chemical or physical measurements. Chemical measurements require a laboratory analysis, while physical measurements include measurements that can be collected within the slaughter plant. Here are some examples:

Chemical Measurement of Firmness

1. Iodine Value (IV)
    a. Directly correlated to the firmness of fat.
    b. Currently the "gold standard" for assessment of fat firmness.
    c. Measure of unsaturated fats expressed in terms of the amount of iodine absorbed by a fat sample.
    d. Number of double bonds in fatty acids used to determine unsaturation level of the fat.
2. Fatty acid analysis
    a. Proportion of different fatty acids is directly related to and influences IV.
    b. Certain fatty acids can be used as a fat firmness indicator.

Physical Measurements of Firmness

1. Fat Color
    a. Fat color indicates firmness.
        i. Whiter fat is firmer, while yellower fat is softer.
    b. Linoleic acid (an unsaturated fatty acid) gives fat the yellow color.
2. Primal Measurements
    a. Subjective measurement for assessing firmness.
    b. Includes belly flop/bend and belly thickness.
    c. Firmer bellies will be thicker and bend or droop less.
3. Bacon Slice Yields
    a. Firmer bellies have higher slice yields.
    b. The effects of firmness on slice yield may not be detected if cooked bellies are not chilled thoroughly prior to slicing.

4.1.2 Measurement of Pork Fat Quality

4.1.2.1 Iodine Value and Fatty Acids

Iodine value, as referenced above, is a measure of the unsaturation of fatty acids in fat. It is expressed in terms of the amount of iodine absorbed by a 100-gram fat sample. Unsaturated fatty acids contain double bonds, and each of the double bonds will absorb iodine.

The Wijs/Hanus method is used to directly determine iodine value. Some labs still perform the Wijs/Hanus method, although it is considered outdated, compared to newer technologies such as gas chromatography (GC) and near infrared spectroscopy (NIR), which are less labor intensive and/or faster.

Gas chromatography does not directly calculate IV but can determine the amount of each individual fatty acid. The IV in a fat sample is then calculated using the American Oil Chemists' Society (AOCS) (1998) equation: [IV = (%C16:1 * 0.95) + (%C18:1 * 0.86) + (%C18:2 * 1.73) + (%C18:3 * 2.62) (%C20:1 * 0.79) + (%C22:1 * 0.723)].

Because GC provides individual fatty acid concentrations, those concentrations can be used to predict firmness. In most conventional swine diets, linoleic acid content (C18:2) is the prevalent polyunsaturated fatty acid that has a negative effect on fat firmness. It is used by some in lieu of IV. However, IV is much more reliable as diets continue to change. Non-traditional ingredients not accounted for in the AOCS equation may be incorporated into diets and affect fat firmness.

For many years GC was considered the "gold standard" for fat quality analysis, as it is very accurate, but it can be quite expensive ($40 - $100 USD/sample), depending on the lab that conducts the analysis. Also, sample analysis turn-around times are typically long (i.e., 2 weeks).

There has been an overwhelming shift in the industry in recent years to NIR technology for fat quality analysis. Fat analysis using NIR is fast, accurate, and inexpensive, especially when conducting routine analyses. Most U.S. slaughter plants that conduct routine fat quality analyses use in-house NIR machines to determine fat quality.
NIR machines in the U.S. generally cost $90,000 to $100,000 USD, but the initial investment is offset quickly by eliminating the use of outside labs for fat quality analysis. NIR machines can also be used for other common lab procedures routinely performed in most slaughter plants. If collecting a large number of samples for routine fat IV analysis, the return on investment generally occurs within 1 to 2 years.

Two main methods for conducting NIR analysis include solid or liquid fat analysis. Solid fat analysis requires minimal sample preparation, while samples for liquid fat analysis must be melted prior to analysis. Both methods are highly accurate, when compared to GC results.

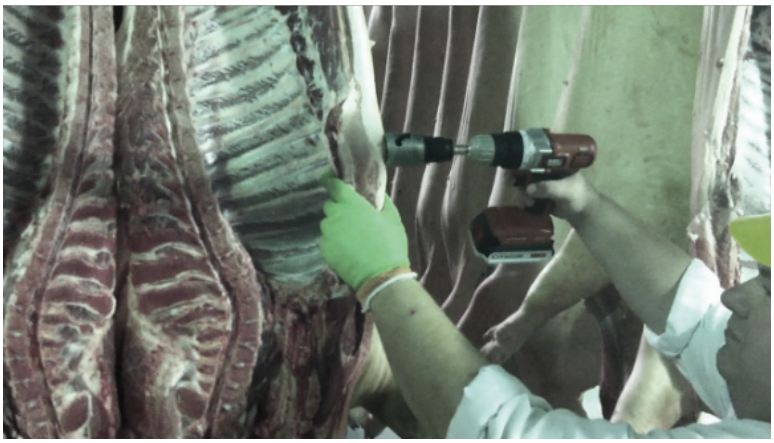
In PIC's internal research, the correlation of solid fat analysis using NIR with GC results was 0.97. The correlation of NIR liquid fat analysis with GC analysis was 0.99. Considering the extra labor associated with melting fat for liquid analysis for a slight improvement in accuracy, it makes sense that the solid fat method is preferred. Increased sample throughput and/or labor costs are important as well.

Sampling is another critical aspect of IV and fatty acid analysis. First, the sampling location should be kept consistent. Pick a location on the carcass to obtain a sample and maintain sampling consistency to ensure that the same fat layers are being sampled and analyzed. Three locations that are commonly sampled include the belly, shoulder/loin backfat, and jowl. Belly fat and shoulder/loin backfat fat samples are relatively easy to collect but collecting samples that are too large can negatively impact carcass value.

The IV of belly fat and shoulder/loin backfat are typically correlated with their fat quality. These two locations are responsive to nutritional changes during the last 4 to 6 weeks of the pig growing period that can influence fat quality. Jowl fat is simple to collect and less destructive to the carcass value. The IV of jowl fat is less indicative of nutritional changes in the diet during the last 4 to 6 weeks prior to slaughter. All issues considered, belly fat or shoulder/loin backfat is the recommended location for sampling.

It is best to collect samples post-chilling to allow for more precise, less destructive sampling. Use a knife, scalpel blade, meat shears, or coring device to collect samples. Most slaughter plants require personal protective equipment (PPE) when using a knife or scalpel blade, but PPE may not be needed when using shears or a coring device. Using a knife for sample removal is less precise and may damage the carcass or primal. Using a scalpel blade is more precise and less destructive but can be time consuming. The coring device is fast and precise, allowing for consistent sampling that leaves minimal damage on the carcass. Combining a coring device with a cordless drill (Figure 4.1) is one the most effective methods for sample collection. PIC recommends including skin on the sample, since this gives a reference point for sample analysis, especially to consistently measure the same fat layer(s).

Figure 4.1 Coring device mounted on a drill to collect fat samples



For population characterization, sampling should represent the population. Do not collect samples from extremely light or heavy carcasses, and don't collect samples only on the average of the population. Sampling should occur within two standard deviations of the mean weight to account for variation. Sex should also be equally represented in the sampling. It is also generally acceptable to only collect one sex in all the sampling, but this needs to be accounted for when making comparisons to other mixed or opposite-sex data.

The next factor to be considered is the number of samples to collect. IV varies from pig to pig and is characterized by a high standard deviation. In most commercial populations, the standard deviation ranges from 2.4 to 4.0 IV units. Many consider a 1.0 IV-unit change to be of practical importance, so it is essential to be able to detect a 1.0-unit change with statistical validity.

Table 4.1 provides the statistically detectable difference depending on the standard deviation of the population and the sample size. From this table, when a sample size of 80 is used, the detectable difference between the analyzed groups ranges from 1.1 to 1.6 IV units, depending on the standard deviation. Based on this table, 80 samples would be on the lower threshold of samples needed to obtain statistically valid results, again depending on the standard deviation.

Table 4.1 Detectable difference in IV (body of table) based on sample size and IV standard deviation

	IV standard deviation				
Sample size	**2.50**	**2.75**	**3.00**	**3.25**	**3.50**
10	3.1	3.5	3.8	4.1	4.4
20	2.2	2.4	2.7	2.9	3.1
40	1.6	1.7	1.9	2.0	2.2
80	1.1	1.2	1.3	1.4	1.6
100	1.0	1.1	1.2	1.3	1.4
150	0.8	0.9	1.0	1.1	1.1
200	0.7	0.8	0.8	0.9	1.0
250	0.6	0.7	0.8	0.8	0.9
500	0.4	0.5	0.5	0.6	0.6
1000	0.3	0.3	0.4	0.4	0.4

The other aspect to consider is how the data sets will be compared. If different processing weeks are compared to detect change, a minimum of 80 samples per week would need to be collected. However, if different months are compared to detect change, at least 20 samples per week would need to be collected.

4.1.2.2 Fat Color

Higher levels of polyunsaturated fatty acids result in higher IV levels and reduced fat firmness. This can cause an increase in beta-carotene, which changes the fat from a white color to a yellowish color. Thus, color assessment of the fat can indicate fat firmness.

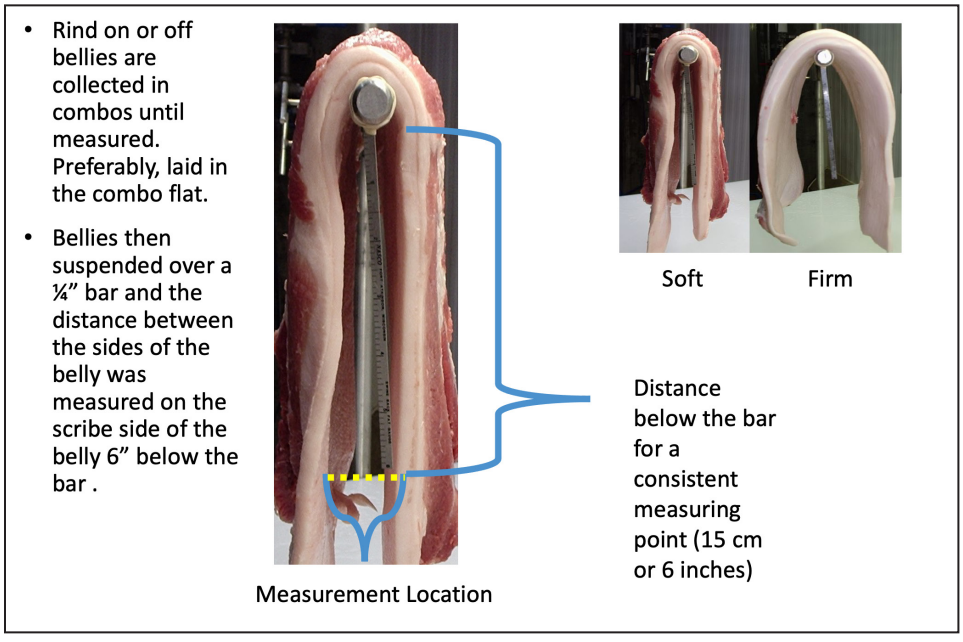
Fat color can be determined objectively using a colorimeter to determine CIE L* a* b* values, with lower L* and higher b* values indicating the fat is less firm. A subjective scoring system that uses Japanese color standards (Figure 4.2) can also determine fat color. The Japanese pork fat color standard is a 4-point system, with 1 being white and 4 being a yellowish/tan color. While the Japanese color standards can be purchased online at (http://hamukumi.lin.gr.jp/color_standard.html), they may be difficult to buy without assistance from a Japanese party to facilitate the purchase.

Figure 4.2 Japanese fat color standards

4.1.2.3 Primal Measurements of Firmness/Fat Quality

Most primal assessments are conducted on the belly, but some have been developed for loins and butts. The most common objective measure of belly firmness is belly flop or bend. Many different variations of this method exist, but the basic premise is to drape a belly over a bar and determine how much it droops on each side of the bar. Distance can be measured between the ends of the belly or at a standardized distance below the bar (Figure 4.3). It is important to place bellies flat prior to measurement and not fold them before putting them on the bar.

Figure 4.3 Belly flop/bend measurement



Under this same premise, numerous proprietary, subjective scoring systems have been developed to measure belly or loin firmness by holding the primal and bending it. These methods are crude but can separate good vs. bad fat quality for these primals. Assessments have also been developed to evaluate butt firmness, which is based on how well the butt holds its shape.

For all the fat quality measuring methods listed above, it is imperative to maintain a constant temperature of the products being evaluated, because fat is generally firmer at lower temperatures than at higher temperatures.

Other measurements that are sometimes used include belly weight/yield and belly thickness. Heavier, higher-yielding bellies will typically be firmer unless they are considerably leaner. Belly thickness is often associated with firmer bellies, since thicker bellies tend to be fatter and heavier.

4.1.2.4 Bacon Slice Yields

Bacon slice yield tests are often conducted to determine the economic consequences of poor fat quality. These slice yield tests are normally conducted in commercial conditions and evaluate the weight yield of the different bacon categories. These tests are not easy to conduct, since tracking individual bellies in a commercial slicing environment is difficult. Thus, these tests are typically conducted in groups or batches of multiple bellies.

Processing conditions, such as the temperature of the bellies at slicing and pump percentage, can also impact fat quality validation. For instance, if a belly is poorly chilled and/or over pumped, it will have a poor slice yield whether the fat is firm or soft. While slice yield tests are difficult to conduct and are not a routine fat quality assessment, they are useful to evaluate the economic implications of changing pigs' diets to improve fat firmness.

4.2 Factors Influencing Fat Quality

Many factors can contribute to fat composition and quality, including genetics, diet, nutrition, carcass composition, age, body weight, gender, anatomical fat location, and growth rate. Of these, nutrition is the key factor that can quickly influence fat quality. This section will review the factors that influence fat quality.

4.2.1 Biology of Fat Quality

An understanding of fat chemistry is essential to understanding the factors that affect basic fat quality. Fat is composed of several components, including fat (triglycerides, or the combination of glycerol and fatty acids), water, and protein. Fatty acids can be classified into three categories based on their chemical structures or saturation level: 1) saturated fatty acids (no double bonds), 2) monounsaturated fatty acids (1 double bond), and 3) polyunsaturated fatty acids (2 or more double bonds) (Figure 4.4). The saturation of fatty acids dictates the melting point of a fat (firmness). A highly saturated fat (firmer) has a higher melting point than an unsaturated fat (softer) (Figure 4.5).

Dietary fats and carbohydrates are the sources of long-chain fatty acids for synthesis of fats in mammals. Dietary fats are readily converted to carcass fat. Carcass fat formed this way takes the general characteristics of dietary fat (soft dietary fat = soft carcass fat). It is often said, "a pig is what it eats."

Dietary carbohydrates are converted to body fat through a process called de novo fatty acid synthesis. This forms saturated and monounsaturated fatty acids, which yield firmer carcass fat (lower fat IV). Although dietary carbohydrates are used to synthesize fatty acids, most mammals, including pigs, are not able to incorporate a double bond past the Δ9 position in a de novo synthesized fatty acid. Thus, pigs can only form saturated and monounsaturated fatty acids from carbohydrates. They require essential fatty acids (polyunsaturated fatty acids such as linoleic acid) from a dietary fat source to incorporate polyunsaturated fatty acids into the fat composition of the carcass.

Figure 4.4 Fatty acid classification

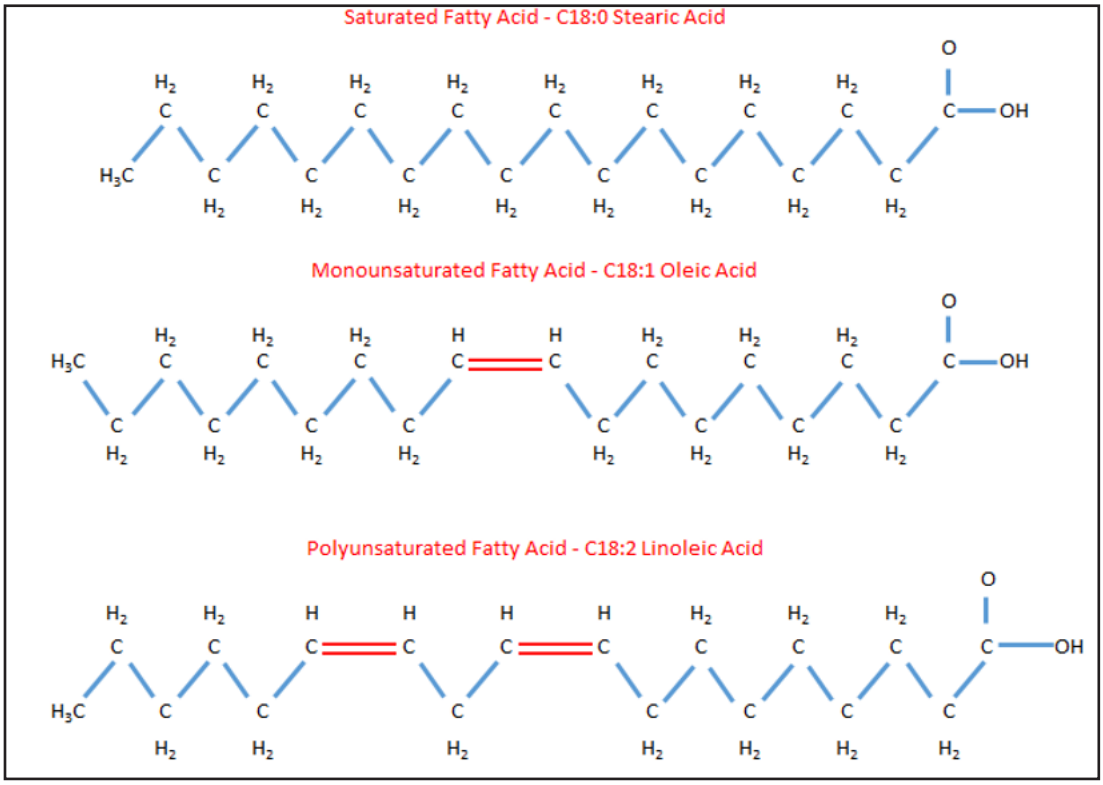
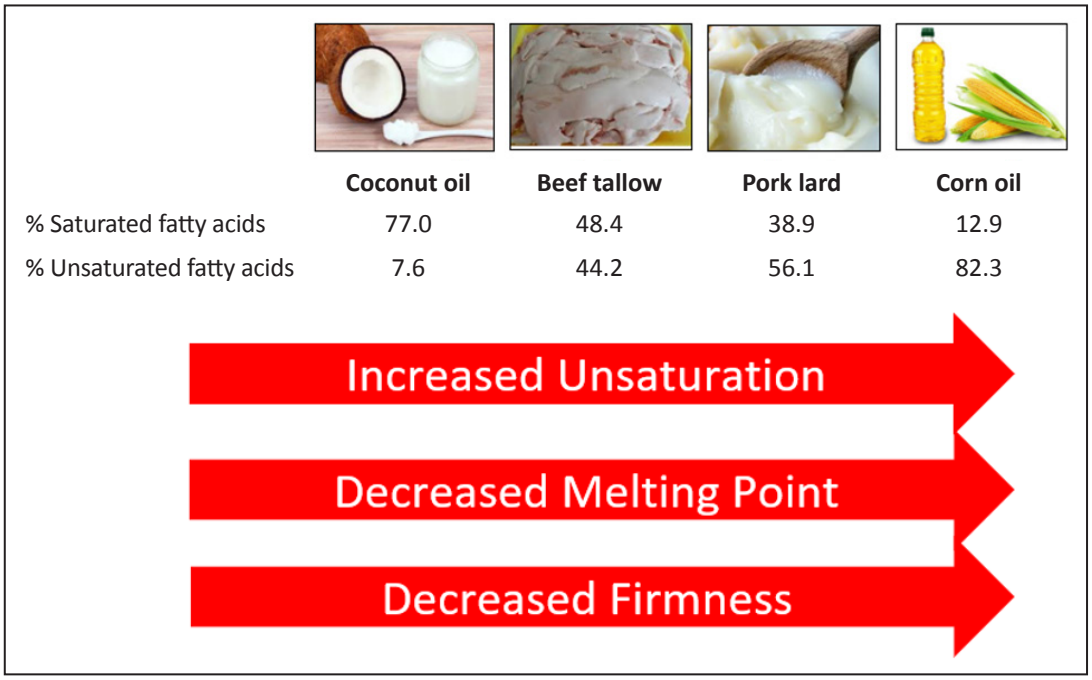


Figure 4.5 How fatty acid composition affects physical properties of various fats



	Coconut oil	Beef tallow	Pork lard	Corn oil
% Saturated fatty acids	77.0	48.4	38.9	12.9
% Unsaturated fatty acids	7.6	44.2	56.1	82.3

Dietary fat additions will alter or even shut down de novo fat synthesis. As the percentage of fat in the diet increases, this further inhibits de novo fatty acid synthesis, resulting in less saturated fat deposition (softer). As the fatty acid profile of dietary fat becomes less saturated (softer), pig body fat (and carcass fat) also becomes less saturated.

The fatty acid profile in pig fat can vary greatly. Table 4.2 contains an average fatty acid profile with variance components of more than 16,000 pigs from a single production system. These numbers show that pig fat is variable and is influenced by many factors.

Table 4.2 Average and variation of fatty acids and IV from a single production system[a]

Item	Average	Minimum	Maximum	STDev
C14:0	2.24	1.06	6.96	0.50
C16:0	24.60	18.79	33.65	1.84
C16:1	3.27	1.35	8.26	0.75
C18:0	8.10	3.57	15.87	1.37
C18:1	40.71	27.44	50.41	2.85
C18:2	16.87	5.88	31.67	3.52
C18:3	0.91	0.06	2.15	0.28
IV	69.67	57.64	90.02	4.99

[a]Data are derived from 16,600 pigs fed a predominantly corn soybean meal diet with added fat and by-products (i.e. DDGS). Ratios of these ingredients were not constant and changed over time.

4.2.2 Non-Nutritional Effects on Fat Quality

Research shows that pig genotype influences fat firmness. Heritability estimates (proportion of the total phenotypic variation in a population for a trait that is attributable to the additive effect of the genes) have been reported for several fatty acids. This indicates there is genetic variation for fatty acid composition and fat quality (Table 4.3).

Table 4.3 Heritability estimates of fatty acids (Suzuki et al., 2006)

	Heritability Estimates[a]			
Fatty acid	OSF	ISF	INMF	ITMF
C14:0	0.07	0.15	0.18	0.09
C16:0	0.50	0.30	0.79	0.32
C16:1	0.20	0.36	0.22	0.20
C18:0	0.54	0.51	0.51	0.40
C18:1	0.26	0.28	0.44	0.36
C18:2	0.44	0.32	0.39	0.44
Melting point	0.56	0.61	-	-

[a]OSF = outer subcutaneous fat; ISF = inner subcutaneous fat; INMF = inter-muscular fat; ITMF = Intramuscular fat.

Some of the fatty acids (C16:0, C18:0, C18:1, and C18:2) and the melting point of fat have been found to have low (<0.20), moderate (0.20-0.40) or high (>0.40) heritability. Although differences between genotypes exist, most of the difference due to fat firmness between genotypes can be attributed to the fatness of the genotype. As the degree of fatness increases, the fat typically becomes more saturated or firmer.

This is consistent with fatter pigs having more de novo fat synthesis, which leads to a greater proportion of saturated fatty acids. For example, the difference between lean and obese pigs (selected for either lower or higher levels of backfat thickness derived from the same population of pigs) has a dramatic effect on fatty acids. This equates to around 9 IV-units difference (Figure 4.6). Other research has found similar results when comparing genetic lines having different fatness/leanness levels (Table 4.4), or when assessing the effect of backfat on iodine value (Figure 4.7).

Figure 4.6 Effect on fat IV when selecting for lean vs. obese within a common line to develop two divergent lines (Scott et al., 1981)

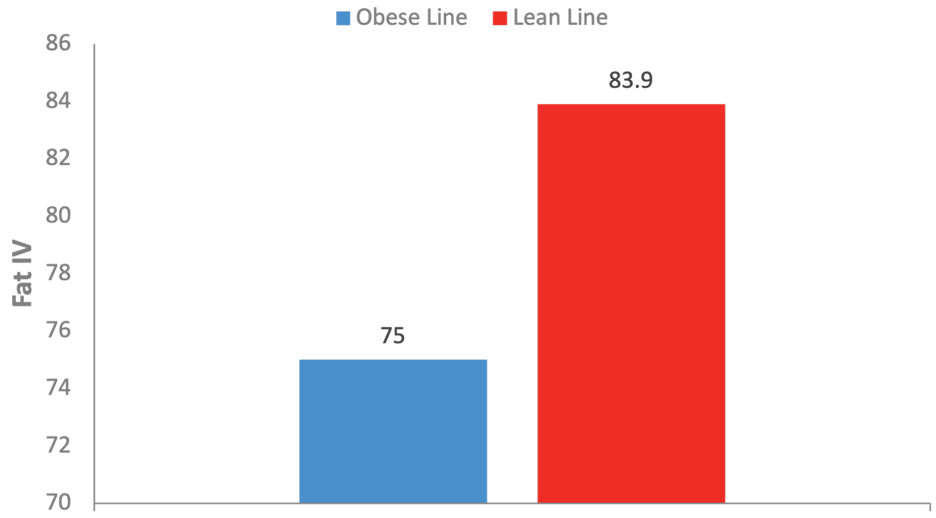
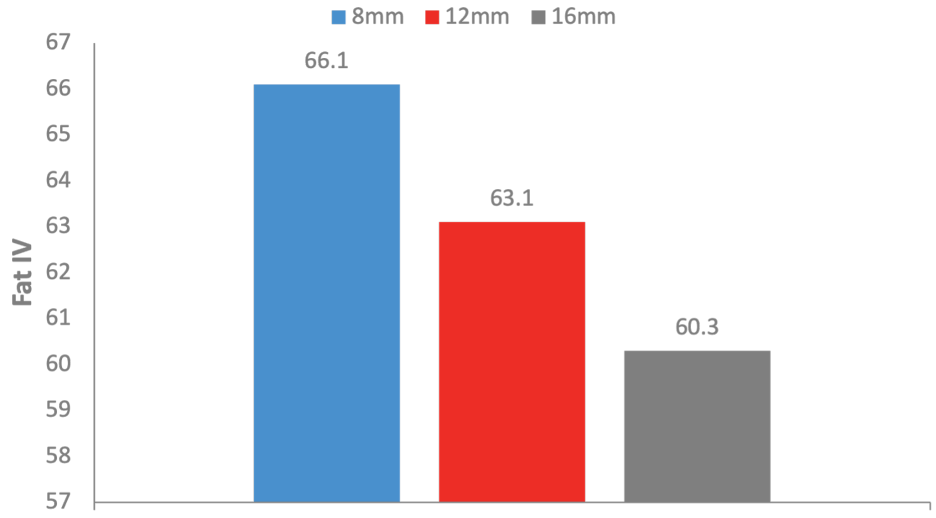


Table 4.4 Effect of breed on IV

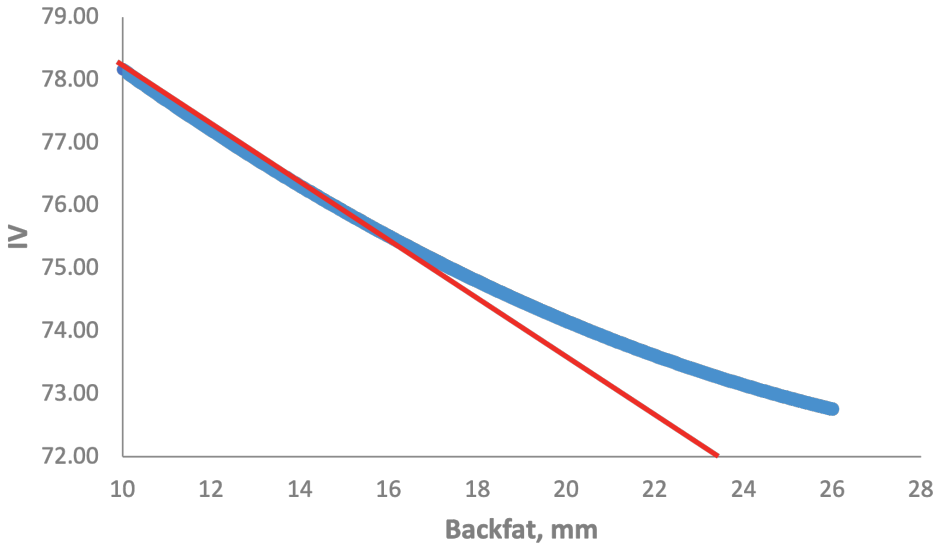
Trait	Lo Fiego et al., 2005		Barton-Gade, 1997		
Breed	L X LW	Hybrid	LW	Duroc	Hamp
Carcass weight, kg	134.9	132.0	68.5	67.3	71.8
Backfat thickness, mm	39.48	29.22	-	-	-
Lean Percentage, %	-	-	54.3	56.0	56.8
Iodine Value	65.2	69.7	61.0	66.0	66.0

Figure 4.7 Effect on back fat level on fat IV (Ellis and McKeith, 1999)



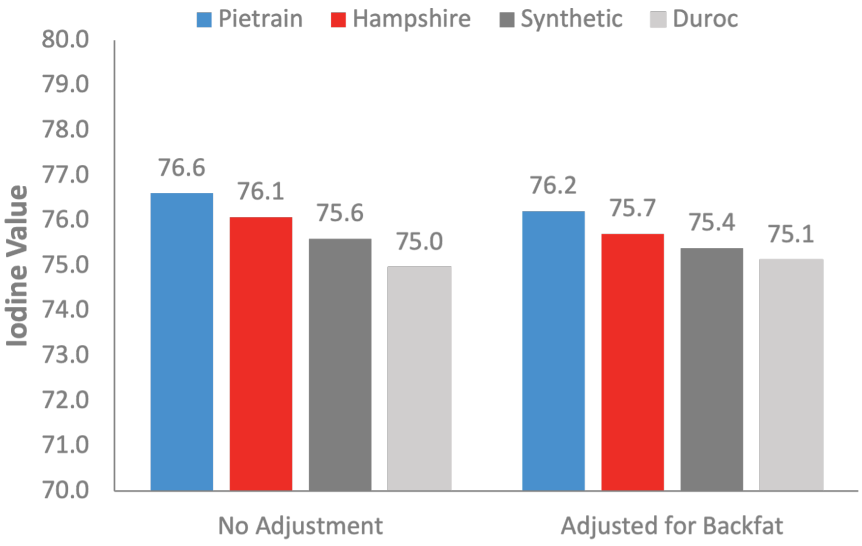
PIC's research indicates a curvilinear decrease in IV as the back-fat level increases (Figure 4.8). The iodine value decreases linearly until about 18 mm of back-fat thickness. Then the rate of decline slows as backfat increases above 18 mm.

Figure 4.8 Effect of backfat thickness on IV (Matthews et al., 2018)



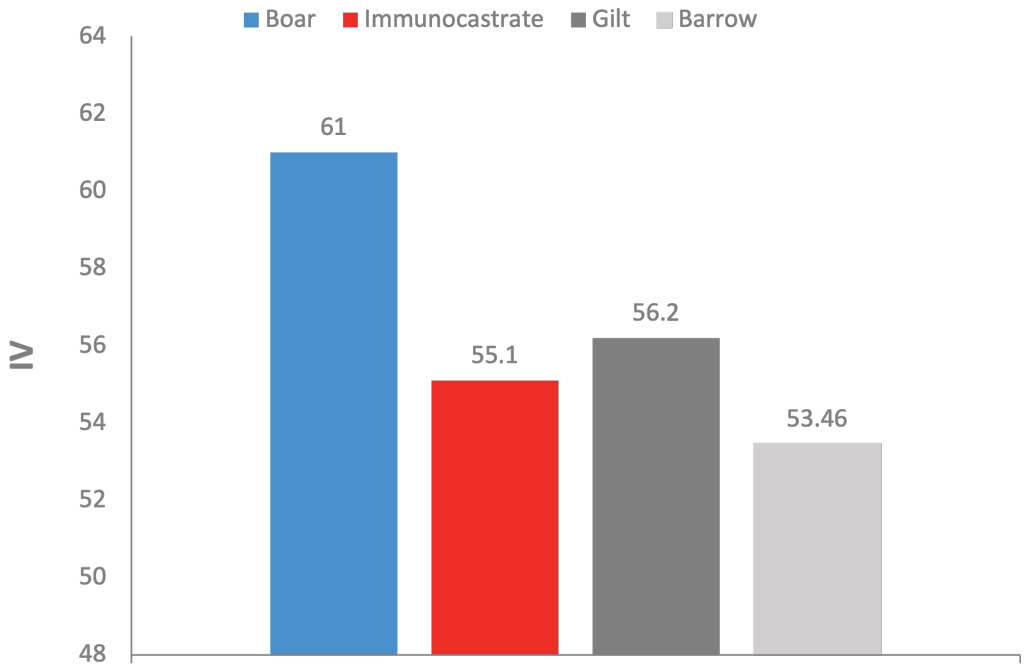
The difference in fat firmness between most modern genetic lines should be minimal, assuming comparisons are made on animals with similar backfat levels (or % lean), live weights, or nutritional formulations. When comparing PIC sire lines, the difference between the Pietrain and Duroc, which are two extremes in the mainstream industry, is about 1.6 IV units when pigs were fed the same diet and reared in the same environment, with no adjustments made for backfat thickness (Figure 4.9). When these data were adjusted for backfat thickness, the difference was only 1.1 IV units between the Pietrain and Duroc.

Figure 4.9 Effect of sire line on fat IV



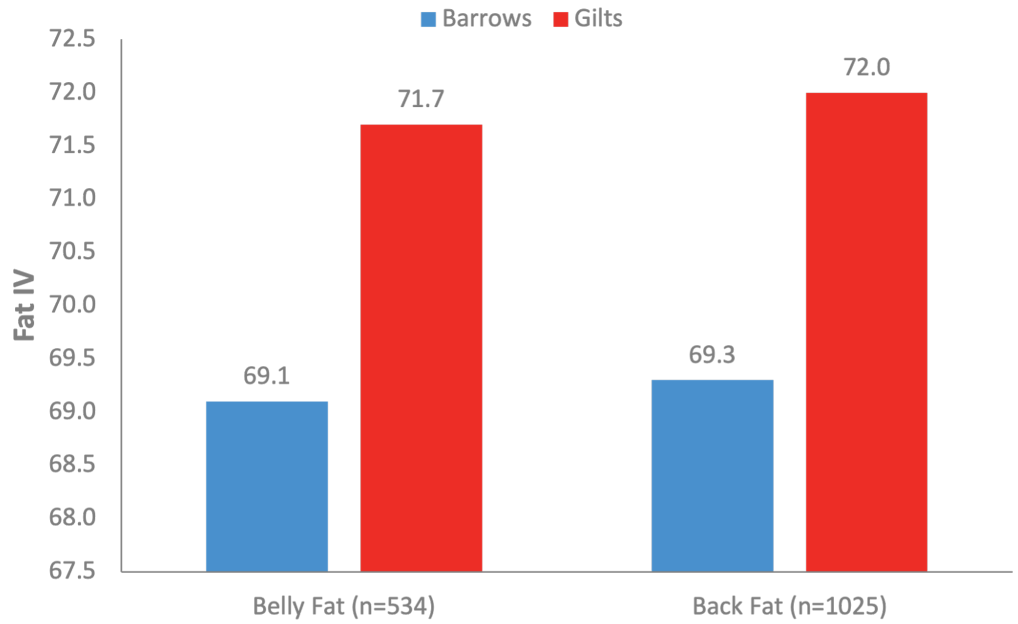
Since the level of fatness plays a large role in fat firmness, it is expected that sex of the pig also will influence fat firmness. Boars have the highest IV, followed by gilts. Barrows have the lowest IV, with immune-castrated boars being comparable to gilts (Figure 4.10). PIC research indicates a difference of 2.6 IV units in the belly fat, or 2.7 IV units in the backfat when comparing barrows vs. gilts (Figure 4.11). This is consistent with many other reports in the literature. It is important to note that the difference between sexes is larger than the difference between the genetic lines previously mentioned.

Figure 4.10 Effect of sex on back fat IV (Grela et al., 2013)[a]



[a] IV was calculated from the fatty acid values in the report thus no statistics are provided.

Figure 4.11 Effect of sex (barrows vs gilts) on fat IV (Matthews et al., 2014)

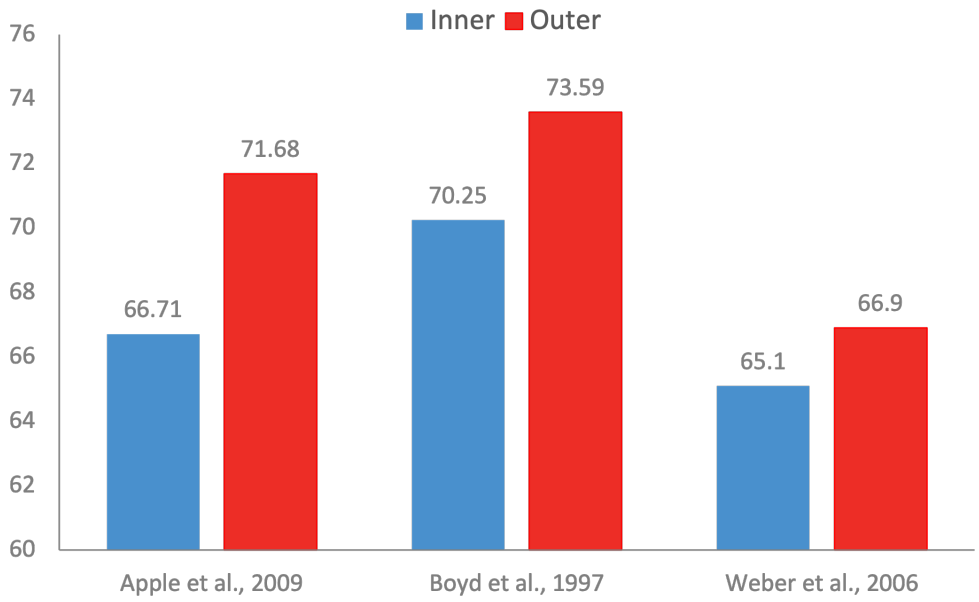


Anatomical location of the fat can also influence its firmness. Typically, fat is sampled from the belly, backfat, or jowl when accessing iodine values. Jowl fat IV is normally higher than the levels observed in belly fat or backfat, but belly and backfat IV levels do not vary enough to be consistently differentiated from one another.

Although jowl fat has a higher IV, many researchers report that jowl fat IV is not changed as much as fat in the belly or backfat when nutritional interventions are implemented to improve IV levels. PIC research concludes that jowl fat IV has a lower standard deviation than that of belly fat IV. The differences between barrows and gilts are less when measured in jowl fat vs. belly fat.

Differences in IV are also evident when comparing the individual fat layers of backfat. The inner fat layers have an IV lower than that of the outer fat layers (Figure 4.12). Given these differences, it is important to consistently measure IV in a single location when benchmarking.

Figure 4.12 Effect of back fat layer on fat IV[a]

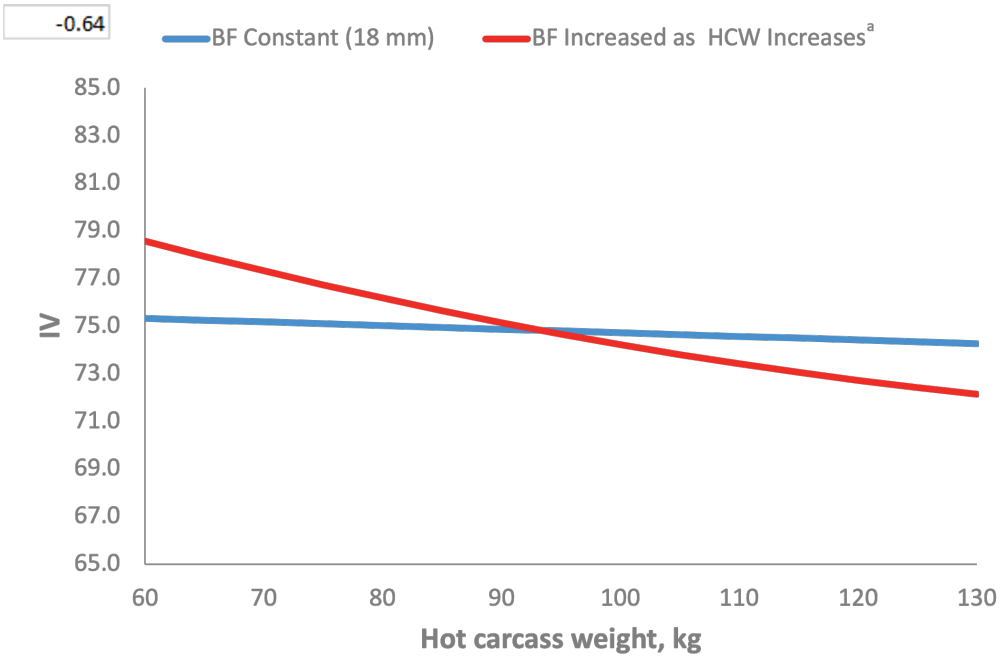


[a] The data for Apple et al., 2009 analyzed 3 back fat layers (inner, middle, and outer), while that of Boyd et al., 1997and Weber et al., 2006 only measured 2 layers (inner and outer). For the purpose of this comparison the middle layer in the data of Apple et al., was used as the inner layer to be consistent with the other researchers as the "true" inner layer is often non-existent or a small proportion of the backfat layers.

It has long been accepted that increasing age/weight of the pigs influences fatty acid composition. From 70 to 220 days of age, saturated fatty acids increase, and unsaturated fatty acids decrease, indicating that fat becomes firmer as pigs age. Some research indicates little difference in fatty acid composition from 107 to 125 kg (236 to 276 lbs.), but other research reports that fat firmness improves with increasing weight up to 159 kg (350 lb).

PIC research shows that if backfat is held constant, carcass weight has a minimal effect on fat IV (Figure 4.13). However, we expect backfat to increase as hot carcass weight increases (≈1.2 mm per 5 kg). Therefore, IV decreases as hot carcass weight increases. Because of the curvilinear response of IV to backfat thickness, the reduction in IV with increased carcass weight is greater at lighter weights (≈0.10 IV units decrease per kg carcass weight increase from 60 to 100 kg), than at heavier weights (≈0.07 IV units decrease per kg carcass weight increase from 100 to 130 kg).

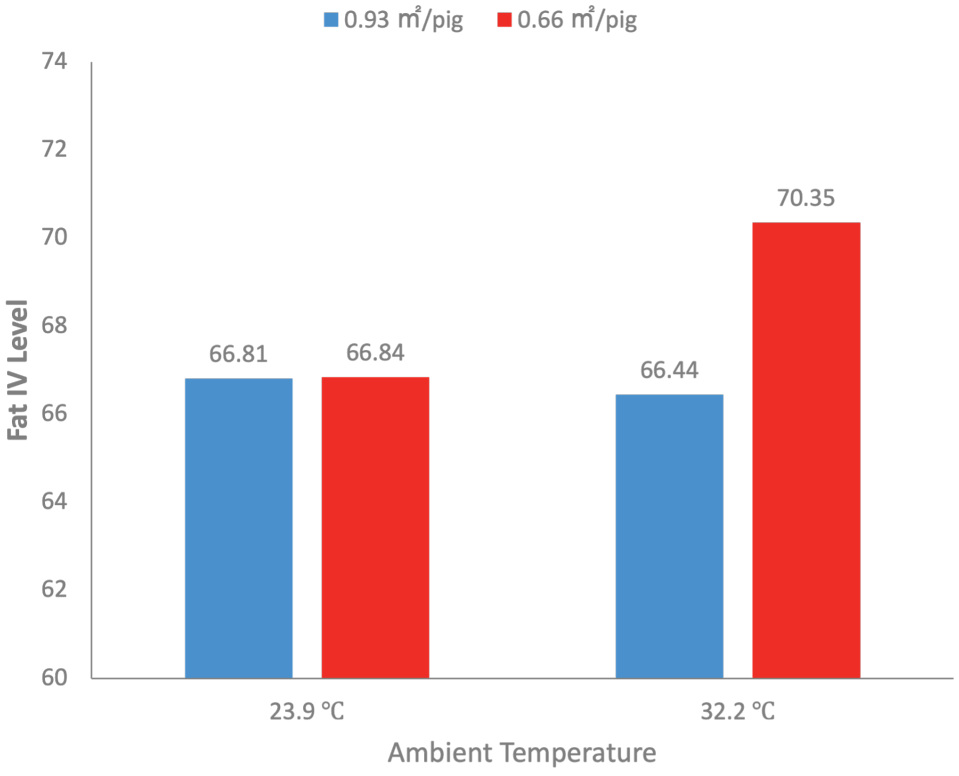
Figure 4.13 Effect of hot carcass weight on IV (Matthews et al., 2018)



[a] Assumes that backfat increases by 1.2 mm for every 5 kg increase in hot carcass weight.

Other factors that may influence fat quality include pig health status or general environmental conditions where pigs are raised. Heat stress increases the IV of belly fat when pigs are reared at higher stocking densities (Figure 4.14). Anecdotal evidence indicates that slower growing, sick pigs often have a higher IV than faster growing, healthy pigs. This may be connected to a reduction in de novo fatty acid synthesis in the slower growing pigs.

Figure 4.14 Effect of heat stress on belly fat IV (White et al., 2008)



4.2.3 Nutritional Effects on Fat Quality

Diet is critical to the development of fat quality. The literature is filled with research evaluating dietary fat sources, inclusion levels of fat sources, and feed ingredients that can potentially affect fat quality.

Adding any feed ingredient that is a source of fat will affect the quality of the fat in two ways. First, as the fat level increases, de novo fatty acid synthesis (saturated fatty acids) decreases. Secondly, the fatty acid profile of the fats in the ingredients affects the fatty acid profile. This means feeding a high-fat diet with a highly unsaturated fatty acid profile results in soft fat, while feeding a low-fat diet with a more saturated fatty acid profile results in firm fat.

By-products such as dried distiller's grains (DDGS), which concentrate or increase fat levels, can have a negative effect on fat quality if inclusion rates are too high or if they are combined with other ingredients with high fat levels. Adding fat ingredients (oils, choice white grease, tallow) has an increasingly negative effect on fat quality, especially if the overall dietary fat level is increased (i.e., added in addition to other fat sources). Also, since these fat sources have different fatty acid profiles (oils are unsaturated, while beef tallow is more saturated), adding them at the same percentage in the diet creates different effects.

Additionally, the form (pelleted vs. meal) of the diet can affect fat quality. Research shows that pelleting the diet can increase belly fat IV by 1.3 to 3.1 IV units (2.4 average IV unit increase: Table 4.5). This may be due to increased fat digestibility from the heat treatment used during the pelleting process, which has been shown to improve nutrient availability.

Table 4.5 Effect of diet form on belly fat IV

Study	Meal	Pellet	Difference
Overholt et al., 2016	70.0	73.1	3.1
Nemechek et al., 2015	70.7	73.6	2.9
Nemechek et al., 2015	72.2	73.5	1.3
Matthews et al., 2014	69.2	71.6	2.4
		Average difference	**2.4**

Some dietary additives like conjugated linoleic acid (CLA), kapok oil, and Lipinate® (NutriQuest®, Mason City, IA) have demonstrated improvements in fat firmness. These products add cost to the diet, which need to be balanced against the fat quality benefits. Some sources of beef tallow can have native CLA, which can improve fat quality. Adding beef tallow to a diet can improve fat quality, or at least reduce the negative effects as dietary energy increases.

The addition of ractopamine has been shown to have a negative effect on fat quality (Table 4.6). The addition of ractopamine increased fat IV from 1.0 to 3.7 IV-units (1.8 IV-unit average increase). This effect is expected, since ractopamine reduces fatness of the carcass, and leanness/fat level is highly correlated with fat quality.

For the most part, nutritional effects on fat quality align with general fat biology principles related to dietary fat. As the percentage of fat increases in the diet, de novo fatty acid synthesis is further inhibited, resulting in less saturated/softer fat. As the fatty acid profile of dietary fat becomes less saturated/softer, carcass fat becomes less saturated/softer. When fat quality is important, evaluate any nutritional change to determine if it will negatively impact fat quality.

Table 4.6 Effect of ractopamine on fat IV from different carcass locations

Study	Fat location	Ractopamine level	Average Duration	Control	Paylean	Difference
Apple et al., 2008	Backfat	10 ppm	35 days	72.7	75.5	2.8
Graham et al., 2014	Belly	10 ppm	24 days	65.4	66.4	1.0
Graham et al., 2014	Jowl	10 ppm	24 days	65.4	66.4	1.0
Matthews et al., 2014	Backfat	5 ppm	23 days	69.9	71.5	1.6
Matthews et al., 2014	Belly	5 ppm	23 days	69.8	71.0	1.2
Weber et al., 2006	Backfat[a]	10 ppm	28 days	62.5	67.6	3.7
Weber et al., 2006	Belly	10 ppm	28 days	59.0	60.2	1.2
					Average difference	**1.8**

[a]Average of inner and outer backfat.

4.3 Managing Fat Quality

Pig nutrition is the most important factor in managing fat quality. Although the non-nutritional factors that affect fat quality are also important, making changes in non-nutritional factors tends to have a minimal effect. Additionally, these changes are often impractical to implement. Changing genetic lines is not practical, since the maximum IV difference would be ≈1.5 IV units within the modern genotypes being used. Sex differences, for the most part, cannot be changed, unless one is able to forego rearing boars or using barrows only to target a specific product mix with good fat quality.

Live weights can be increased if coinciding with increased fatness, as long as the increased fatness and weight are not detrimental to the pig or pork production efficiency. Ensuring a good health status in pigs and helping pigs avoid heat stress are the most important factors we can manage from a non-nutritional standpoint.

The importance of nutrition is best exemplified by the volume of research focused on dietary influences on fat quality vs. research into non-dietary effects on fat quality. Using nutrition to manage fat quality is carried out through three factors, including diet formulation, diet form, and inclusion of specific micro ingredients that affect fat quality.

4.3.1 Diet Formulation to Improve Fat Quality

Nutritionists take many different approaches to formulate diets to meet specific fat quality requirements, but the two most prevalent are formulating to a specific C18:2 level, and formulating based on the iodine value product (IVP).
Formulating to a specific C18:2 level can be effective if standard ingredients are used, and other polyunsaturated fatty acids are not changed significantly. However, formulating with IVP accounts for the common mono- and polyunsaturated fatty acids found in pig diets.

IVP is calculated using the formula: *IVP = (iodine value of the feed source fat) X (% of fat in the feed source) X 0.10. Table 4.7* contains IV, level of fat, and IVP of selected dietary ingredients. Table 4.8 contains IV, level of fat, and IVP of selected fat sources used in pig diets.

Table 4.7 Iodine Value (IV), percentage of fat, and Iodine Value Product (IVP) of common feed ingredients

Ingredient	IV[a]	% Fat[a]	IVP[b]
Bakery waste	125	11.3	141.3
Barley	125	1.9	23.8
Canola meal	118	3.5	41.3
DDGS	125	9.9	123.8
DDGS high protein	125	3.4	42.5
Corn germ	125	17.5	218.8
Corn gluten meal	125	2.9	36.3
Corn	125	3.9	48.8
Corn high oil	125	6.0	75.0
Corn hominy	125	6.7	83.8
Meat and bone meal	70	10.1	70.7
Meat meal	70	11.2	78.4
Millet	135	3.5	47.3
Oats	106	4.7	49.8
Oat groats	106	6.2	65.7
Peas	135	1.2	16.2
Sorghum	116	2.9	33.6
Soy hulls	130	2.2	28.6
SBM 47.5% CP	130	3.0	39.0
SBM 46.5% CP	130	3.0	39.0
SBM 44% CP	130	1.5	19.5
Full fat soybeans	130	18.0	234.0
Sunflower meal, 42% CP	120	2.9	34.8
Triticale	87	1.8	15.7
Wheat bran	83	4.0	33.2
Wheat hard red winter	83	2.0	16.6
Wheat midds	83	4.2	34.9

[a]IV levels and % fat levels were obtained from the National Swine Nutrition Guide 2009.

[b]Determined using the following equation: (IV x %fat x0.1).

Table 4.8 Iodine Value (IV), percentage of fat, and Iodine Value Product (IVP) of common fat sources added to diets

Ingredient	IV[a]	% Fat[a]	IVP[b]
Beef tallow	44.0	99	435.6
Canola oil	118.0	100	1180.0
Coconut oil[c]	8.0	99	79.2
Choice white grease	60.0	99	594.0
Corn oil	125.0	100	1250.0
Palm oil[c]	13.0	99	128.7
Poultry fat	78.0	99	772.2
Soy lecithin[c]	97.0	100	970.0
Soy oil	130.0	100	1300.0
Sunflower oil[c]	114.0	100	1140.0

[a]Unless noted, IV levels and % fat levels were obtained from the National Swine Nutrition Guide 2009.

[b]Determined using the following equation: (IV x %fat x0.1).

[c]IV levels were obtained from the NRC (2012).

To formulate based on IVP, add IVP as a nutrient for each ingredient that contains a fat source and set nutrient constraints on IVP in the formulation software. The constraints placed on IVP depend on the desired IV in the carcass fat. Formulas were developed that estimate the iodine value of carcass fat based on the iodine value product of the diet, as well as C18:2 levels and levels of DDGS. More complex equations include factors such as essential fatty acids, energy concentration, feeding duration, body weight, carcass weight, daily feed intake, and backfat thickness. (Table 4.9).

PIC developed the following equation [*Predicted Fat IV = 52.4 + (0.315 x* Diet IVP)] (Boyd et al., 1997) for all predicted fat IVs within this document. Most of these equations are accurate within the population/environmental conditions for which they were developed. When used outside of those parameters, they lose accuracy due to nutrient digestibility, health status, environmental conditions, differences in sampling or laboratory procedures, sex differences, or fatness of the carcass.

The least accurate of these equations are those that only account for DDGS in the diet, since oil content and digestibility of DDGS can vary greatly. Also, not all diets include DDGS. Furthermore, other ingredients could be added at varying concentrations that can affect the diet as much as DDGS.

Gigure 4.15 contains IVPs for late finishing diets from three university trials that were calculated using the diet compositions provided in each trial. This figure illustrates that although the diets used similar levels of DDGS, the effect on fat quality may be different as a result of other dietary ingredients that influence the IVP. This shows the fallacy of using an equation which only accounts for DDGS.

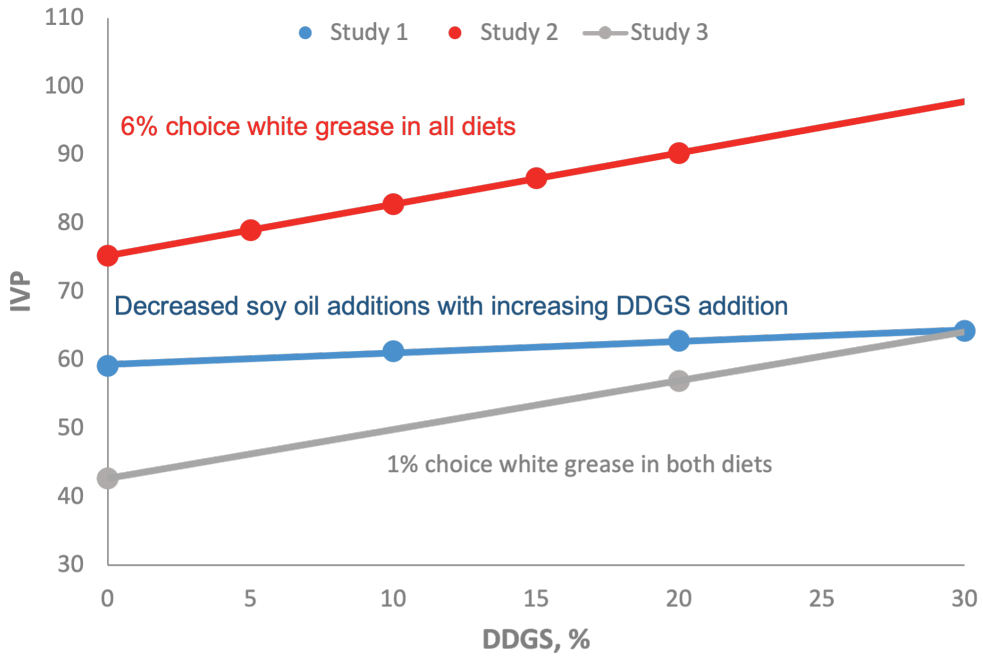
Table 4.9 Equations to predict carcass fat iodine value

Equation Type	Reference	Prediction Location	Equation	R2
IVP	Madsen et al., 1992	Backfat	47.1 + 0.14 × IVP intake/d	0.86
IVP	Boyd et al., 1997	Backfat	52.4 + 0.315 × Diet IVP	–
IVP	Benz et al., 2011	Backfat	51.946 + 0.2715 × Diet IVP	0.16
IVP	Benz et al., 2011	Jowl Fat	56.479 + 0.247 × Diet IVP	0.32
IVP	Estrada Restrepo, 2013	Backfat	60.13 + 0.27 × Diet IVP	0.81
IVP	Estrada Restrepo, 2013	Jowl Fat	64.54 + 0.27 × Diet IVP	0.81
IVP	Estrada Restrepo, 2013	Belly Fat	58.32 + 0.25 × Diet IVP	0.74
IVP	Kellner, 2014	Averagea	58.102 + 0.2149 × Diet IVP	0.93
C18:2	Benz et al., 2011	Backfat	35.458 + 14.324 × Diet C18:2, %	0.73
C18:2	Benz et al., 2011	Jowl Fat	47.469 + 10.111 × Diet C18:2,%	0.90
C18:2	Kellner, 2014	Average	58.566 + 0.1393 × C18:2 intake/d, g	0.94
DDGS	Cromwell et al., 2011	Backfat	64.5 + 0.432 × DDGS in diet, %	0.92
DDGS	Estrada Restrepo, 2013	Backfat	70.06 + 0.29 × DDGS in diet, %	0.81
DDGS	Estrada Restrepo, 2013	Jowl Fat	72.99 + 0.24 × DDGS in diet, %	0.81
DDGS	Estrada Restrepo, 2013	Belly Fat	67.35 + 0.26 × DDGS in diet, %	0.75
Complex	Paulk et al., 2015	Backfat	84.83 + (6.87 × I EFA) – (3.90 × F EFA) – (0.12 × I d) – (1.30 × F d) – (0.11 × I EFA × F d) + (0.048 × F EFA × I d) + (0.12 × F EFA × F d) – (0.0060 × F NE) + (0.0005 × F NE × F d) – (0.26 × BF) b	0.95
Complex	Paulk et al., 2015	Jowl Fat	85.50 + (1.08 × I EFA) + (0.87 × F EFA) – (0.014 × I d) – (0.050 × F d) + (0.038 × I EFA × I d) + (0.054 × F EFA × F d)- (0.0066 × I NE) + (0.071× I BW) – (2.19 × ADFI) – (0.29 × BF) b	0.93
Complex	Paulk et al., 2015	Belly Fat	106.16 + (6.21 × I EFA) – (1.50 × F d) – (0.11 × I EFA × F d) – (0.012 × I NE) + (0.00069 × I NE × F d) – (0.18 × HCW) – (0.25 × BF) b	0.94

[a]Average = the average of jowl, back, and belly fat.

[b]Components of the equations are as follows: I = initial diet, F = final diet, d = days of diet fed, EFA = essential fatty acids (C18:2 and C18:3; %), NE (kcal/kg), BW (kg), ADFI (kg), HCW (kg), and BF = backfat depth (mm).

Figure 4.15 Effect of percentage DDGS on IVP with varying diet compositions



Although the IVP is not perfect in predicting carcass fat IV, it is an excellent monitoring tool if all critical components are in place in a systemic approach. These components include:

- Consistency of Feed Ingredients
  - Ingredients must have a relatively consistent IVP (fat level and IV of fat), or an analysis conducted when new batches of ingredients are received.
  - This is especially important when using ingredients such as DDGS, or when adding a different ingredient supplier or unfamiliar ingredient.
  - The same lab methods are used for measuring fat and IV levels of the feeds.
- Choose a single formula for estimating carcass fat IV and use it consistently.
  - Make sure the equation predicts the fat location that the slaughter plant uses for measurement.
- Continuous feedback from the slaughter plant is essential.
  - Since these equations are not completely accurate, the slaughter plant must routinely provide carcass fat IV analysis to determine if the formulation value for IVP is adequate, or if it needs to be adjusted.
  - The slaughter plant needs to measure the fat IV in a consistent location and use a consistent methodology for analysis.
    - The samples should either have an equal representation of sexes or always sample the same sex.
    - Avoid getting samples from extremely light or heavy pigs but ensure variation around the mean of the population.
- Be aware of any environmental issues aside from nutrition that could affect carcass fat IV. These may include but are not limited to health issues or heat stress.
- Analyze the data.
  - Monitor data using statistical process control measures.
  - Be sure to monitor frequently (weekly or monthly).
    - This allows changes in IVP to be aligned with changes in carcass fat IV levels.
  - Although this methodology is somewhat trial and error in the beginning, in time the accumulated data provide a clearer picture of how to adjust IVP to obtain a specific carcass fat IV.

4.3.2 Diet Form and Use of Micro Ingredients to Manage Fat Quality

As mentioned earlier, pelleting the diet has a negative effect on fat quality. If fat quality is an issue, consider feeding a mash/meal diet, if it is economically feasible and if fat quality cannot be improved through other nutritional aspects. Be aware of the reduced growth performance associated with a mash/meal diet, however, and understand how this affects the overall economics.

Commercially available micro ingredients like CLA and Lipinate® help improve fat quality. In most cases, however, the cost of CLA has prevented wide-scale use in the swine industry. Use micro ingredients like ractopamine or other carcass modifiers (resulting in leaner carcasses) with caution when fat quality is important. Assess the overall economic impact of these products before you decide whether to use them.

Section 5

Sex Effects on Quality

The sex (or gender) of the pigs can influence both lean and fat quality. While some of the effects on fat quality were discussed in Section 4.2.2, the effects on lean quality have not been discussed in previous sections.

It is often difficult to determine the differences between sexes in meat quality based on information in the literature as sex data is not often reported or the sample sizes to determine sex effects are relatively small. In many of the studies with larger sample sizes, the overall quality was poor (ultimate pH < 5.5; drip loss > 5%) which may limit the capability of determining meaningful differences between the sexes. However, based on PIC's large pork quality data base, combined with reviewing the literature and interaction within the industry, we can offer a good perspective on what to expect regarding pork quality differences between the sexes.

Currently, semen sexing is possible from a technical aspect, but not practical or economically feasible from a large-scale production aspect. Thus, based on basic biology of birthrate, we can expect roughly 50% males and 50% females. However, the males may remain intact (boars) or be castrated (barrows) and this is where a decision can be made that may improve the quality of the pork. As the pork industry continues to evolve, the practice of castration without pain management is becoming increasingly scrutinized, with many countries either banning or suggesting the abolishment of castration. This may have an actual or perceived impact on pork quality. This section will discuss these differences.

5.1 Lean Quality Differences Between Barrows, Gilts, and Boars

A literature review indicates the difference in lean quality between barrows and gilts is often inconsistent. Many reports indicate that color is slightly darker in gilts, and barrows consistently have a higher level of intramuscular fat. The responses for ultimate pH, water-holding capacity (drip loss), and shear force (tenderness) are much less consistent.

PIC has high-quality data from thousands of pigs, so the effect of sex on pork quality can be analyzed (Table 5.1). Our data indicate that L*, a*, and b* values were lower (darker, less red, and less yellow) in gilts. Subjective color and firmness scores were not different between barrows and gilts. Barrows had higher ultimate pH and marbling scores, with lower drip loss and Warner-Bratzler shear force (WBS) values. This data, on average, would suggest that loins from barrows have slightly better eating quality than loins from gilts.

Table 5.1 Difference in pork quality trait between barrows and gilts

Trait	Barrows	Gilts	Advantage	Sample Size (Barrows/Gilts)
pH	5.74[a]	5.72[b]	Barrows (0.02 higher)	12817/13167
JCS	3.18	3.19	None	12797/13140
L*	47.21[a]	46.51[b]	Gilts (0.7 lower)	12731/13032
a*	8.54[c]	8.49[d]	Barrows (0.05 higher)	12731/13032
b*	2.34[a]	2.05[b]	Gilts (0.29 lower)	12731/13032
Marbling	2.42[a]	2.12[b]	Barrows (0.30% higher)	12065/12523
Firmness	3.19	3.18	None	9257/9863
Drip loss	2.49[a]	2.61[b]	Barrows (0.12% lower)	7108/7795
WBS	3.26[a]	3.50[b]	Barrows (0.24 kg lower)	3435/3344

[ab]Means with different superscripts were significantly different (P<0.0001).

[cd]Means with different superscripts were significantly different (P<0.005).

Large-scale data sets comparing boars to barrows are more difficult to find. Pauly et al., (2012) conducted a meta-analysis study that compared boars to barrows and immunocastrates. This research indicated that boars had lower ultimate pH, less marbling, higher shear force, and higher L* values. Other traits were not affected.

Most research indicates that the order of best eating quality would be loins from barrows > gilts > boars, with immunocastrates being somewhere between barrows and gilts. This would agree with anecdotal observations heard from slaughter plants that have moved to killing boars instead of barrows. These plants indicate there are more drip-loss complaints from retailers, and higher carcass shrink is also observed (hot carcass weight vs. cold carcass weight). In some markets where only boars or immunocastrates are used, meat from gilts can be sold at a premium.

5.2 Fat Quality Differences Between Barrows, Gilts, and Boars

As previously mentioned in section 4.2.2, boars have the highest IV (softest fat), followed by gilts. Barrows have the lowest IV (firmest fat), and immunocastrated boars' levels were similar to gilts (Figure 4.10).

The firmness of the fat coincides with the degree of fatness. Boars have the least amount of fat, followed by gilts, with barrows having the highest degree of fatness. Before transitioning from barrow to boar production, it is important to understand the impact of the change in fat level and firmness, since this can affect fat quality in some products.

While boars have been reared with no perceived fat quality issues in many regions, this is not the case everywhere when barrow production shifts to boar production. These regions are evaluating ways to increase the fat content and firmness in boars. Some slaughter plants suggest that the effect on fat is more difficult to deal with than boar taint. Depending on the product mix and individual markets the effects on fat should be fully evaluated before moving entirely to boar production.

5.3 Boar Taint

Boar taint is primarily caused by androstenone and skatole, which are found in the fat of pigs. Indole has also been associated with boar taint. Androstenone and skatole are released during cooking, resulting in an unpleasant odor. Intact males have higher levels of androstenone and skatole, along with a higher incidence of boar taint. Boar taint can also be present in females and castrated male pigs.

Not all individuals are sensitive to boar taint. Women are more sensitive to boar taint than men. Research from the 1970s and 1980s suggested that androstenone can be detected by 90% of women and 50% of men, but skatole can be detected by all people. More recent information from the USDA suggests that 30% or more of the population can detect boar taint.

Based on proposed thresholds [androstenone (> 0.5-1.0 mg/kg) and skatole (0.20-0.25 mg/kg)], around 20% of boars would have boar taint. This relationship is variable, though. Pigs with low levels of these compounds may still exhibit boar taint, and pigs with high levels may not exhibit boar taint. Reports based on human nose scoring suggest only about 4% of boars will exhibit boar taint at a detectable level.

Regardless of the low incidence, managing boar taint is critical, since it reduces the eating quality of pork and may decrease favorability of pork as a preferred animal protein. This is especially critical in areas where boar production is not practiced, and the likelihood of exposure to boar taint has been historically low. Boar taint can be managed through three key areas: genetics, farm production management, and slaughter plant management.

5.3.1 Genetic Management of Boar Taint

The levels of androstenone and skatole have been evaluated between different genetic lines, and differences do exist. Frieden et al., 2011 reviewed breed comparison studies within the literature and found that Durocs had the highest levels of androstenone (3.27 µg/g fat). The level of androstenone in Pietrains (and Pietrain crosses) varied with a range of 0.54 to 2.40 µg/g fat. Large white and Landrace androstenone levels were relatively low, with a range of 0.44 to 1.19 µg/g fat.

Furthermore, heritability estimates for androstenone range from 0.50 to 0.75 (high). Estimates for skatole range from 0.23 to 0.56 (moderate to high). These findings suggest that androstenone and skatole can be used as selection criteria in managing boar taint levels.

In 2015, the German 'Warentest' revealed that male offspring of two boar lines with some form of selection against boar taint (levels of androstenone and skatole) had reduced boar taint when compared to boar lines with no selection (2.35% vs. 4.4% with detected boar taint). However, it is unlikely that genetics are the single solution, since many factors influence boar taint.

5.3.2 Farm Production Management of Boar Taint

Many farm factors can be managed to reduce the incidence of boar taint. The easiest, most reliable management practice is castration of the males, which virtually eliminates the risk of boar taint.

In many countries or regions, however, castration is either not an accepted practice, or boars are reared to capture the growth performance advantages over barrows. In lieu of physical castration, many producers have adapted the technology of immunocastration, which takes advantage of the growth performance aspects of boars while limiting the incidence of boar taint. Nevertheless, many factors can be managed on-farm in a boar production system to mitigate the likelihood of boar taint.

Several studies suggest that androstenone levels increase as live weight increases and skatole increases with the onset of puberty. It is a common practice in many countries to slaughter boars at a live weight of 100 kg (220 lbs.) or less. Other areas have a maximum age for boar slaughter as an attempt to minimize boar taint. However, some research did not observe differences due to live weight or age. This may be due to differences in the age or weight at the onset of puberty or other confounding factors.

The level of backfat thickness also affects boar taint, with the incidence rate increasing as the level of back fat increases (Figure 5.1). This could explain some of the differences between breeds, and the reliability of weight and age as an effective tool to manage boar taint.

Much of the research has addressed environmental factors within farm systems to mitigate boar taint It's important to keep pigs clean to reduce levels of boar taint (skatole). Pigs kept in dirty (urine- and fecal-soiled) pens have a higher incidence of boar taint. Pigs kept on solid floors or small, slatted floors have a higher incidence of boar taint than those kept on slat widths that allow the pen to remain relatively clean. High stocking densities also increase the incidence of boar taint. Temperature can also affect levels of boar taint. Skatole levels are typically higher during the warmer summer months.

Researchers have evaluated the social aspects of different production systems, but there is no clear consensus on how it affects the level of boar taint in pork. Recent research with mixed vs. split sex production indicates that mixed-sex production may be slightly better from a boar taint perspective. Establishment and/or reestablishment of social hierarchy due to production practices such as mixing of pigs or split marketing may also negatively affect boar taint by raising androstenone levels.

Nutrition plays an important role in reducing boar taint, especially in reduction of skatole. Adjust diet formulations to reduce the incidence of boar taint. Feeding lower levels of tryptophan, adjusting fiber levels and types, and adding organic acids have all been shown to reduce skatole levels. Many boar producers add non-digestible carbohydrates like chicory, which has been shown to have a positive effect.

Liquid feeding as opposed to dry feeding and adequate feeder space can also reduce skatole levels. Ad libitum feeding has been shown to increase skatole levels, when compared to restricted fed pigs when slaughtered at the same age, but not when pigs are slaughtered at the same weight.

It is clear that a variety of production practices can affect boar taint, and many of these factors are interrelated. While addressing these factors (other than castration) will not eliminate boar taint, taking these factors into consideration can help reduce the risk of boar taint affecting pork quality.

5.3.3 Slaughter Plant Management of Boar Taint

For the most part, slaughter plants are limited to identifying pigs with boar taint, as opposed to mitigating the likelihood of boar taint. The limited management practices include sanitation and segregation. Lairage pens should be kept as clean as possible. Also, avoid mixing unfamiliar pigs in lairage to minimize potential effects on boar taint.

Identifying pigs (carcasses) with boar taint is the top priority once boars are at the slaughter plant. Identifying the boar carcasses with taint allows removal from normal production, so the carcass can be used for products that mask negative effects of tainted pork, such as emulsion-type sausages, diluting the product in sausages, masking the odor, or smoking the product.

One subjective method of detecting boar taint on the line is the hot-iron test. This involves placing a hot iron (soldering iron) on neck fat. Trained individuals are then able to smell the fat and determine the presence and degree of boar taint.

5.4 Immunocastration

Immunocastration (IC) was previously mentioned as a method for mitigating the risk of boar taint. Immunocastration involves an injection of a protein compound that works like an immunization to induce antibody production against gonadotropin-releasing factor hormone (GnRF), which suppresses pigs' sexual development.

Two shots are required for immunocastration. The first shot is a priming dose given after 9 weeks of age that prepares the immune system. The second dose is given at least 4 weeks after the first dose. This dose stimulates the immune response that suppresses testicular development and reduces androstenone and skatole levels.

Pigs should not be marketed sooner than 3 weeks or more than 10 weeks after the second dose, since there is a risk of detecting boar taint outside this marketing window. The second dose needs time to take effect and for the body to clear the hormones from the system. Furthermore, the effects diminish over time.

If shots are administered appropriately in boars, immunocastration is quite effective in eliminating boar taint. The problem arises if a boar fails to receive one of the shots and then is not effectively immunized against GnRF. It is essential to have good vaccination protocols to ensure each boar receives both shots.

One online monitoring method at the slaughter plant for ensuring proper vaccination is evaluating the size of the testes. Testicles will not fully develop in properly vaccinated boars. Any boar with fully formed testes should be further evaluated for boar taint.

Because immunocastration suppresses pigs' sexual development, researchers have also evaluated the effects of immunocastration in gilts. While this is not an approach to control boar taint, it is a tool for managing gilt production in some regions to fit product preferences.

Most commercial gilt immunocastration started in Spain with Iberian pig production. Traditionally, the outdoor-raised Iberian gilts were surgically castrated (spayed), as they were raised to heavier weights (150 kg/330 lb) to prevent the gilts from becoming pregnant. The use of immunocastration effectively eliminates the need for surgical castration and allows for improvements in production and carcass traits for that market. Immunocastrated gilts grow faster, allowing earlier marketing of the high-value products. These pigs are also fatter, which is more desirable in the Iberian pig sector.

The use of immunocastration has also been evaluated and used in conventional commercial production pigs. Currently, live weights are increasing in many regions, which leads to gilts maturing and coming into heat before marketing. This will slow growth rates, lengthening the amount of time to close out a barn.

As a result, many of these producers are looking at the advantages of immunocastrated gilts, whose growth rates are more like those of intact/castrated males. This allows barns to be emptied quicker, which is important when finishing space is limited. Also, because the gilts are fatter and the quality of the fat (firmness) is better, bellies are more suitable for bacon production.

Thus, immunocastration can be an effective tool for producing intact males and females. The use of immunocastration should be evaluated on a case-by-case basis to determine if it is practical and legal to implement and whether it is financially advantageous to the producer.

Concluding Remarks

PIC is proud to play a key role in various global pork supply chains. We are fully committed to the industry's success, via genetic improvement programs and interconnected Technical Services.

The PIC Applied Meat Science Team's Technical Services center around hands-on assistance provided to our customers to develop plant-specific, pork quality assurance programs. We deliver these services through extensive assessments of routine plant operations that impact pork quality, starting from pig pre-slaughter handling and stunning, through carcass chilling practices, to pork quality evaluations.

Furthermore, we have developed the PIC® Pork Quality Compass™, a unique, global, pork quality benchmark that determines plant performance and enables customers to examine pork quality in an objective manner. This benchmark program: (1) provides a system of assessing pork quality where all measurements are standardized across all plants; (2) helps identify areas for improvement; and (3) provides an independent reference for pork processing companies to compare their pork quality on a national or global basis.

We have also developed a PIC sire line-specific Carcass Merit Appraisal tool. This utilizes primal and sub-primal weight distribution data linked to carcass weight to optimize the mix of pork cuts offered for sale and boost processors' profit potential.

For comments and questions, please contact PIC's Applied Meats Science team.

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